Master Thesis

Czech
Technical
University
in Prague

F3

Faculty of Electrical Engineering
Department of Microelectronics

Design of Power Conditioning Circuit for Energy Harvester

Po-Wen Chen

Supervisor: Ing. Vladimír Janíček, Ph.D.
Co-Supervisor: Prof. Huang-Jen Chiu, Prof. Jing-Yuan Lin
January 2021

MASTER‘S THESIS ASSIGNMENT

I. Personal and study details

Student's name:	**Chen Po-Wen**	Personal ID number:	**495572**
Faculty / Institute:	**Faculty of Electrical Engineering**		
Department / Institute:	**Department of Microelectronics**		
Study program:	**Electronics and Communications**		
Specialisation:	**Electronics**		

II. Master’s thesis details

Master’s thesis title in English:

Design of Power Conditioning Circuit for Energy Harvester

Master’s thesis title in Czech:

Návrh obvodu "power managementu" pro Energy Harvester

Guidelines:

1) Study the power conditioning circuits principles used for energy harvesters. Analyze available commercial products.
2) Design a circuit used for harvesting, managing, storing the energy from energy harvester designed in Coventor.
3) Simulate the properties of this circuit in Cadence and make a connection between the Coventor simulation results and the proposed conditioning circuit.
4) Optimize the properties of the circuit for maximum performance.
5) Compare reached parameters with common design proposals.

Bibliography / sources:

1) CMOS Circuits for Piezoelectric Energy Harvesters: Efficient Power Extraction, Interface Modeling and Loss Analysis, ISBN-13: 978-9401792875
2) Nanostructured Piezoelectric Energy Harvesters, ISBN-13: 978-3319096315
3) Coventor Tutorials, www.coventor.com
4) Cadence Design Tutorials, www.cadence.com

Name and workplace of master’s thesis supervisor:

Ing. Vladimír Janíček, Ph.D., Department of Microelectronics, FEE

Name and workplace of second master’s thesis supervisor or consultant:

Date of master’s thesis assignment: **18.09.2020** Deadline for master's thesis submission: **05.01.2021**

Assignment valid until: **19.02.2022**

Ing. Vladimír Janíček, Ph.D. Supervisor’s signature	prof. Ing. Pavel Hazdra, CSc. Head of department’s signature	prof. Mgr. Petr Páta, Ph.D. Dean’s signature

III. Assignment receipt

The student acknowledges that the master’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master’s thesis, the author must state the names of consultants and include a list of references.

.	
Date of assignment receipt	Student’s signature

Acknowledgements

I am grateful to Ing. Vladimír Janíček, Ph.D. (janicev@fel.cvut.cz) for his guidance. This thesis would not have been possible without his contribution. The experiments' quality was greatly enhanced by the gracious assistance of Zhong-lin, Ashish, and Ruhani. Thanks to Shou-Yue for advising on the whole thesis design. Thanks to Prof. Huang-Jen Chiu and Prof. Jing-Yuan Lin for strong support in the double-degree program. This research has been supported by the Electronics and Communications group of the Department of Microelectronics of Czech Technical University in Prague and the Power Electronics Lab(EE502) of the Department of Electronics and Computer Engineering of National Taiwan University of Science and Technology.

Declaration

I declare that this work is all my work, and I have cited all sources I have used in the bibliography.

Prague, January 2021

Abstract

This work proposes and demonstrates an IC design based on a simple piezoelectric energy harvesting model combined with a boost converter. A piezoelectric energy harvesting model was made, and to respond to each azimuth's vibration, and the size limitation of IC production, a piezoelectric energy harvesting matrix smaller than 4mm*4mm was made. Moreover, analyzed using CoventorWare and MEMS+. Cadence constructed and analyzed an energy conversion circuit suitable for the piezoelectric energy harvesting matrix model. The piezoelectric energy harvesting matrix model and the energy conversion circuit are implemented in cooperation with MEMS+ and Cadence. Analyze and produce integrated IC on Cadence. Experimental results show that an integrated circuit integrating energy harvesting and energy conversion can be realized more easily through the above software's cooperation. The cost and workforce of design and manufacture are greatly reduced.

Keywords: Piezoelectric Energy Harvesting, Energy management, CoventorMP, Cadence

Supervisor: Ing. Vladimír Janíček, Ph.D.

Co-Supervisor: Prof. Huang-Jen Chiu, Prof. Jing-Yuan Lin

Acronym-list

EH - Energy Harvesting
SHM - Simple Harmonic Motion
PV - Photovoltaic
IoT - Internet of Things
REM - Renewable Energy Management
MPP - Maximum power point
WSN - Wireless Sensor Network
TES - Thermal Energy Harvesting System
SES - Solar Energy Harvesting System
VEH - Vibration Energy Harvesting System
EHS - Energy Harvesting System
TEG - Thermoelectric Generator
MEMS - Microelectromechanical System
PDPA - Power Density Per Acceleration
PEH - Piezoelectric Energy Harvester
EMH - Electromagneticenergy Harvester
EHC - Energy Harvesting Circuit
WFEH - Work Function Energy Harvester
PZT - Lead Zirconate Titanate
PVDF - Polyvinylidene Fluoride
AIN - Aluminum Nitride
MFC - Piezoelectric Microfiber Composites
WPT - Wireless Power Transfer
PLC - Programmable Logic Controller
IC - Integrated Circuit
ACBEH - Auxetic Cantilever Beam Energy Harvester
MPPT - Maximum Power Point Tracking
ZCS - Zero-Current Switching
SC - Switching Capacitor
FEA - Finite Element Analysis
FEM - Finite Element Method
PWM - Pulse-Width Modulation

Contents

Figures

Chapter 1

Introduction

1.1 Energy Harvesting

This article will discuss the basics of energy production and its forms to obtain energy from different sources. After extensive literature research, the students summarize possible environmental energy sources and explain the potential for future energy - harvesting plants for the production and generation of electrical energy without the support of conventional energy storage systems. This chapter gives a brief overview of the current research state in renewable energies and discusses some of their possible applications. Calculations show that energy production can be increased by assembling more devices.[1]

Energy harvesting, also known as energy recovery or environmental energy, refers to extracting energy from the environment and converting it into electricity. Energy generation works by using ambient energy that is otherwise dissipated or wasted in the form of heat, vibration, or light. This is where energy comes in, which offers several advantages over other renewable energy forms such as wind and solar.[2]

We are also looking at energy harvesting approaches that complement conventional energy storage systems, such as those found in wind turbines, solar panels, and wind farms. Figure 1.1 is a schematic diagram of the basic principles of energy harvesting. There are several ideas and options currently being developed that can provide new energy resources. These are also considered in the context of the complement of the energy harvesting approach.[1][3]

The fuel sources needed to operate harvesters are readily available and can be collected free of charge. Energy harvesting techniques offer a great alternative to energy saving to replace batteries in many low-power applications. When it comes to power-saving electronics, it is promising as a potential solution to battery scarcity.[2][4]

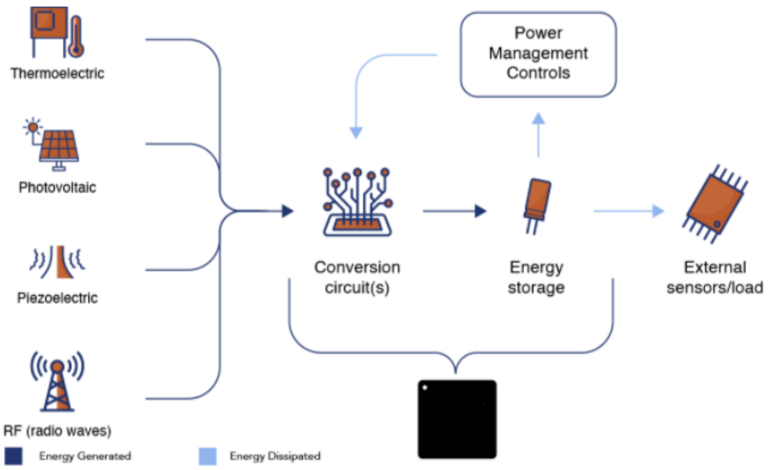

Figure 1.1: The basic principles of energy harvesting.[2]

For example, temperature gradients occur during internal combustion engines, and electromagnetic energy is generated by television and radio broadcasts. This technology captures the energy in heat, light, radio waves, or other electromagnetic waves.[4][5]

The selection of the appropriate energy harvesting technique depends on the application, whereby movement, light, and temperature are selected as the system's primary energy source. Coils and transformers must also be considered environmental energy sources, depending on how much energy is required for each application. The performance of energy harvesting depends on the efficiency of the system and the quality of its components. Energy harvesting can offer a variety of benefits, such as lower power consumption, and lower maintenance costs, etc.[1][6]

Despite advances, batteries' supply to portable microelectronics and wireless devices provides only a limited amount of electricity. Energy harvesting can sustainably power portable devices such as mobile phones, tablets, computers, and other portable electronic devices. Environmental energy conservation is a process in which energy is extracted from the environment and is also known as energy-saving or power harvesting. This article investigates the use of environmental energy obtained to supply micro-nano devices with sustainable electricity. A variety of techniques are available for energy recovery, including the use of micro-nano devices, photovoltaics, solar cells, and other forms of energy production.[1][5]

For example, some systems convert random movements, including ocean waves, into useful electrical energy used for autonomous monitoring through oceanographic monitoring and wireless sensor nodes. Environmental energy sources can also be classified in various ways, such as wind, solar, hydroelectric, geothermal, and hydrothermal sources, all of which can make portable wireless systems fully battery-independent and self-sufficient. Systems with PV cells, therefore, require integrated energy storage systems for the high power density.[1][3]

The increasing energy demand in the future, such as energy storage, electricity generation, and transport, must be met with the associated building blocks of energy production. These efforts should be identified and defined by exploring the physics behind energy - the harvest and technologies that can capture and store energy. The research reviewed in this paper focuses on energy recovery systems, which are relatively well-developed technologies. Although energy generation is comprehensive and most energy generation technologies have some applicability to SHM, the paper is not intended to provide an exhaustive literature review.[6]

On the other hand, energy harvesting technology provides efficient restart options for essential goods such as batteries and makes replacing batteries unnecessary when costly, impractical, and dangerous. Energy harvesting is beneficial because it provides an efficient way to power electronics where there is no conventional power source, eliminating the need to run end-to-end wires for applications. The extreme scarcity of energy makes it an ideal candidate for a wide range of energy harvesting applications, including solar panels, wind turbines, solar photovoltaic cells, and solar thermal power plants. Figure 1.2 is a schematic diagram of basic components of an energy harvesting system. The energy production process takes different forms depending on the source, amount, and type of energy converted into electrical energy. Energy harvesting means extracting energy lost to the environment, capturing it, and using it to enable self-sustaining high-efficiency technology. The size of the power to be delivered is not the only factor determining a designed device's movement, but its efficiency is a key factor, as is its cost-effectiveness and reliability. All of these energy and harvesting devices described above are capable of converting mechanical work into electricity, and all are highly efficient in their ability to convert mechanical work into electricity.[7]

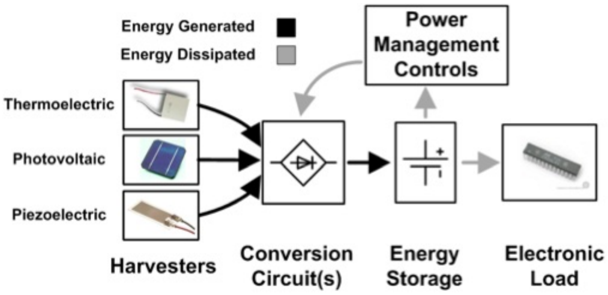

Figure 1.2: Basic components of an energy harvesting system.[7]

Generating energy from the sun offers a clean solution to growing energy problems and can help reduce fossil fuels such as coal, oil, natural gas, and renewable energy sources. To meet the demanding energy supply - demanding requirements for modern equipment - high-efficiency solar conversion is required, and solar energy is also a preferred candidate for operating highly efficient, cost-effective energy storage and power generation systems. Solar energy is also an important energy source for many other applications, from power plants to medical devices and industrial plants.[8]

The energy production process takes different forms depending on the source, amount, and type of energy converted into electrical energy. In its simplest form, an energy harvesting system requires the following three key components: If this energy is sufficient to power the device directly, the application or device that runs on this energy can operate without batteries. The converter and its harvester are the energy sources collected by an energy-saving device, such as solar panels, wind turbines, solar cells, and other energy-generating devices. This article will discuss the basics of energy production and what form it takes to obtain energy from different sources. Energy harvesting consists of electrical energy, conditioned for direct use but stored and accumulated for later use. [7]

The selection of the appropriate energy harvesting technique depends on the application, whereby movement, light, and temperature are selected as the system's primary energy source. Once identified, however, the use of a complete platform that provides space for component optimization can help facilitate product integration and improve the energy harvesting system's overall performance. If there is a need for a powerful, cost-effective, energy-efficient system, this is the place to do it. As the name suggests, it is electrical energy that becomes available immediately as it moves from one component to the next.[6][9]

However, especially in the industrial and automotive sectors, the next product range will benefit from energy generation from the environment. As IoT moves more into industrial spaces, harvesting vibrations, heat, and internal light sources are becoming increasingly important.[9]

The researchers conducted a study on alternative energy sources that could supply electronic devices with small amounts of electricity, and this is explained in this section of this article. The researchers conducted a series of experiments on various energy production methods, such as wind, solar, geothermal, and hydropower.[1]

1.2 Replace the Battery with Energy Harvesting

Today, Renesas Electronics Corporation introduced an innovative embedded controller for energy harvesting that eliminates the need for batteries in IoT devices and can replace them. Energy harvesting generates available energy from the environment through vibrations, heat gradients, and solar radiation and converting it into storable electrical energy. The project aims to increase energy obtained through vibration and human movement by replacing batteries in small wireless electronic devices with a small, cost-effective, high-performance, energy-efficient battery storage system. Renewable Energy Management (REM), a process for generating energy, in which energy is converted into usable electrical energy. Dutch start-up Nowi has launched a small energy harvesting chip that could solve one of the biggest problems facing the battery industry - the lack of energy storage. Furthermore, replace the battery inside smart devices such as smart thermostats, smart lighting, and smart sensors. This enables industrial IoT and wireless product designers to significantly extend the battery life and eliminate the need for battery replacement in a way that reduces reliability.[10] [11] [12] [13] [14]

This means that a weather sensor can supplement its battery power with solar energy. Energy harvesting is the process in which a small amount of energy is absorbed and stored from the environment by vibration, heat gradient, and solar radiation, as well as by human movement. MPP tracking to ensure that most energy is recovered and no batteries are needed in the device, such as a wind turbine, solar panel, and so on.[15] [16] [17]

This article looks at an energy-limited device that can generate energy from a surrounding energy source (for example, two energy-supply nodes) and formulate an energy planning problem. The key question is how to reduce the power consumption of the wireless sensor nodes so that energy harvesting can meet the supply needs. Energy harvesting increases the possibility of self-operated systems that are more efficient in energy consumption, energy storage, and energy efficiency.[13] [18]

Many engineers need to evaluate whether energy harvesting solutions can replace or complement existing energy solutions. Some designers put all the work and effort into evaluating energy harvesting solutions to find that the energy harvested is not enough to power a particular system. Successful products that use non-rechargeable batteries could extend the life of the system by adding energy harvesting. This problem can be solved with controlled - energy - harvesting technology, which allows for eternal battery life.[16] [17]

The cost of changing batteries can quickly add up, and harmful materials can enter the system if batteries are thrown away improperly. Although batteries have a long battery life, the cost of changing batteries has risen, which will be a major obstacle to introducing smart meters and other energy-saving devices. The next generation of energy harvesters is expected to cost less than 1% of the cost of replacing a battery, but it will be able to harvest a useful amount of energy with increased flexibility, allowing more efficient use of battery energy and lower unit costs. This reduces the dependence on batteries in an environment where the available environmental energy types change periodically.[16] [19] [20] [21]

For this reason, an alternative solution for batteries must be sought, and environmental energy harvesting devices are a possible alternative. Energy harvesting, also known as energy-saving, uses renewable energy to power autonomous electronic devices and circuits. Energy harvesting is not a new concept and is practiced in various ways, from wind turbines using wind to hydroelectric generators that generate energy by moving water to solar energy for satellites. Unlike battery-powered appliances, harvesters use renewable energy sources such as wind and solar power, as well as solar panels, wind turbines, solar cells, or solar photovoltaics to power them.[13] [22] [23]

In an environment where the available types of environmental energy change periodically, batteries' dependence can be further reduced. In addition to saving costs by operating battery-free sensors, the sensors can also be operated using the energy harvested, saving costs.[19] [20]

The energy harvester could replace the battery in many applications and offer an unlimited run time if complete independence from the power supply is desired. We have looked at and discussed the harvesting of vibration energy with a piezoelectric generator. The device is used in various applications such as solar panels, wind turbines, and wind farms. There provides an overview of the possible applications of vibration energy harvesters and their potential applications. A miniaturized fuel cell with an energy harvester can replace a battery if it is needed in the future if complete independence from energy networks and energy storage and storage from renewable sources is desired.[13] [24]

Energy harvesting technology also investigates the use of small sensors in IoT devices in places where batteries cannot be easily replaced. Replacing batteries in hard-to-reach places could easily set you back a few hundred dollars. The problem with IoT sensors, he says, is that many of them need to be used and their batteries recharged and replaced, and if there are thousands of them, it can become a strain to track battery status and install a spare battery.[21] [25] [26] [27]

So we are waiting for batteries and accumulators - powered technologies such as lithium-ion batteries - to meet our power needs and the required lifetime together. Energy harvesting is an opportunity to meet the challenge currently posed by the finite life of energy sources such as batteries. Even when batteries have a longer battery life, changing batteries leads to higher costs, which is a major obstacle to introducing energy harvesting technology in the IoT industry. [13] [21] [28]

Energy generation will evolve at the chip and small-device level, but whether it is considered powerful enough to compete with battery technology improvements remains to be seen. If we look further into a hypothetical future in which energy harvesting technology is improved, and the energy requirement for operating larger, more complex devices is reduced, there are many possibilities. While we once considered achieving near-unlimited performance on mobile devices, we are now content with more modest expectations.[26] [29]

If complete independence from the grid is desired, we could replace the battery with a miniaturized fuel cell energy harvesting cart and ensure an unlimited lifetime. The battery can be replaced in many applications, but only if it is battery-free and used during use.[24]

Successful products that use non-rechargeable batteries could extend the life of the system by adding energy harvesting. This problem can be solved with controlled - energy - harvesting technology, which allows for eternal battery life.[16] [17]

The problem with IoT sensors is that many of them have to be used, i.e., either recharged or the batteries have to be replaced. Fortunately, other ways to generate energy include plugging into the grid and constantly replacing the battery. This could work for ten or a few hundred nodes, but imagine what you could do if your factory had 1,000 nodes and battery replacement was essentially a weekly or daily activity. Imagine replacing batteries at several hundred or a thousand nodes; imagine doing this in a factory with 1,000 nodes.[19] [26] [27] [29] [30]

The longer life of the device leads to lower costs and less invasive procedures for replacing the battery nodes. Battery-less systems are designed to reduce the cost of changing batteries and the number of batteries in a device, such as smart meters.[18] [31]

Energy harvesting promises longer battery life, offers smaller, cheaper batteries, and allows more efficient use of the battery's energy storage capacity. Considering the added value of not replacing batteries and the cost of generating electricity, the total cost of generating energy is significantly lower than the primary battery - based on, but still significantly higher than, a secondary battery. For the reasons mentioned above, we observe that secondary batteries replace more and more primary batteries, thus reducing batteries at a much larger number of nodes than primary batteries in a factory.[19] [32]

As a result, energy harvesting technology could prove useful for replacing batteries at a much larger number of nodes, regardless of the industry. Indeed, it could replace, for example, the entire production line of a large power plant.[28] [33]

This performance will mean that piezoelectric generators will forever be an attractive alternative energy source that offers wireless sensors and devices the potential for energy autonomy. This will become a reality in the coming years by developing new technologies and applications for energy production.[13] [19]

For this reason, an alternative solution for the battery must be sought, and environmental energy harvesters are a possible alternative. Although batteries have a long battery life, their replacement has increased the cost, which will be much more expensive than the original cost of a new battery for the same time.[13] [21]

Energy production is not a new concept and has been practiced for centuries, from windmills that use energy from the wind to hydroelectric generators that generate energy by moving water to satellites that use solar energy. Unlike battery-powered devices, energy harvesting devices use the power of their batteries to self-sustain themselves.[13] [23]

When the surrounding energy sources are continuous and readily available, energy harvesting can minimize routine battery maintenance and extend the device's life. Energy harvesting is an important step in addressing the challenges currently posed by power sources and batteries' finite life. A steady reduction in power consumption opens the door to the next generation of harvesting tools that have the potential to eliminate billions of batteries, according to a new study by researchers at the University of California, San Diego.[13] [19] [23]

Nevertheless - to be developed - energy harvesting techniques could use body heat to extend your phone's battery life in your pocket. Looking further into a hypothetical future in which energy production technology is improved and the energy requirement for larger and more complex devices is reduced, there are many possibilities. Energy generation will continue to evolve at the chip and small-device level, but whether it is considered powerful enough to compete with battery technology improvements remains to be seen. Those who once considered achieving near-unlimited performance on mobile devices may have to settle for more modest expectations.[26] [29]

Energy harvesting techniques are also exploring the possibility of using small sensors in IoT devices to replace batteries in places where they cannot be easily replaced. The problem with IoT sensors is that they have to use many of them, and they have to charge and replace their batteries. If there are thousands of them, it can become a burden to track battery status and install replacement batteries. This challenge could lead to a significant increase in the cost of changing batteries as we grow out of battery production and ongoing environmental problems in battery disposal.[25] [26] [27] [30]

Technology is evolving so fast that it is likely that we will soon be using energy harvesting and eliminating the need for battery replacement. There is much potential for the use of energy harvesting as a battery replacement in IoT devices and other applications.[20] [25]

However, batteries have a limited service life, are expensive to maintain, and cannot embed viable energy sources into WSNs and embedded systems. Researchers are studying numerous methods of generating energy in the body to address these problems that could lead to infinite battery life for medical implants. For the reasons mentioned above, we are seeing that secondary batteries are increasingly replacing primary batteries and are helping to enable the use of renewable energy sources such as wind, solar, geothermal, hydropower, etc.[13] [19] [32] [34]

For this reason, an alternative solution for batteries must be sought, and environmental energy producers are a possible alternative. One of the big advantages of energy solutions - harvesting and low electricity costs - is that they are small and do not require cables to operate. A range of power levels are offered by devices such as the Thermal Energy Harvesting System (TES) and the Solar Energy Harvesting System (SES).[13] [26] [29]

This steady reduction in power consumption opens the way for the next generation of energy harvesting devices, potentially eliminating billions of batteries. By not changing batteries, battery-based systems can be charged and dripped to extend the lives of these systems' disposable batteries. This will also reduce the costs of using disposable battery exchangers and replace many battery packs. Energy harvesting is an important step in addressing the challenges currently posed by the finite life of power sources and batteries, such as the need for batteries for power generation and storage. When power is continuously and easily available from the environment source, it can extend the device's life and minimize routine battery maintenance. [13] [19] [33] [34]

1.3 Various Energy Harvester

Energy harvesting is one of the most important aspects of the life cycle of IoT devices. This article will discuss the basics of energy production and its form to obtain energy from different sources.[7]

Energy generation works by using ambient energy that is otherwise dissipated or wasted in the form of heat, vibration, or light. It can obtain energy from various sources such as wind, solar, hydro, wind turbines, and other sources. Inductive coils and transformers can be considered as environmental or energy sources, depending on how much energy is required for the application. The most common types of energy harvesting equipment available today include coils, transistors, generators, heat exchangers, power plants, solar cells, etc.[1] [2] [35]

Other types of energy harvesters cannot be used individually to generate high performance, but some good candidates are considered if you consider electricity generation alone. The gearbox generator type of the energy harvester can produce higher power with 10 W gearbox generators but does not make sense due to the negative work done in human gear and motion. Meanwhile, gear generators of this type, like all energy harvesting machines, are bulky, lead to high consumption of metabolic energy, and can generate high power with up to 10W gear generators.[36]

Human energy harvesting devices are currently being investigated due to the power consumption limitations for permanent use in portable devices. There are ideas and options currently being developed that have been overlooked, and they can provide new energy resources, but they exist.[1] [37]

With the maturity of individual energy harvesters, the hybridization of various energy harvesting mechanisms is a direction for future research moving in future research.[38]

Most power plants worldwide use turbines that convert heat into mechanical energy, converted into electricity. There are parts of the system that convert ambient energy into electrical energy. For example, a new mechanical "energy harvester" that uses rotational movements can use energy from flowing gases and liquids. The converter and its "harvesters" are the energy source collected by an energy harvester.[2] [6] [7]

In certain situations, energy storage systems can act simultaneously as harvesters, and the dependence on batteries will be further reduced in environments where the available environmental energy types change periodically. Given the growing demand for renewable energy sources such as wind and solar, combining generators based on two or more different principles is much more efficient than using gearbox generators alone. The selection of the appropriate energy harvesting technique depends on the application, whereby movement, light, and temperature are selected as the system's primary energy source. The work also includes the integration of an energy harvester with energy storage for end users.[6] [20] [34]

A simple law of scale was established to investigate the fundamental principles of energy-saving systems and uncover the underlying physics.[39]

Figure 1.3 shows an example of an energy-saving system that includes converting stored energy into useful regulated voltages.[40]

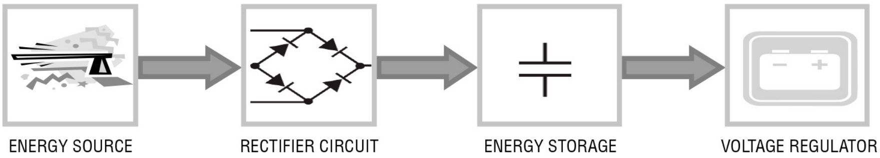

Figure 1.3: Energy harvesting system components.[40]

IoT systems, and we recently reviewed the ultra-low-power management used for their power supply. The generation of vibration energy is based on electromagnetic induction, which uses magnets and copper coils to generate a current that can be converted into electricity in its simplest version. A relatively well-established energy production technology for solar plants is based on the fact that these materials generate an electrical charge when pressed or pressed. Yang et al. have developed a new type of Vibration Energy Harvesting System (VEH), based on a combination of photovoltaics, piezoelectric and pyroelectric effects, to generate solar kinetic and thermal energy from a single material.[20] [27] [38]

Overall, photovoltaic energy conversion is a well-known integrated circuit with a high power output compared to other energy production mechanisms.[1]

It has also been documented that thermoelectric energy recovery systems can be suitable for various applications, such as energy storage and energy conversion, depending on the application type. Special attention has been paid to developing an energy harvester designed to convert mechanical energy into electrical energy that can be consumed directly or stored in the host system for later use. To work, electrostatic energy sources need a source of polarization to convert mechanical energy into electricity by vibration.[1] [20] [35]

The efficiency must be high enough to ensure that the energy consumed by an energy harvesting cycle is much smaller than the energy generated from the source. A piezoelectric energy harvester can achieve maximum power transmission when the external load matches the internal impedance, and this maximum is achieved by using an external power supply. The difference between the energy stored in the battery and the energy stored in an electrostatic energy source can be defined as the difference in energy conversion efficiency between the two energy sources.[7][39][41][42]

The main advantage of pyroelectric energy generation over electrostatic energy generation is that most of its materials and elements are stable at 1200°C or more. The capacitor is charged at a very low voltage, and the current is very different when it comes to converting the required voltage of 3 V.[1][43]

Energy harvesting is often thought of as harnessing ambient energy to produce low levels of electricity. However, you can argue that energy harvesting can also be seen as a subset of renewable energy because it usually can use the same engineering technology, namely photovoltaic or magnetic effect, although renewable energy tends to focus on higher power applications rather than the implementation of environmental energy than low power application is one of the barriers created by these techniques of the electric power and efficiency of relatively low, lead to waste of energy is efficient without using applications, people realize that this will not be bringing their barriers. Similarly, advances in low-power enhancements and energy storage technologies have been driving factors, and it is now possible to create energy harvesting systems that can generate useful electricity levels to power other electronic systems.[44]

1.4 Miniature Energy Harvester

It is a novel technology that is paper-thin and capable of powering wireless sensors and devices. It is uniquely capable of developing an integrated energy and environmental energy recovery solution, and it provides a cost-effective, high-performance, energy-efficient solution for wireless sensor and sensor-to-sensor communication. Micro energy derives energy from vibrations based on electromagnetic induction, which in its simplest form uses magnets and copper coils to generate a current that can be converted into electricity.[13] [20] [45]

Energy harvesting is converting energy into usable electrical energy, whereby any source, amount, or type of energy is converted into electrical energy. It takes different forms based on the source of energy and its ability to convert it into electricity, which in its simplest form generates electricity. Energy harvesting is a method of meeting the challenges currently posed by finite life sources such as batteries. Compared to batteries, energy harvesting represents a new approach to power embedded electronics, increasing the possibility of self-powered systems that are more efficient, energy-efficient, and cost-efficient. Although the energy harvested is in milliwatts' small order, it can provide enough power for a range of embedded systems such as computers, smartphones, tablets, televisions, and other electronic devices. It can meet the challenge of the current finite life of the power source (batteries).[7] [13]

Since the individual energy harvesters are mature, the hybridization of different energy harvesting mechanisms is a future research direction. We recently reviewed several publications on ultra-low-power management used to power IoT systems with energy harvesting. As individual components of Energy Harvesters become more mature, there will be more and more publications demonstrating the use of integrated Energy Harvesting Systems (EHS) as an alternative to batteries as a power source for embedded systems and developing new approaches to the design and implementation of these systems.[13] [38]

Human energy harvesting devices are currently being investigated due to the power consumption limitations for permanent use in portable devices. On the other hand, energy harvesting technology offers batteries as a power source for portable systems and makes the replacement of batteries unnecessary when costly, impractical, and dangerous. However, what is new about these energy sources? Harvested technologies can design and implement efficient energy technologies - harvesting capabilities in modern embedded systems to meet their limitations. We have studied and discussed the potential applications of vibration harvesters using piezoelectric generators and their potential as energy sources for wearable.[7] [13] [37]

Wensi et al. also presented the Tyndall Zigbee WSN mote and compared the energy produced by a thermoelectric power harvester with the energy harvesting capacity of a non-piezo selected generator and presented a comparison of its power consumption. To illustrate the potential of energy harvesting, Wensi et al. show the required performance values for energy harvesting devices. Depending on size, each of these energy harvesters is smaller than the average power harvesting device. Chin et al. with a volume of harvester that is 20 times smaller than any other harvester.[46] [47] [48]

There are some design issues related to thermoelectric energy generation and energy management. To ensure continuous, intention-free WSN particle operations, the device size limitations of ultra-low voltage (less than 0.5 V), small power (1 mW or less), and Thermoelectric Generators (TEG) are severely limited. Efficiency must be high enough to ensure that one energy source's energy consumption-harvest cycle is much smaller than another. To complete the thermoelectric energy harvester's design, a circuit for power control was introduced, connected to a non-piezoelectric generator or a small power source.[7] [46]

In certain situations, the energy storage system can operate simultaneously with the harvester. This mini test focuses on the integration of an integrated energy storage sensor with a small power source. Our work also includes the integration of energy harvesters into energy storage for end users.[38]

In a significant approach to thermal energy production, the researchers demonstrated a novel thermo-magnetic energy harvester that harnesses the energy from a thermal source, such as a magnetic field, and converts it into electrical energy to power a wireless sensor.[48] [49]

Compared to the recent work on thermoelectric energy generation, the energy harvester proposed in this work, based on thermoelectric, can achieve the self-start capability and be used in a wide range of applications. Elizabeth's article mention that now that the device is modeled, the next step for the researchers is to manufacture and test the energy harvesters.[46] [50]

1.4.1 Vibration Energy Harvesting

Korean researchers have developed an energy harvester that generates electrical energy from ambient vibrations of different frequencies through an automatic resonance and tuning mechanism. Figure 1.4 is a schematic diagram of how vibration energy harvester works. Figure 1.5 is a schematic diagram of cantilevered electromagnetic vibration energy harvester. According to leading scientists, the future of vibratory energy harvesting, one of the most promising research areas, looks bright.[51] [52]

This type of energy production, formally known as Vibration Energy Harvesting (VEH), is one of the most promising research areas in the field of renewable energy and is the main focus of our research. We have been

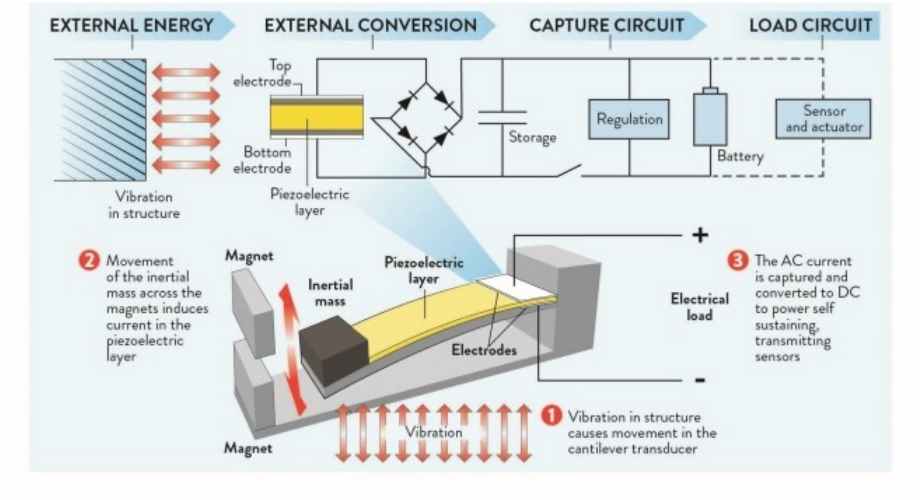

Figure 1.4: How vibration energy harvester works.[52]

developing a decentralized generator that converts mechanical energy into electrical energy that can be directly consumed or stored for later use in a host system. Special attention was paid to the construction of an energy harvester, which is to convert ambient vibration energies into useful electrical energy at the site of operation, according to a press release from the Korea Institute of Technology.[35] [53] [54]

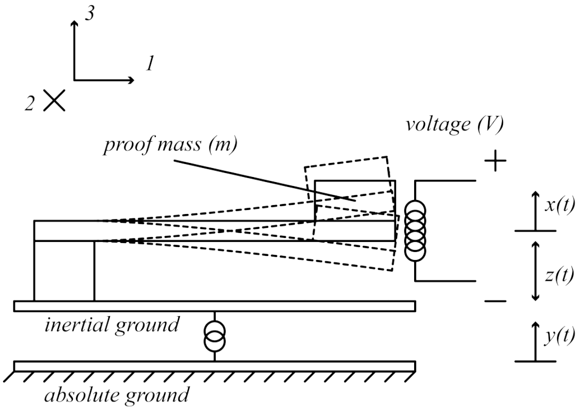

Figure 1.5: Cantilevered electromagnetic vibration energy harvester.[53]

The reported energy harvesters for bridge vibrations were classified according to the acceleration of the vibrations. The classification of bridge vibrations in the energy harvester was carried out—figure 1.6, 1.7 show three different architectures of piezoelectric energy harvesting of this work.[55]

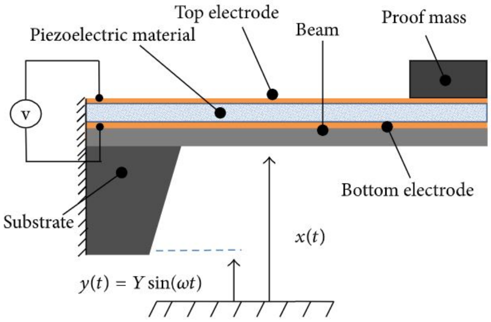

Figure 1.6: Unimorph cantilever type PE-VEH.[55]

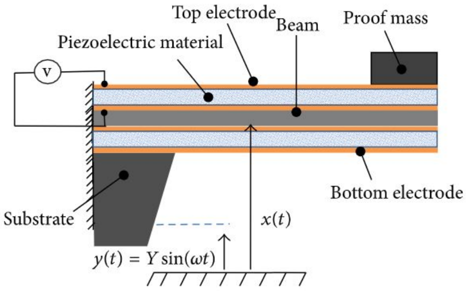

Figure 1.7: Bimorph cantilever type PE-VEH.[55]

When working with kinetic energy, movement can be divided into two groups: vibration and impulse. These lines should help us understand the energy harvesters' vibrations based on accelerating the bridge vibrations in the energy harvesters and their effects on the energy harvesters.[56] [57]

Hypothetically, vibrational energy can be converted into electrical energy and vice versa. When generating energy through vibration, the energy harvesting devices should be designed to match the frequency at which the environment vibrates. Certain types of vibrations are preferred when there is an intention to power a sensor or monitoring system.[56] [58]

In most bridge vibration energy harvesters, the resonance frequency is in the range. The vibrations drive the mechanical generator at a frequency that corresponds to the resonance frequency of the energy harvesting generator.[55] [56]

This article will discuss the basics of vibration energy harvesting and look at different types of energy harvesters. Firstly, the article suggests that we should offer the possibility of generating more energy from multi-frequency vibrations. If you want to power a complicated system or is in a place full of kinetic energy, harvesting vibration energy is an option. If you look at a linear motor driven by a mechanical generator with a resonance frequency and a vibration frequency, you can operate it at any frequency.[57] [59]

COMSOL Multiphysics was used to model the vibration energy harvesting cart's design, optimize output power, and predict the power density attainable. Dynamic tests showed that the energy harvesters could operate operating conditions that were not previously demonstrated by MEMS vibration energy systems. The ability to harness the energy of vibration over a wide frequency range has also been demonstrated in several studies, and the work found that this is independent of the size of the device, making it an ideal candidate for use in a wide range of energy harvesting applications.[60][61]

Two new techniques for linear harvesting have been introduced in the field of multi-frequency vibration energy production. The second tool introduced is Piezoelectric Energy Harvester (PHR) technology, which estimates the vibrational energy over a wide frequency range, such as the frequency of light and sound. We have also used it to investigate this technique's use to extract energy from high-frequency vibrations in various applications.[55][62]

This energy, also known as kinetic energy production, is the next field to receive greater attention, as this field has been studied for many years but has so far led to a few commercial applications. This includes energy storage and energy storage from high-frequency vibrations in various solar panels, wind turbines, solar cells, and other energy sources. Vibration energy harvesting can be used in applications where sensors and measuring instruments are used to collect data on certain aspects and where traditional energy sources such as batteries are either too expensive or simply not functional. It can supply electricity to systems that connect to and communicate with a company's movable assets' conditions and location.[35][56][58]

An article on freight trains estimates the potential for energy storage and storage from vibrations in various applications such as solar panels, wind turbines, solar cells, and other energy sources. The energy harvesters have a resonance frequency of 10 Hz and are therefore expected to operate simultaneously as the commercially available wireless sensor nodes described in this introduction. Besides, the Power Density Per Acceleration (PDPA) values for these devices are on the high side and are therefore expected to work similarly to other energy harvesting devices. The specified bridge vibration energy harvester is based on an electromagnetic transduction mechanism and can be operated at certain frequencies. The main problem in developing a bridge vibration energy harvester is the resonator, so would it produce optimum performance resonance conditions?[55]

In combination with the OMRON electret energy harvester, it can store the energy from vibrations in the uW range and convert it into drive voltage for general sensors with high efficiency. Dynamic tests have shown that the energy harvesters can operate operating conditions that have not been demonstrated before by a MEMS vibration energy harvester.[60][63]

Here is the rub: The vibration harvest by human movement is not nearly ideal, and you will not get nearly 10 mW of harvested power from a reasonably large vibration harvester unless it is an electromagnetic piezoelectric. This is independent of the device's size, which makes OMRON electret energy Harvesters a good candidate for use as a cost-effective, highly efficient energy harvesting device. It could also be used in several other applications, such as energy storage for sensors.[60] [64]

The biggest problem is that the harvester's energy declines rapidly as the size of the harvester decreases. Therefore, a balance between size and energy must be found, and for this reason, energy harvesters must be either adapted to the environment in which they are installed (resonance - induced resonance) or to a certain temperature, pressure, humidity, or other environmental conditions, which limits their use.[51] [65]

The bandwidth of kinetic energy generators is often a few Hz, which requires a vibrating environment and a fixed frequency. The main reason for this is that environmental vibrations have a lower frequency spectrum, while small energy harvesters tend to have much higher resonance frequencies due to their size. Vibrations in an energy harvester are based on resonance jet structures, and the frequency range of the beam ranges 100 Hz.[56] [60]

When energy is generated from motion, power electronics must handle the variable amount of energy generated. This line is intended to help you understand how vibrations in an energy harvester can be based on resonance beam structures, the frequency range of the beam, and the energy yield. Figure 1.8 is a schematic diagram of basic model of a vibration energy harvester.[56] [57]

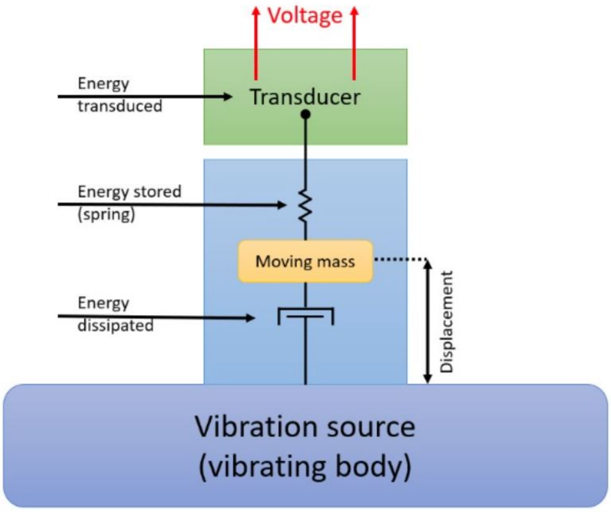

Figure 1.8: Basic model of a vibration energy harvester.[57]

A typical piezoelectric vibration energy harvester can deliver up to 10 mW of power, ideal for high-frequency machine vibrations. Generally, a mesoscale device can generate several microwatts of power from ambient vibrations and microwatts of power from microwave devices, but this covers a wide frequency range, from low to high frequency.[35] [64] [66]

Piezoelectric vibrations and energy generation represent several problems associated with their use, especially in industrial environments where vibrations are ubiquitous. A wide range of energy harvesting equipment has been studied and more on this in the current issue of the Journal of Electrical Engineering and Computer Science, which is available here.[66] [67]

A piezoelectric energy harvester consists of a vibrating spring-mass system coupled with a series of piezoelectric elements designed to convert elastic energy into electrical energy. These are compact devices that allow energy to be used to power autonomous electronic devices. Electromagnetic Energy Harvesters (EMH) are similar to the PEH, except that the mass is still used instead of excitation, but magnets and coils have replaced the piezo material. Figure 1.9 shows an example of an electromagnetic energy harvesting device similar in design and function to the PEH.[57] [65] [68]

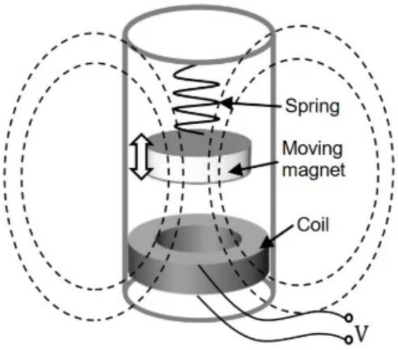

Figure 1.9: Example of an electromagnetic energy harvesting device.[57]

In this study, we observed that the energy harvesting device's output vibration depends on the number of vibration cycles per second of a 3 mm displacement process in the magnet. The magnet is shifted by 3mm for each cycle to generate energy in the form of voltages.[69]

The vibrations drive a mechanical generator with a frequency that corresponds to the Energy Harvesting Generator's resonance frequency. The vibration-driven generator usually consists of a resonator that uses an amplified vibration source and a conversion mechanism that converts energy from the vibration into electrical energy. A magnetic vibration energy harvesting cart developed at the University of Southampton is half the size of such a generator, but the system's multi-magnet arrangement has been improved.[56] [69] [70]

Various Techniques of Vibration Energy Harvesting

A. Piezoelectric Energy Harvesting. Recently, new technology has been developed that uses piezoelectric materials to extract energy from a vehicle's wheels. In this paper, electrical energy production by inserting a Piezoelectric material into tires is investigated to reduce fossil fuels' consumption ultimately. Mechanical energy is the most widely available energy source globally and one of the most important renewable energy sources for vehicles.[68] [71]

The piezoelectric material that is exposed to it is a phenomenon that has been used in various experiments to generate energy and voltage. In the article, they find that the thick laminate produces a high level of energy when it is fully induced by snap-through.[72] [73]

The piezoelectric energy harvesting is designed to convert small movements into electrical energy. We are interested in compact devices that allow us to use this energy to power autonomous electronic devices. These energy harvesters can supplement other energy reserves such as batteries and extend their life in other forms. One of the biggest problems with electrically powered prosthetic implants is that many of them need to be recharged, cumbersome when the power source is outside the body.[65] [68] [74]

Piezoelectric energy harvesting offers a good solution for this area, as the economic disadvantage can be compensated. Piezoelectric energy harvesters provide alternating current, but connecting them to electronics requires rectification that is unsuitable for conventional battery drives. Therefore, the energy that the Piezoelectric material gains from the vibration power (alternating current) must be operated at high voltages to generate a usable direct current. This is unlikely, as the Piezoelectric element cannot convert enough energy to overcome the capacitor's energy electrode through a high charge. In this case, the electronics have to step in and out, which can have economic disadvantages.[68] [75]

One last area bearing fruit in the emerging piezoelectric energy generation technology is the so-called smart road. This has the potential to advance basic research and development, which should ultimately be beneficial, leading to the harvest of good vibrations that ultimately benefit all of us.[68]

The energy generated is proportional to the load's frequency, and the operation of a resonance system can produce higher energy. Piezoelectric energy generation is a process in which piezoelectric materials are converted into electricity. One of the most interesting energy production applications, where piezoelectric materials are used to convert mechanical energy, which is normally wasted, into an electrical energy source. The application areas and applications are wide-ranging, from generating energy from vehicle vibrations to harnessing pedestrian traffic and supplying electricity with localized lighting.[74] [75]

The energy harvesting mechanism has ten unique applications, the respective orientations and groupings of piezoelectric elements are maintained, and the energy is forcibly withdrawn.[74]

The ZnO columns generate electricity by self-loading, while the Schottky barrier behavior serves to separate and maintain the electric charge and build up potentials that are later released on the compressed side of the piezoelectric nanowires.[68]

Piezoelectricity is a material property that manifests as the voltage generated by the application of mechanical forces. It is described by coupling the electric field in the horizontal direction and the electric energy in the vertical direction, and vice versa. The effect describes the direct reverse play. The planar deformation of a piezoelectric material generates electric fields in both vertical directions; these are achieved by a rectifier (DC / DC converter circuit) for storing the generated electrical energy. A combination of 31 modes achieves the conversion of these energies. When a piezoelectric crystal is placed between two metal plates and exposed to mechanical force, an electrical charge is created on the crystal balance, which causes the planar deformations in its surface, and when coupled to a metal plate, it converts this charge into energy.[65] [71] [72] [74]

Mechanical strain is usually converted to electrical energy by piezoelectric effects. However, most piezoelectric devices produce power of milliwatts' order, limiting their use to small system applications. In this method, the piezoelectric material is usually incorporated into the bending structure in the form of a composite layered cantilever, which oscillates to strain the active piezoelectric material and generate electrical energy. Figure 1.10 shows the basic architecture of piezoelectric energy harvesting.[76]

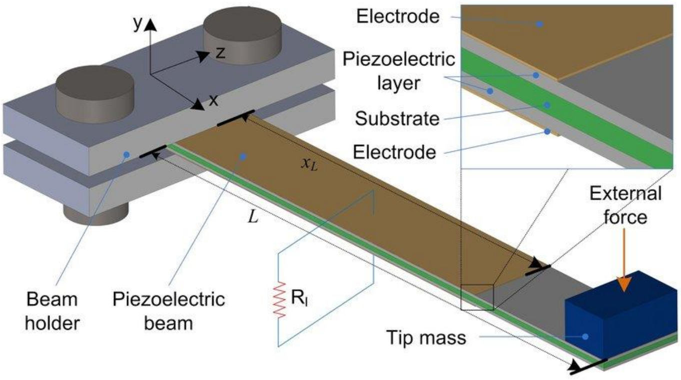

Figure 1.10: Piezoelectric energy harvesting.[76]

Many piezoelectric harvesters use piezoelectric material properties to power a variety of applications. The efficiency and performance of piezoelectric harvesters set vary according to the material.[77] [78] [79] [80]

B. Electrostatic Energy Harvesting. Energy consumption is increasing rapidly worldwide, and extensive research is continuing to find workable solutions to the energy crisis problem. To reduce demand rates, energy production as an alternative energy source is gaining in importance.[35]

The work, published in the journal (Toward Large-Scale Energy Harvesting by a Nanoparticle-Enhanced Triboelectric Nanogenerator), represents a new approach to effectively convert environmental, mechanical energy into electrical energy. The thesis aimed to investigate the feasibility of a novel CMOS-based energy-saving circuit to increase mechanical energy production efficiency from surrounding thermal energy sources such as wind, solar, and wind turbines. This work proposes an integrated Energy Harvesting Circuit (EHC) with high efficiency and low operating costs based on the previous analysis. This work has produced and used a combination of high-performance, cost-effective, and energy-efficient materials for the characterization and construction of an EHC.[81] [82]

This is connected to a storage capacitor C_{sto}, which supplies the current load circuit. This work shows the accumulated electrical energy in the storage capacitor C_{sto} as it is represented by the amount of electric energy and the power of the E_{sto}. The stored electric energy in E_{sto} is normalized with the maximum electrical energy stored in each of these storage capacitors. The movement and working function of the energy harvester is assumed in a periodic period t, but the amount of energy taken along this way is also somewhat different. This work considers the coherence between the E_{sto} and the storage capacitor C_{sto}. In this way, coherence can synchronize the energy transfer process to create the perfect conditions to transport energy to the reaction center.[83]

Railways, platforms, footpaths, highways, and gyms are places where harvesting machines can generate electrical energy caused by large mechanical vibrations from human activities. Circuits in work already use electrostatic electrostatics, in which the operation of the energy harvester is comparable to that of the Work Function Energy Harvester (WFEH). This also includes using many electrical capacitors, such as those used in the EHC and the storage capacitor.[35] [83]

Electrostatic energy harvesting devices have the most specific advantages, and this is the performance of an electrostatic harvesting device. They have significantly lower operating costs than WFEH, higher efficiency, and lower power consumption.[84] [85]

In other words, the harvest efficiency in the variable load case is the mechanical resonance frequency corresponding to the vibration frequency (underlined by the matching). In membrane-based energy harvesters, stiffness is stretched, and this work determines the loaded mass and stiffness of the membrane.[83] [86]

The energy storage unit connected to the line is charged, and the voltage difference between the electrified body and its non-electrifying body is generated. This effect is caused by the difference in the energy storage systems' charging power and the energy harvesters.[83] [85]

As far as the output power is concerned, the maximum average power of 24uW is recorded at the end of the experiment. The ideal working function of an energy harvester operating in a confined mode is shown in this work. A numerical model showing the working functions of energy harvesters, which are estimated using numerical models. The same trend in performance function is determined for each load in both simulations and experiments.[83] [86]

This work is a perspective that illustrates the performance of energy harvesting equipment in different operation modes. This includes both conventional energy harvesting machines and energy-harvested equipment such as wind turbines and solar cells.[85]

Normal energy management and energy generation, which includes the release and storage of the collected energy, is achieved by CMOS-based switches and microcontrollers. Special attention is paid to the design of energy harvesters designed to convert mechanical energy into electrical energy for direct consumption or storage in the host system for later use. Electronic circuits, which facilitate the mechanical-electrical - energy conversion by using variable capacitors, can be constructed either synchronously or asynchronously. This approach can be used to develop other geometric shapes and to design different types of mechanical and electrical components such as mechanical generators, generators and generators.[35] [82] [86] [87]

When an electric field is applied to a piezoelectric material, a mechanical load is created. This electric charge, in turn, leads to electric fields and voltage gaps in the material. On the contrary, electret-based conversion does not require the initial electrical energy to function. The structural deformation directly induces the output voltage, just like with a piezoelectric material![35] [83] [88]

This work shows a surface - a technology platform that promises an important step toward developing electrostatic energy-saving technology with low energy consumption. This work uses charged droplets to demonstrate the jumping - the electrostatic energy generation of droplets - and define an ideal charge - a limited cycle. This addresses the challenge of designing circuits with limited power and charge - both with an electrostatic harvester and with a current-limited electrostatic energy harvester.[82] [83] [89]

Electrostatic harvesting is one of the most popular types of harvesting currently in use. Changes in capacitance are fundamental to how this type of energy harvesting works. A physically induced vibration changes the capacitance through the appropriate medium. Figure 1.11 and Figure 1.12 show a typical setup for an electrostatic harvester device. As shown, a set of electrodes (stationary and mobile) is used in the device. Since physically induced vibrations separate the electrodes by moving one of them, the capacitance change is proportional to the mechanical energy (vibration) applied to the device. The polarization source is necessary for the electrostatic harvester to convert the vibration into electrical energy. Figure 1.13 is a schematic diagram of simple electrostatic energy harvesting structure.[90]

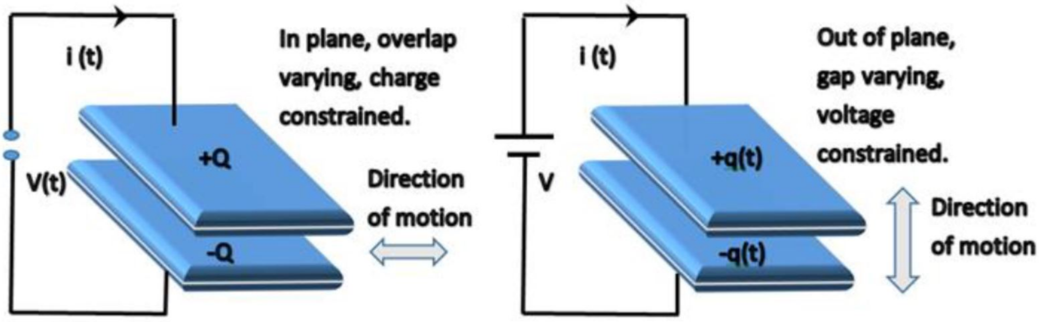

Figure 1.11: Electrostatic energy harvesting.[90]

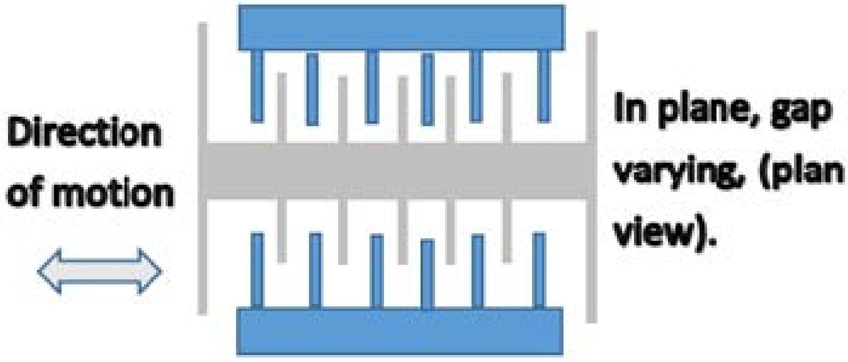

Figure 1.12: Electrostatic energy harvesting.[90]

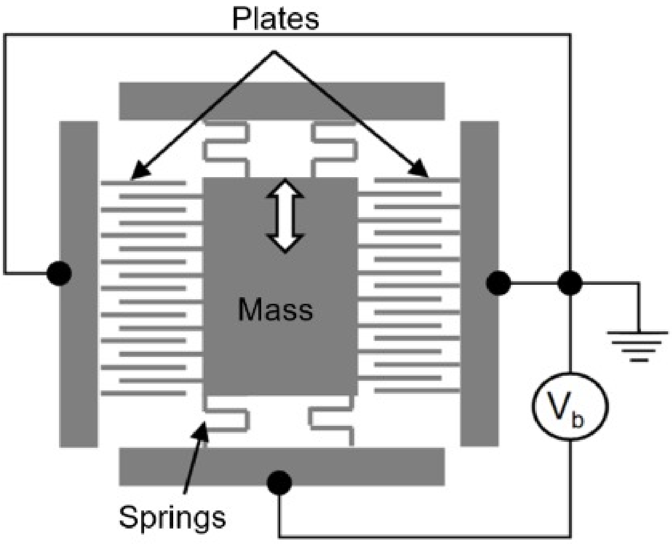

Figure 1.13: Simple electrostatic energy harvesting structure.[57]

Dr. Vladimír Janíček designed a 3D electrostatic generator, a powerful component in a self-powered microsystem, and can provide enough energy to power smart sensors or other devices that need to monitor electronic devices. One of the importance and requirements of such an analyzer is mobility, so the power supply is designed to expect that alternative means of obtaining power will power the device, rather than relying on periodic external sources (such as rechargeable batteries). In this case, the most appropriate power supply method is EH. This study explains the topology design of the electrostatic generator structure.[91][92][93]

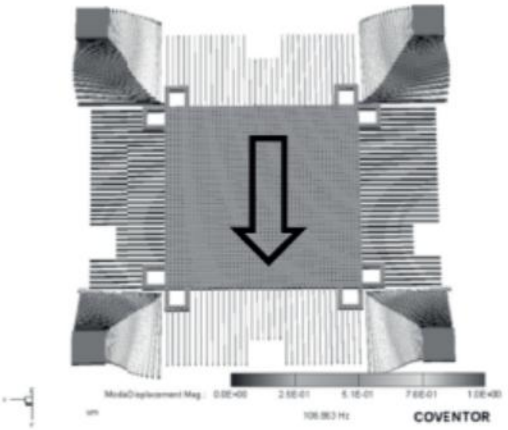

Figure 1.14: 1*st* Modal frequency simulation.[91]

Besides, the structure was developed and modeled as a 3D silicon-based MEMS (micro-electro-mechanical system). The innovative approach involved in achieving very low resonant structure frequencies, where the minimum chip area has the potential to work on all three coordinate axes and the potential must be adjusted to meet the required parameters as Figure 1.14, Figure 1.15, and Figure 1.16, thus ensuring possible directional problems through further development of such approaches. The study included simulations of the structure's electrical and electromechanical characteristics and described the behavior in various modes during the operation and activity phases. The simulation results are compared with the chip measurements provided in the prototype. Such results may suggest possible changes to the developed architecture to extend optimization and adaptability in the application environment.[91] [92] [93]

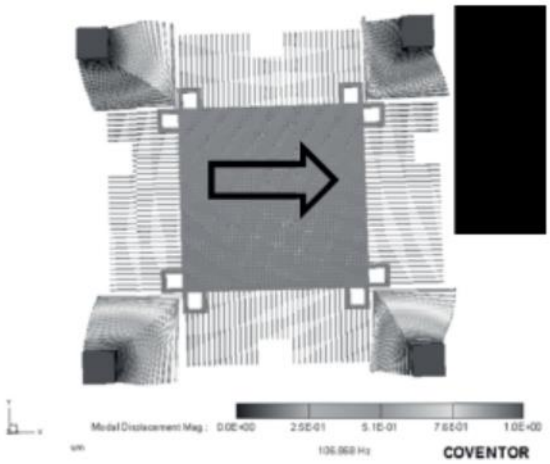

Figure 1.15: $2nd$ Modal frequency simulation.[91]

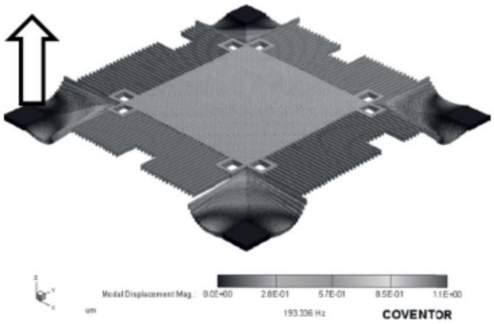

Figure 1.16: $3rd$ Modal frequency simulation.[91]

Chapter 2

Advanced Discussion of Piezoelectric Energy Harvesting

2.1 Theoretical background of piezoelectric energy harvesting

Piezoelectricity was discovered by Jacques Curie and Pierre Curie in 1880. The piezoelectric effect is the direct conversion of mechanical energy into electrical energy through the material's characteristics. They observed that certain crystals responded to the pressure by separating charges on opposite faces and called this phenomenon piezoelectricity. The material types are PZT, PVDF, AIN, and so on. Materials with a high-quality factor (Q factor) will generate more energy. Recently, Piezoelectric Microfiber Composites (MFC) have higher power generation efficiency, generating up to 65% of the input mechanical energy.[94] [95] [96] [97]

In the literature, several design parameters have been studied to maximize the use of piezoelectric materials, from mechanical vibration to electrical output. These parameters are as follows[94] [98] [99]:

Resonance frequency: Must match the vibration frequency of the application.

Structure: For example, the output of using bimorph structure is higher than that of unimorph structure.

Geometry: Different forms of models can generate different energy, and the strip form is the most common.

Thickness: A thinner layer can respond better and generate more energy.

Electrical connection: The model is connected in series to increase the output voltage. Parallel models increase the output current.

Fixation: Cantilever beams produce greater strain than simple beams.

Load impedance: must match the piezoelectric impedance at the operating frequency.

Loading mode: d_{31} will produce larger strain and more energy under smaller external force action.
%%These terms are the ratio of strain to peak stress, and the index indicates the direction of stress that causes strain on the electrode in one direction and direction.
d_{xy} = (strain)/(applied electric field)=(short circuit)/(electrode area)/(applied stress)
Let me divide x and y for you in d_{xy} (assuming a cubic system)
x defines the direction of stress or induced strain in three directions 1 (i.e. x1), 2 (i.e. x2), or 3 (i.e. x3)
y, if the electrode is on the x1x2 surface, the electrode's surface normal will point to the x3 direction.
E.g.:
d_{33} represents the strain in the x3 direction when the electrode is on the x1-x2 surface.
d_{31} indicates that the strain is in the x3 direction when the electrode is on the x2-x3 surface.
d_{32} indicates that the strain is in the x3 direction when the electrode is on the x1-x3 surface.[100]

In W. Ali et al.'s work, the development is focused on the necessary conditions to maximize the AC output power obtained by the piezoelectric harvester using fixed-dimensions MFC material. The piezoelectric harvester is a cantilever whose effective length (L_b) extends from the clamping end to the free end, and the tip mass (m), as shown in Figure 2.1. Electrodes must be plated on piezoelectric materials to collect the generated charges and bend as electron beams.[94]

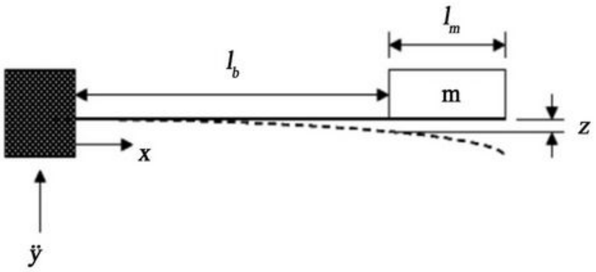

Figure 2.1: Piezoelectric cantilsever.[99]

Williams et al. developed a general model based on inertial kinetic energy. The model is a second-order dynamic system with lumped parameters, which correlates input vibration y(t) with output relative displacement z(t), as shown in Figure 2.2. Where k is the spring constant (device stiffness), d is the total damping (parasitic damping and resistance), z(t) is the relative displacement of the mass relative to the vibrating cantilever, m is the effective mass of the cantilever, y(t) is the input vibration, and $\ddot{y}$(t) is the input acceleration. By applying D'Almbert's law, the dynamic equation of the system is[94] [101]:

$$m\ddot{z} + d\dot{z} + kz = -m\ddot{y} \tag{2.1}$$

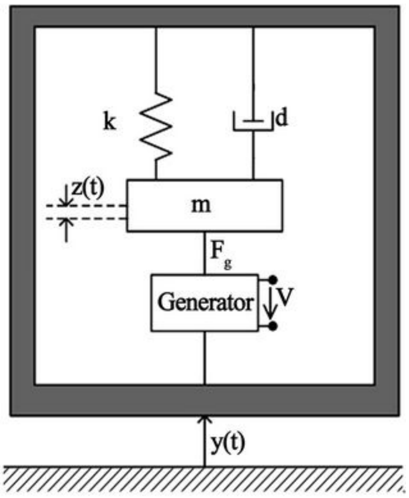

Figure 2.2: Dynamic model of vibration harvester.[101]

The transfer function G(s) of this system is given as[94] [101]:

$$G(s) = \frac{-m}{ms^2 + ds + k} \tag{2.2}$$

The natural frequency equation where Y is the young's modulus, w, h, and l is the width, the thickness, length of the cantilever, m_t is the tip mass, and m_c is the cantilever mass. The natural frequency ω_n is given as[94] [101]:

$$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{Ywh^3}{4l^3(m_t + 0.24m_c)}} \tag{2.3}$$

The total damping coefficient η (mechanical and electrical) is given by[94] [101]:

$$\eta = \frac{d}{2m\omega_n} \tag{2.4}$$

The quality factor is inversely proportional to the damping factor and can be calculated as the resonance frequency ratio (f_n) to the frequency bandwidth (f_{bw}). The total quality factor is given by[94] [99] [102]:

$$Q = \frac{1}{2\eta} = \frac{f_n}{f_{bw}} \tag{2.5}$$

For a sinusoidal vibration signal ($y(t) = Asin(\omega t)$), the instantaneous power dissipation (P) in the damper is equal to the product of the speed and the damping force. The formula where A is the amplitude of vibration. Use the following formula to calculate the efficacy[94] [102]:

$$P = \frac{m\eta A^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\eta\frac{\omega}{\omega_n}\right]^2} \tag{2.6}$$

The maximum power dissipated in the damper appears at the natural frequency. The formula where the peak value of the input acceleration (a) is given by Aω^2. The maximum power can be calculated by the following formula[94] [102]:

$$P = \frac{mA^2\omega_n^3}{4\eta} \tag{2.7}$$

When the mechanical damping is equal to the electrical damping, the maximum power is converted into the electrical domain. Therefore, the maximum electrical output power is equal to half of the equation (2.7).[94] [102]

$$P = \frac{mA^2\omega_n^3}{8\eta} = \frac{ma^2}{8\eta\omega_n} = \frac{ma^2Q}{4\omega_n} \tag{2.8}$$

The above formula shows that the maximum power is directly proportional to the effective mass, input acceleration, and quality factor. In any case, it is inversely proportional to natural frequency and total damping. The piezoelectric cantilever itself generates an output voltage due to relative displacement (mechanical strain). The strain effect uses the deformation of piezoelectric materials to generate positive and negative charges on both sides.[94] [102]

2.2 Resonant frequency of piezoelectric energy harvesting

A cymbal transformer, a power-enhancing structure that can be used to improve the performance of energy harvesters. Piezoelectric Energy Harvesting (PEH) is based on a phenomenon demonstrated by a certain material class, the piezoelectric materials. It consists of a vibrating spring - a mass system coupled to a series of cake elements designed to convert elastic energy into electrical energy.[35] [65] [103]

One of the most interesting energy production applications, where piezoelectric materials are used to convert mechanical energy, which is normally wasted, into an electrical energy source. Some of these plants include solar panels, solar panels, wind turbines, and even solar panels. Piezoelectric ceramics are used for their energy production - harvesters in various applications, such as solar photovoltaics and solar thermal power generation.[35] [75] [103]

Because these elements have high natural frequencies, it is not easy to design an appropriate energy density for their energy harvesters' production. On the other hand, using piezoelectric ceramics for mechanical energy production could provide suitable energies and densities for practical implementation.[104] [105]

On the other hand, a piezoelectric energy harvesting wagon could be characterized by its high energy density and natural frequency. This work derives a new type of energy harvesting device for mechanical energy production from the power reaction of the piezoelectric converter.[103] [104]

We can determine a fixed excitation level by monitoring the maximum output power depending on the excitation frequency. On this basis, it can be emphasized that the energy density harvested and the voltage density produced by the piezoelectric wagon will be at a high level. We can increase the performance of this new type of energy harvesting device for mechanical energy production according to the above criteria.[94] [104] [106]

The question is to capture the optimal amount of energy available when the beam is high enough to fall sharply after a frequency shift. The application of such a functional principle offers a possibility to maintain and increase the maximum output power of the piezoelectric cart at the natural frequency. Besides, this method could also be used to adjust the resonance frequency since the fundamental frequency of the vibration source is predetermined.[68] [94] [104]

However, the potential of piezoelectric energy-saving systems is hindered by the lack of accurate measurement of the frequency of environmental vibrations and their energy content. Energy harvesting is the process whereby

RF is converted into usable electrical energy to power electronic devices. To effectively extract energy from vibrations, we need to understand how much vibration energy is available for harvesting due to the wide range in which the ambient vibrations' frequencies vary.[103] [107] [108]

As mentioned earlier, our work's primary goal is to develop an automatic system that adjusts the harvester's resonance frequency in real-time to the main frequency of the vibration source. In this case, a piezoelectric harvester will be able to adjust its resonance frequency autonomously. So it can be said that their operation at the first resonance frequency will be more stable despite fluctuations in the excitation frequency. The generally researched range for the frequency range of vibration energy generation is between 20 and 100 Hz.[94] [104] [106] [109]

If the natural frequency of the harvester matches the vibration source, the power will be higher. To facilitate the development of a piezoelectric energy harvesting system with a natural resonance frequency, this work derives the maximum vibration amplitude of the conventional system.[106] [108]

The comparison of resonance frequencies shows that the experimentally obtained resonance frequencies are lower than the numerically obtained frequency. The work shows that the energy harvester has a much lower energy density at the fourth resonance frequency. One way to quantify an energy harvesting structure's ability to change its resonance frequency is to estimate its tuning ratio. The more dimensions and weight restrictions are limited to achieve the desired basic frequencies, the more complex it becomes to design energy - harvesting structures.[103] [104] [109]

The piezoelectric buzzer is the same for all three energy harvesters in this study, but the entire system's electrical energy density is lower. Other studies have been conducted to improve output power and reduce the base frequency. These investigations show that the energy harvester has a higher frequency at the four resonance frequencies. Such design principles for harvesters allow multiple resonance frequencies to be obtained close to each other. Although the piezoelectric sums in the three studies in our study are the same, the effect of different working frequencies on the frequency distribution of energy production differs, as each harvest truck operates at different working frequencies.[104] [105] [110]

2.3 Cantilever of piezoelectric energy harvesting

In the last decade, the use of devices that convert ambient vibration energy into electrical energy has increased. One of the most interesting applications is energy harvesting, where piezoelectric materials convert mechanical energy normally wasted into an electrical energy source.[75] [111]

Piezoelectric energy harvesters offer very high efficiency and power density compared to other renewable energy technologies. This suggests that these improvements are reflected in the vibration performance based on MEMS piezoelectric and energy harvester. In this study, they use piezoelectrical ceramic as PZE-1, a type of ceramic, for the first time as an energy harvesting device is a non-mechanical, cost-effective, high efficiency, and environmentally friendly way.[68] [103] [112]

A final area bearing fruit in emerging piezoelectric energy production technology is the so-called "smart road" of renewable energy. In this area, conventional battery power is unsuitable due to the high energy storage cost and the lack of a reliable power supply. Piezoelectric energy harvesting offers the best solution in these areas, as the economic disadvantage can be incidental - gradually and with increasing energy efficiency.[68]

From the device design point of view, there are two main components of a piezoelectric boom: the fundamental vibration source and the strain - the induced piezoelectric layer. A spring-mass suspension inserted into the vibration drives its tip and its mass end by directly exciting fundamental vibrations. The stress caused by this is similar to the pressure-related stress in its base layer but at a much lower level.[68] [103] [112]

The double mass piezoelectric cantilever model has been experimentally validated. Vibration-based on energy harvesting of bimorph - Vibration bars with high - energy - harvesting capacity. Maximum energy harvester for increased electrical performance in traffic-induced bridge vibrations. Vibe - vibrating bimorph cantilever beams for maximum energy generation in bridge traffic.[113]

In this article, the piezoelectric double-mass cantilever girder is presented, which is installed on a cable and inclined bridge. This work shows a comparison of the performance of smooth and Cantilever beams using the PEH - enhanced bimorph - high energy vibration bar - harvesting capacity. Experimental measurements were made to quantify power density and tuning. In summary, a surface of $7cm^2$ has been developed for the maximum energy production capacity of microwatts for a single beam bimorph. The piezoelectric energy harvesting wagon zigzags between the varying peak mass and the electrical connection. Here we see how a maximum energy production capacity of microwatts results from this for the case under consideration.[113] [114]

The future of piezoelectric energy generation will probably depend on developing and improving the rotational energy used for piezoelectric transduction and frequency conversion. Furthermore, on the material side, due to the current performance of piezoelectric materials, it is quite a challenge to develop energy harvesters that can replace batteries as a large power source. In this paper, we analyze the potential of using piezoelectric materials for energy and harvesting applications. To some extent, energy generation's performance has been improved, but it remains a challenge in this area. To characterize the proposed vibration harvesting device's performance, a test rig was constructed according to measurement principles, as shown in this work.[103] [106]

The proposed ACBEH vibratory cable provided higher performance than the previous version of the cantilever vibratory harvester. Compared to the original prototype, the proposed ACBEH recovers significantly more energy from ambient vibrations than the current design.[113]

The energy generated by the piezoelectric harvester can be used as a regenerative power supply for batteries and would certainly help develop electronic sensors in cars. Although our engineers have been researching how to improve the piezoelectric energy harvesting device, we have not produced enough energy.[75] [112]

This work has developed a versatile linear model that can accurately predict the piezoelectric energy harvester's performance.[111]

If the excitation frequency matches the natural frequency of the harvester, a resonance is obtained. This means that the cantilever chair is more efficient in efficiency than the traditional piezoelectric energy generation system. Two cases of realistic appliances should be considered, as the energy harvesters are much smaller and more expensive than conventional energy producers - harvesters. The big problem is that the energy generated by harvesters declines rapidly as these devices' size decreases. So we have to find a balance - away from size and energy.[65] [106] [114]

Chapter 3

Power Conversion

3.1 Energy harvesting power conversion

This article will discuss the basics of energy production and what forms can be taken when extracting energy from different sources. The energy harvested from the environment is converted and transmitted to a DC voltage and then transmitted back again for power conversion.[7] [38] [115]

Energy harvesting is a form of piezoelectric energy production with other energy storage applications, such as power storage and antennas. Traditional system topologies lose some of the energy generated in scenarios where it is below the threshold required to charge an energy storage system or when the light is too low. There are cases where an ambient signal's power level is already below microwatts, and more energy is required to generate enough power for an ultralow-power wireless sensor node. The efficiency of crop integration is key to RF energy transmission and wireless energy conversion (bai et al., 2018). Figure 3.1 is a schematic diagram of conventional power conversion in energy harvesting systems.[38] [115] [116] [117]

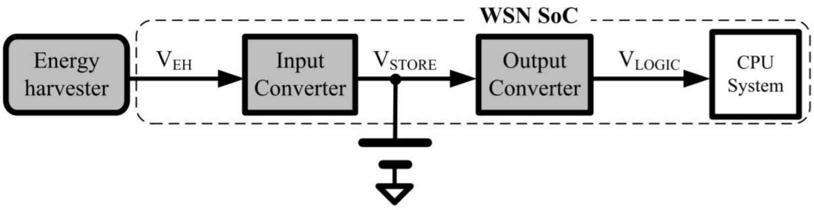

Figure 3.1: Conventional power conversion in energy harvesting systems.[117]

When individual energy harvesters are mature, the hybridization of different energy harvesting mechanisms is a future research direction. For example, different types of power harvesting systems serve different purposes based on different requirements (Bai et al., 2018).[38] [115]

Many engineers have to assess whether an energy harvesting solution can replace or supplement an existing energy solution. Designers often put a lot of work and effort into assessing energy - and reap the rewards only to find that the energy generated is not enough to power a particular system. Figure 3.2 is a schematic diagram of different energy sources and energy requirements for different applications. Energy harvesting is generally a combination of two components: the harvester and the secondary storage. Hybrid structures are often used, which are connected to both harvesters and secondary energy storage systems. Figure 3.3 is a schematic diagram of energy harvesting system setup.[17] [118]

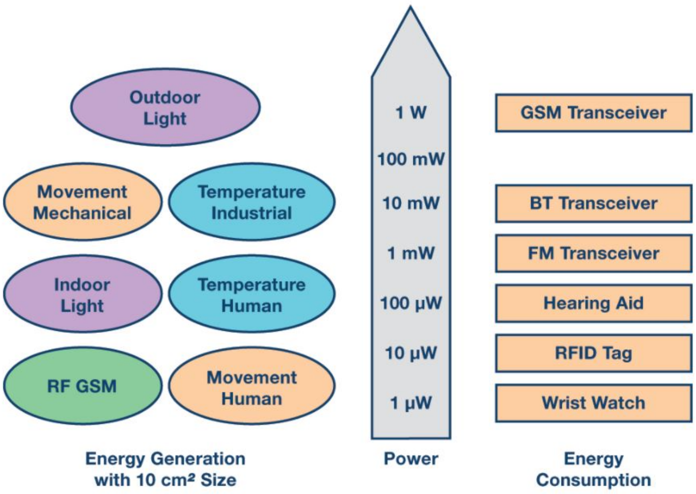

Figure 3.2: Different energy sources and energy requirements for different applications.[17]

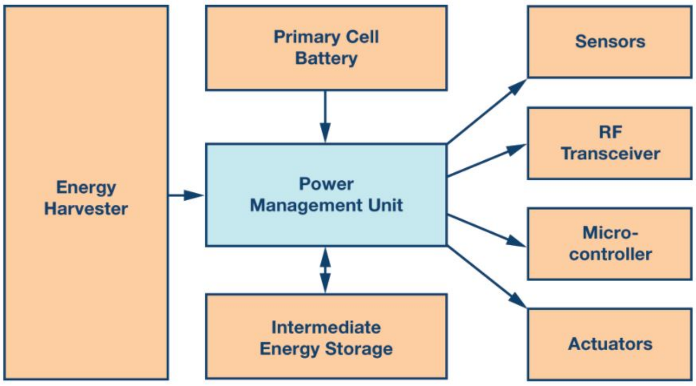

Figure 3.3: Energy harvesting system setup.[17]

It is common to connect solar cells with Li-ion batteries for simultaneous energy generation and storage in practice. Approximately 1 W battery pack can be used to store the harvested useful energy. When harvesters are exposed to the real world, they can produce more energy than a conventional solar cell, even though the average energy harvest is much lower.[38] [119]

The power transformer should draw maximum power from the energy harvester and act as a battery manager. If so, the applications and devices powered by this energy can be battery-free and sufficient to power the device.[7] [119]

The circuit's energy conversion efficiency is important, but the efficiency must be high enough to ensure that the energy it consumes is much smaller than that absorbed by another source. Moreover, the amount of energy available for the circuits is not the only factor in the energy harvesting circuit's total energy consumption. Nevertheless, at the lower end of the power spectrum, nano-power converters (WSN) sensors that can operate with meager power and current volumes are increasingly needed. Even if the energy harvested is in milliwatts' small order, it can still provide a large amount of energy for embedded systems such as sensors, batteries, and other energy harvesting devices.[7] [118]

This work proposes a hybrid multimode energy harvesting system that can achieve high efficiency by maximizing power transformers' efficiency and the energy harvesting power conversion process. The result is a current transformer that withdraws maximum power from the energy harvesters by implementing battery protection techniques. PLC has developed a hybrid harvester that will significantly complement our roadmap for product technology and will be able to generate energy from flow, vibration, and temperature.[119]

A circuit is required to convert the 3-phase alternating current energy from the battery pack into direct current in the harvester. Converters convert kinetic energy and vibrations into AC output voltages, rectified, regulated, and stored. With the output voltage rising, this approach could become expensive and lead to power losses due to energy conversion power and/or power consumption.[7] [119] [120]

Since the energy generated from this source is only sporadic and small, the system must be designed to capture, condition, and store the energy efficiently. Energy harvesting is advantageous because it provides power electronics with no conventional power source, eliminating the need to lead cables to the end applications. Less consuming devices can directly power battery-less systems, but in some cases, the energy storage unit can also act as a harvester. This work also includes the integration of the energy harvesters into the energy supply - storage and end-users.[7] [38] [115]

The harvesters can also be embedded in the energy system, such as part of an energy storage system or an electricity supply component.[118]

Although significant advances have been made in energy harvesting technologies in recent years, generating enough electricity for use in other electrical or electronic systems remains a challenge. In general, the resulting voltage, current, or power may be too low to be fully utilized. However, parallel developments in low-power boost and DC-DC converter technology and energy storage in dual-layer capacitors or supercapacitors have achieved low power consumption. Electrostatic energy harvesting system fully realized.

Figure 3.4 shows a typical AC and DC energy harvesting system that includes different energy harvesting sources that generate AC or DC power supplies, a low-power boost and dc-dc converter, energy storage (usual supercapacitors), and an electrical load. In general, the collected ac is rectified to dc, which is then boosted and stored, as dc is usually more useful in applications related to energy harvesting. This type of system is best suited for applications where the load is not always active, i.e., the duty cycle of the load is less than 100% since the load shutdown time provides time for supercapacitors or other electrical equipment. Store the device to be charged before it needs to power the load during the event.

For remote applications, including wireless sensor nodes, replacing onboard batteries may be impractical and an ideal application for e energy harvesting systems, including rechargeable energy storage devices (i.e., supercapacitors or rechargeable batteries). Thin-film rechargeable batteries have also made advances integrated into an integrated circuit (IC) packages in various shapes and sizes. Wearable technology is also a key area for achieving energy capture, as it requires small, lightweight, and self-sufficient energy to power wearable electronic devices such as smartwatches and hand-held consumer electronics.[121]

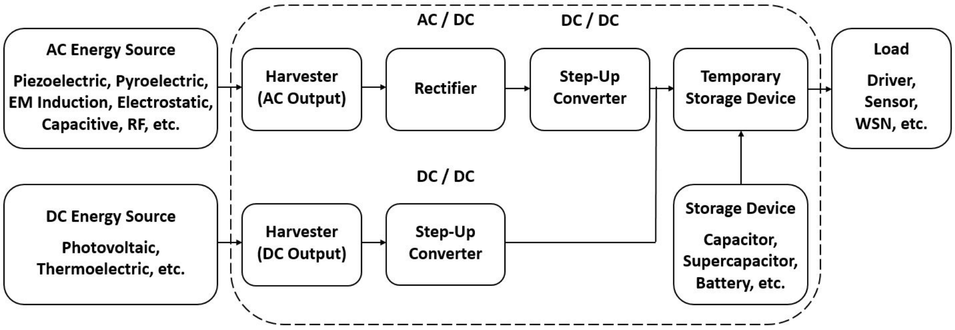

Figure 3.4: Visual representation of a typical energy harvesting system with both AC and DC inputs shown.

3.2 Piezoelectric Energy Harvesting Power Conversion By Energy Management circuit

Linear Technology has announced a complete energy harvesting solution that can deliver up to 50 mA continuous output current to extend battery life when recoverable energy is available. LTC3331 integrates a rechargeable battery powered by a lithium-ion battery and an energy harvester, producing a single, continuous, regulated power. The energy can also be used at high power, making it suitable for a wide range of applications such as energy storage and power generation.[122]

Special attention was paid to the energy harvester's design, designed to convert mechanical energy from the host system into electrical energy for direct consumption or storage for later consumption, storage, or use. In particular, the crop is installed as an insole, which directly converts human walking and walking motion into usable electrical form and is a good substitute for batteries. The work also includes integration into energy storage and end-users: in certain situations, an energy storage system can also function as a harvester. Special applications influence generator sizes, such as power generation, power distribution, and storage.[4] [20] [35] [123]

Generally, there are three techniques to extract energy from vibrations: basin, transducer, and force - reinforcing structures can improve the energy harvester's performance. There are different types of energy harvesting systems, but there is generally a need for a more efficient and efficient method of obtaining energy through vibration.[94] [103]

Energy harvesting devices that convert ambient energy into electrical energy have aroused great interest from the military and commercial sectors. The future of piezoelectric energy generation will probably consist of developing and improving the efficiency and efficiency of piezoelectric materials used in energy production - harvesting. Several parameters could improve the performance, a piezoelectric energy generation system that uses piezoelectric elements.[20] [103] [124]

The energy generation's power supply consists of a full-wave bridge rectifier, accommodating both AC and DC inputs. The energy - harvesting electrical device can increase the output power. Highly oriented bimorph PZT foil with fully integrated self-start control, MPPT, and ZCS control.[4] [122] [125] [126]

The concept of energy production is generally related to using piezoelectric materials such as copper, copper oxide, and other semiconductors made of metal oxides to convert ambient energy into electrical energy. Energy harvesting technology covers a wide range of applications, from power generation to energy storage and storage of renewable energy sources. It uses electrical signals with amplitude and frequency, depending on the circuit connected to a piezo-selected material. In short, it worships the available energy in the environment, which is absorbed by vibrations, thermal gradients, or solar radiation and transformed into storable electrical energy.[4][14][94][126]

A typical PEH device requires a circuit to convert alternating current (AC) from the Electronic Power Directive (DC Power) to the piezoelectric element. A DC-DC converter must extend the working range, increase the output voltage of the energy generated from a piezo-selected energy harvesting circuit, and significantly increase its efficiency. The result is a voltage multiplier that extends the working range of a piezoelectric energy harvester, increases its output voltages, and increases its power conversion efficiency.[123][126]

This paper examines the conditions necessary to improve the efficiency of alternating current by using piezoelectric materials. This paper will examine the requirements for developing a piezoelectric energy harvester with a DC-DC converter and necessary for the improvement of the ability to generate alternating current from a piezoelectric material.[94]

The internal threshold voltage compensation can be used in a piezoelectric energy harvester with a DC-DC converter using internal thresholds and voltage compensation to generate alternating current. The different architectures of energy harvesters are represented by different infrastructure types based on vibration energy generation, electromagnetic induction, and electrostatic energy production. The vibrational energy harvesting is based on electromagnetic inductance, which uses magnets and copper coils to generate a current that can be converted into electricity in the simplest version. Electrostatic energy harvesters require a source of polarization to work and convert mechanical energy from vibration into electricity.[4][20][103]

Since the beginning of 2015, a single crystal-based energy harvester has been proven to deliver only a few milliwatts of power. A single crystal-based electrostatic energy generation system is with a single electron beam and an electric current of 1.5 volts. Review the available boost converter circuits for low power energy harvesting supplied wireless sensors, including inductors, switching capacitors (SC), and transformer-based converters. The power output, input voltage, and boost ratio converter performance comparison determine the appropriate solution for different application conditions. This paper specializes in switching capacitors (SC) converters because of their characteristics suitable for low power Energy Harvesting.[127]

3.3 Process of Piezoelectric Energy Harvesting Power Conversion

The equivalent circuit is shown in Figure 3.5. The electrical impedance of the piezoelectric harvester is mega Ohm, and the capacitance value is nano Farad. At resonance, the current source I_{piezo} is equal to $mA\omega_n^2$ in equation (2.8).[94] [102]

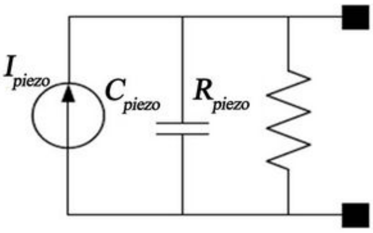

Figure 3.5: Equivalent circuit at resonance.[102]

Since the resistance value of the harvester is too high (mega ohm), it can be ignored, so its effective impedance is of capacitive type. This impedance Z_i can be calculated using the following formula[94] [102]:

$$Z_i = \frac{1}{\omega_n C_{piezo}} = \frac{1}{2\pi f_n C_{piezo}} \tag{3.1}$$

When the value of this load is close to the internal AC of the harvester, it will happen that the maximum power is transferred to the external load. To store energy in the capacitive load, a 4-bridge rectifier must rectify the extracted AC power. The equation where $W(t)$ is the energy stored in Joules at instant time t, C is the capacitance value in Farads, and $V(t)$ is the measured voltage across the capacitor t. The stored energy is[94] [102]:

$$W(t) = \frac{1}{2}C[V(t)]^2 \tag{3.2}$$

The accumulated energy must be sufficient to run the load within a predetermined time. The application's running time depends on the current consumed, the output voltage of the load, and the capacitor's energy stored. The formula Where W is the energy stored in Joules, and V is the voltage across the capacitor to the load, and I_{app} is the current consumed by the application. The running time of an application can be calculated in the following formula[94] [102]:

$$T = \frac{W}{VI_{app}} \tag{3.3}$$

As shown in Figure 3.6, the piezoelectric energy harvester's output is alternating current, and a full bridge rectifier is connected first to convert the alternating current to direct current. Then use the DC-DC converter to convert the pulsed direct current into a stable direct current. The stable DC output is connected to the energy storage components and provides the device's power.[126]

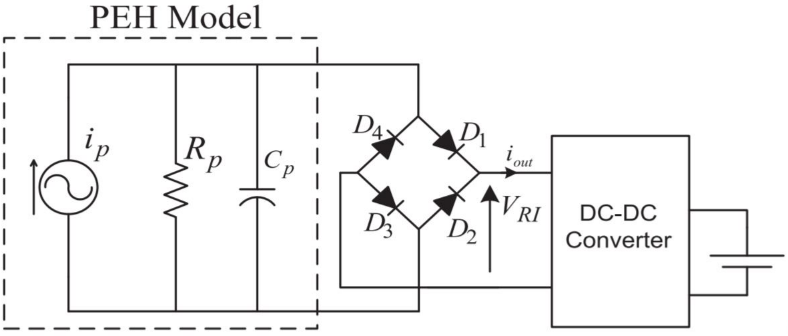

Figure 3.6: PEH circuit diagram with dc–dc converter.[126]

Since the output voltage of piezoelectric energy harvesting is usually low, it cannot meet the application side's needs. So the selected DC-DC converter will usually be a step-up converter. Figure 3.7 shows the Boost converter, which controls the switch's duty (D) and determines the ratio of the output voltage rise. Figure 3.8 shows the Charge pump, which uses a switch and capacitor to achieve the step-up demand easily. Based on different application requirements, different step-up circuit architectures will be selected.

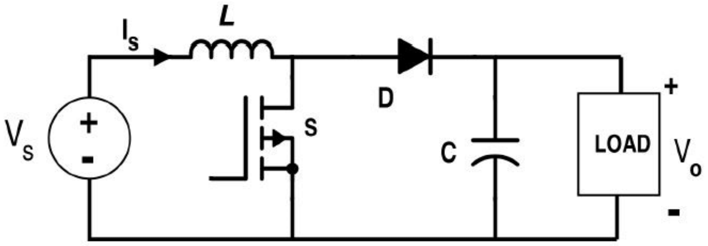

Figure 3.7: Boost converter.[128]

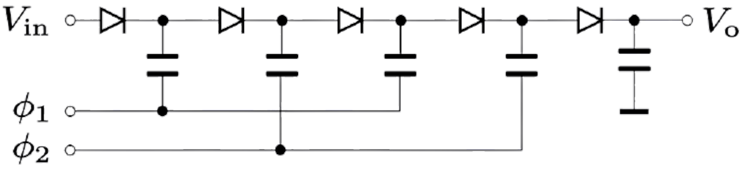

Figure 3.8: Dickson charge pump.[129]

Chapter 4

Implementation

4.1 MEMS Energy Harvesters Design and Simulation

The piezoelectric energy harvester's design criteria include the operating frequency, the power generated, and the power transmitted to the management circuit. The operating frequency can be determined by running a modal analysis in a conventional Finite Element Analysis (FEA) tool. However, the generated and transmitted power is highly dependent on the power management circuit and, therefore, must be simulated in a closed-loop circuit. Therefore, the chosen design platform must simulate the coupling of the piezoelectric machinery to the electronic device before it can be used to design the energy harvester.[130] [131]

The design process of Coventor begins with the construction of the parameter model of piezoelectric vibration harvester in MEMS+. Designers work in a 3D graphics environment to create parametric models by assembling MEMS specific higher-order finite elements (piezoelectric mechanical shells). Each element is linked to the MEMS process description and material database to assign piezoelectric material characteristics and electrodes automatically. Higher-order elements provide a precise mathematical description of the devices' physics and include the inherent nonlinear mechanisms of these devices.[130] [131]

IC engineers typically use Cadence Virtuoso to design analog/mixed-signal electronics connected to MEMS devices. To be successful, IC engineers need to provide fast, accurate models of MEMS devices in the Cadence model library. The MEMS model is then used as a component in the IC schematic to perform MEMS+IC co-simulation. Co-simulation is very important to verify IC design and predict the sensitivity of yield to manufacturing deviation.[130] [131]

There are many benefits to using MEMS+ higher-order finite elements. First, design teams no longer need to spend valuable time manually building step-down models from FEA and/or analytic expressions. Second, unlike manual models, which are usually linear, MEMS+ models contain nonlinear effects. The MEMS+ model includes nonlinear effects that affect device performance, reducing the chance that devices will have to be redesigned in the final development stages.[130][131]

The integration of the Coventor MEMS+ tool suite with Cadence makes the required model exchange between MEMS engineers and IC designers more seamless than ever before. Cadence library units with parameterized simulation models and layout Pcells can be generated almost immediately without any FEM analysis or time- consuming drop-down modeling.[130][131]

The MEMS+ model can be easily imported into a CadenceVirtuoso® environment and placed in a schematic containing tuned circuits. The combined harvesters and harvesters can then be simulated in Cadence Spectre. You can then change the parameters of the harvester and circuit to optimize equipment performance. For example, the designer may adjust the harvester's size and resistance load to obtain the maximum power transmission from the harvester to the regulating circuit. Different circuits can also be tested to achieve the desired performance requirements.[130][131]

More detailed modeling can be done using CoventorWare's field solver. For example, you can examine areas of high stress in your design that may be overloaded due to mechanical impact. The gas damping coefficient can also be obtained by CoventorWare and included in the MEMS+ model to predict the Q factor more accurately. If necessary, the simulation results of MEMS+ and CoventorWare can be verified mutually to improve the front code's confidence. For example, closed-loop harmonic responses with linear resistance loads can be simulated and compared in two tools.[130][131]

Coventor's piezoelectric energy collection platform combines MEMS+ and CoventorWare to provide a complete design solution. The CoventorWare platform solves the coupling and multi-domain physics problems that traditional FEA analysis cannot solve. This hybrid approach has many advantages. It allows the design of energy collection devices and co-simulation with regulating circuits. These models are parameterized and can be quickly simulated, making rapid exploration of design and process changes a reality. The resulting model is very accurate to eliminate the time-consuming process of creating a reduced-order model from FEA data and/or parsing expressions.[130][131]

4.2 Implementation process with ConvertorWare and MEMS+

Figure 4.1 shows the example piezoelectric energy harvesting of ConvertorMP is displayed in MEMS+. All the experimental steps can refer to the official tutorial of ConvertorMP, where there are detailed and step-by-step teaching. Modularization in MEMS+: material setting, production layer setting, component sets, and layout. Export the model to ConvertorWare for simulation analysis. Figure 4.2 Resonance frequency response diagram of this piezoelectric energy harvesting.

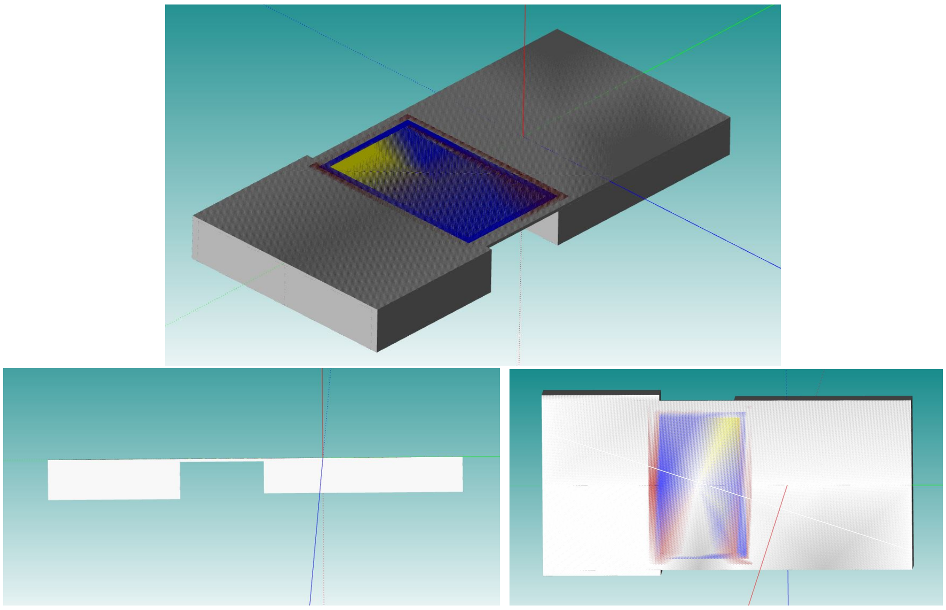

Figure 4.1: Example MEMS piezoelectric energy harvester in MEMS+.

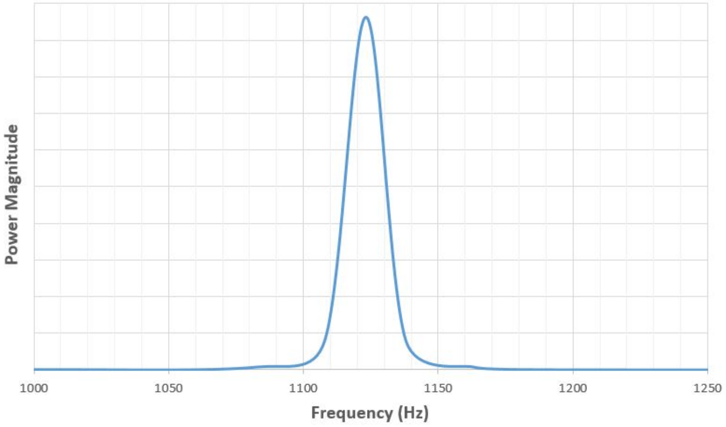

Figure 4.2: Example MEMS piezoelectric energy harvester at a resonance frequency of 1123 Hz.

The original example's piezoelectric energy harvesting (Figure 4.1) was modified architecturally to analyze and observe component characteristics changes. As the original piezoelectric energy harvesting model's total length remains unchanged, mass-the end of the cantilever in the original model is shortened as shown in Figure 4.3, which means that the weight of mass will be reduced, and the resonance frequency will be increased. When the cantilever's charging plate is extended to a shortened mass length, the resonant frequency will decrease. Figure 4.4 shows that the resonant frequency decreases when this change is made compared with the original model. However, this does not mean that there is a certain conclusion. Each model must be simulated experimentally to obtain the corresponding resonant frequency.

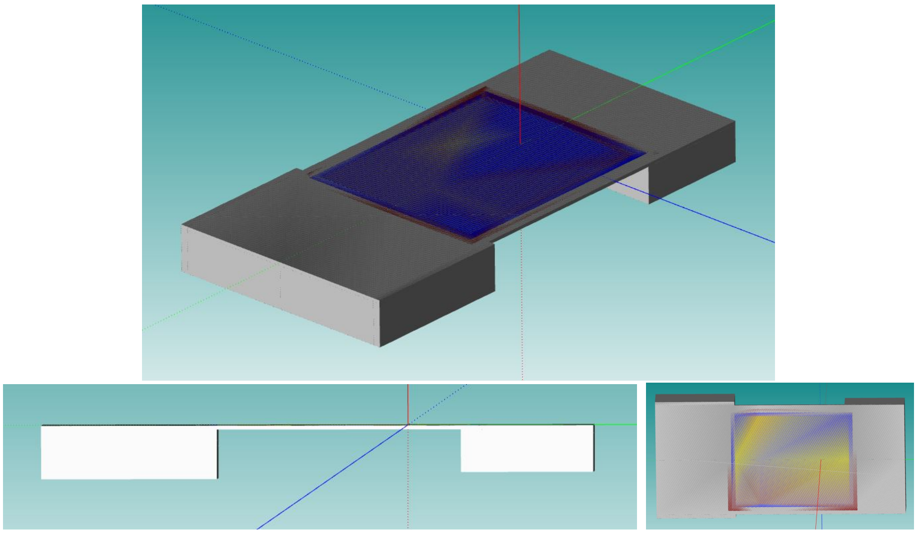

Figure 4.3: Modified Example MEMS piezoelectric energy harvester in MEMS+.

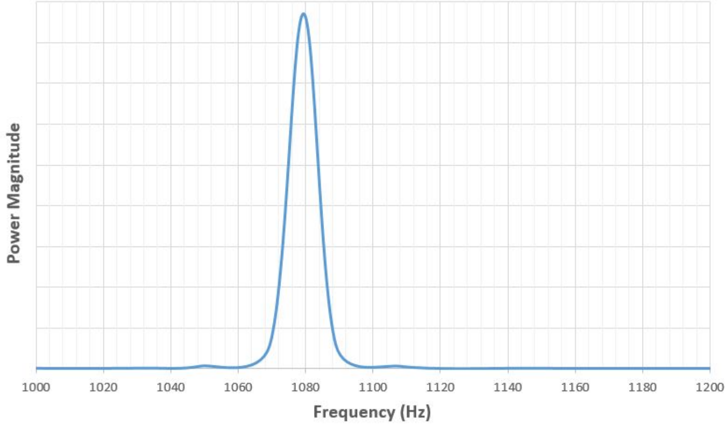

Figure 4.4: Modified Example MEMS piezoelectric energy harvester at a resonance frequency of 1079 Hz.

The resonant frequency of the original example's piezoelectric energy harvesting can respond between 50 Hz and 100Hz. Then more adjustments and changes were made to the original model. Through the experiment of making the model, various lengths of the model were tried, and the length ratio between the mass block and the charging plate was adjusted. It also increased the whole model's thickness, making mass heavier, and achieving a lower resonance frequency. Figure 4.5 shows the MEMS piezoelectric energy harvesting at the resonant frequency of 60Hz in MEMS+. Figure 4.6 Resonance frequency response diagram of this model.

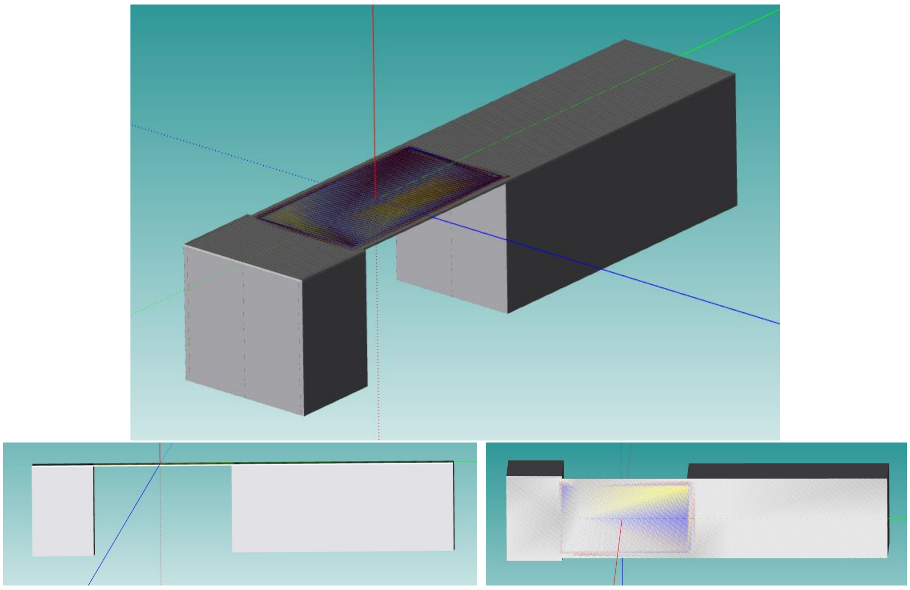

Figure 4.5: MEMS piezoelectric energy harvester at a resonance frequency of 60 Hz in MEMS+.

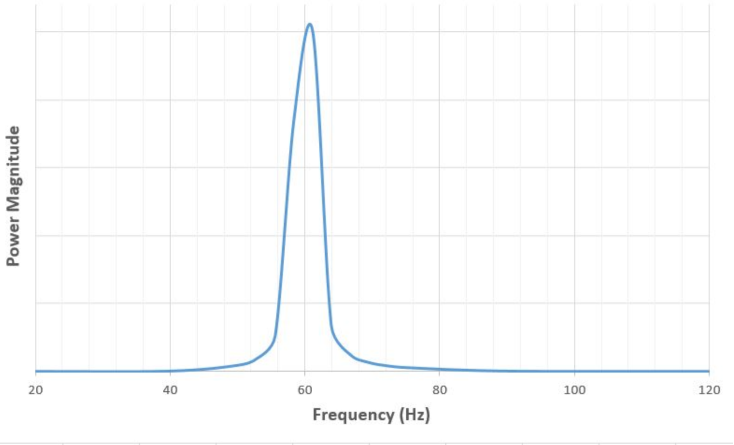

Figure 4.6: MEMS piezoelectric energy harvester at a resonance frequency of 60 Hz.

However, there is no absolute parameter configuration to make a model, and it is designed according to the application. If there is a limited length at the same resonant frequency, try to thicken the model's thickness or adjust the length between the mass and the charging plate. Alternatively, there is a height limit; you can make adjustments from the length and get the target's resonant frequency. Adjust and fabricate MEMS piezoelectric energy harvesting for application. Figure 4.7 shows the model with a resonant frequency of 90Hz in MEMS+. Figure 4.8 Resonance frequency response diagram of this model. Besides, other models with resonant frequencies between 50 and 100 Hz were made in the experiment, but these models will not be displayed due to space constraints.

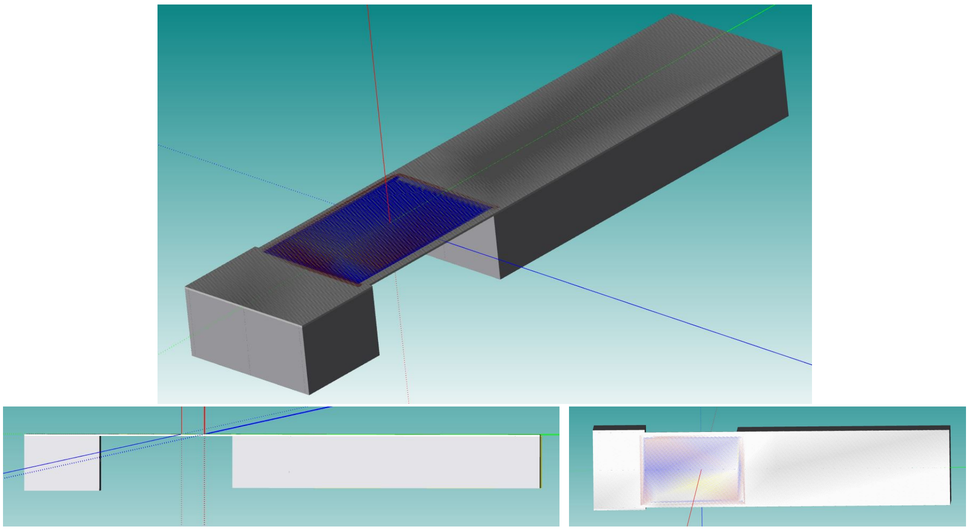

Figure 4.7: MEMS piezoelectric energy harvester at a resonance frequency of 90 Hz in MEMS+.

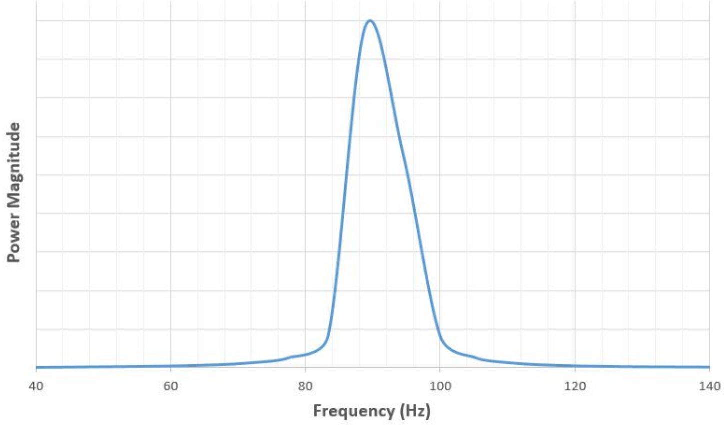

Figure 4.8: MEMS piezoelectric energy harvester at a resonance frequency of 90 Hz.

When the models in Figure 4.7 and Figure 4.9 work at the resonant frequency, after simulation, it can be seen that when the external vibration kinetic energy is bigger than the excepted, the mass of the model will hit the ground below, thus making the device unable to work normally or even damaged. Therefore, some shape changes must be made to mass to operate smoothly under the same weight. After several attempts, a T-shaped structure was developed in the experiment, as shown in Figure 4.9, and Figure 4.10 shows the resonant frequency of 60 Hz.

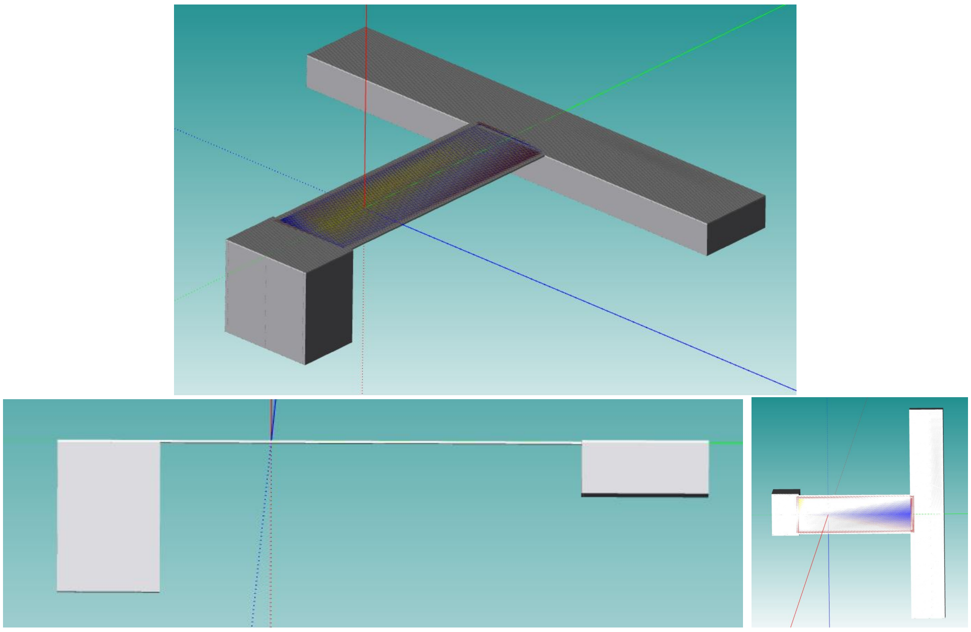

Figure 4.9: T-shaped MEMS piezoelectric energy harvester at a resonance frequency of 60 Hz in MEMS+.

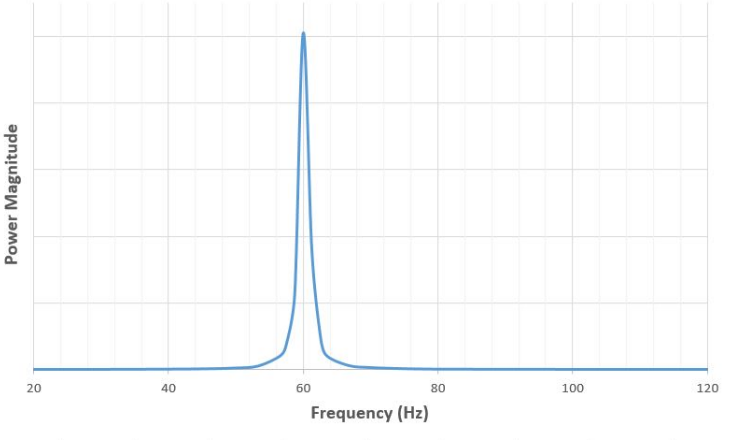

Figure 4.10: T-shaped MEMS piezoelectric energy harvester at a resonance frequency of 60 Hz.

To achieve different resonant frequencies between 50 and 100 Hz, the experiment only changed the length of the charging plate in different T-shaped models, while the remaining parameters remained unchanged. This makes the results of each experiment more predictable. However, it is still going to be application-based. Moreover, this work is just for the convenience of showing the finished product. Figure 4.11 shows the T-shaped piezoelectric energy harvesting with a resonant frequency of 90Hz in MEMS+. Figure 4.12 Response diagram of this resonant frequency.

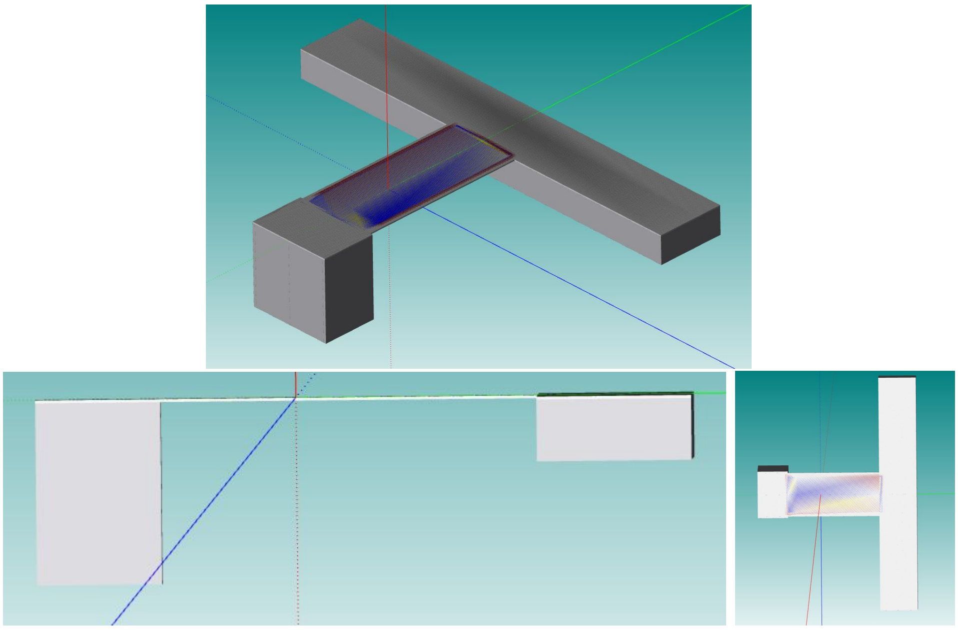

Figure 4.11: T-shaped MEMS piezoelectric energy harvester at a resonance frequency of 90 Hz in MEMS+.

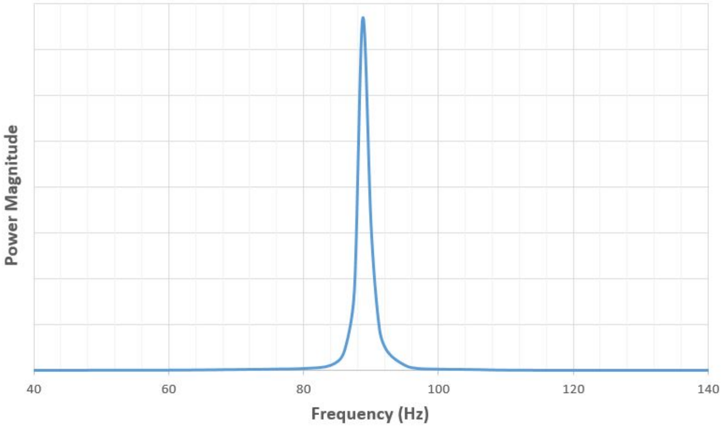

Figure 4.12: T-shaped MEMS piezoelectric energy harvester at a resonance frequency of 90 Hz.

In application, in order to effectively collect the vibration energy in each direction, a MEMS piezoelectric energy harvesting matrix composed of four T-shaped MEMS piezoelectric energy harvesting at the same resonant frequency was created. Figure 4.13 shows the MEMS piezoelectric energy harvesting matrix composed of four T-shaped MEMS piezoelectric energy harvesting in MEMS+, which is at the same resonant frequency of 90Hz. The advantage of this matrix is that it can more effectively collect the vibration energy from all directions, without the dilemma that the required energy cannot be collected due to the change of the application's vibration direction. The manufacturing application also determines the composition of this matrix. You can use models with the same resonance frequency or models with different resonance frequencies. This matrix's arrangement hopes that under the same combination, the more space left, the better, which means that the model has a higher energy collection density. More energy can be collected under the same volume, or space can be saved more effectively under the same energy collection. After several tests, Figure 4.13 shows the best arrangement of the MEMS piezoelectric energy harvesting matrix composed of four T-shaped MEMS piezoelectric energy harvesting with a resonance frequency of 90 Hz. However, the result still looks unsatisfactory, as you can see from the picture that there is too much idle space. This means that much space is wasted, and the energy density of the collected energy is greatly reduced. So the work will be referred back to the improved model later.

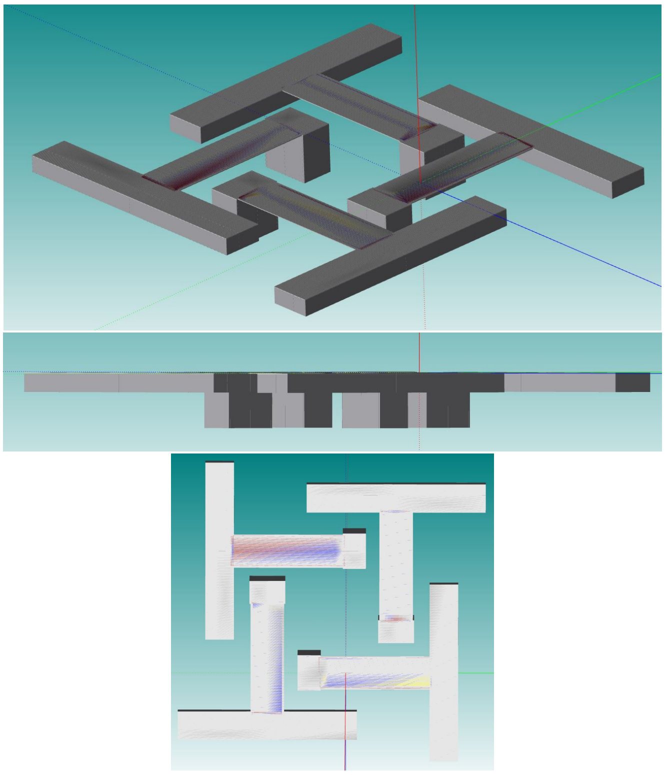

Figure 4.13: T-shaped MEMS piezoelectric energy harvester matrix in MEMS+.

The model in Figure 4.13 is designed to adapt to scenarios where the frequency is 50 to 100 Hz. However, in response to natural frequencies, the model's area is too large, exceeding 10mm*10mm. However, this is not a big and urgent problem for larger applications (suspension bridges, cars...). However, since the energy harvesting model's application scenario is designed for IoT small devices (sensors), reducing the size to match the application scenario is the primary goal. Figure 4.14 shows the 3mm*3mm MEMS piezoelectric energy harvesting matrix in MEMS+. Compared with the model in Figure 4.13, this model makes more effective use of restricted space, increases the density of collected energy, and achieves better miniaturization, which can be better suited for small devices. Special attention should be paid to saving space while maintaining the range of movement of each energy harvesting cantilever to prevent work errors caused by collisions and even damage and reduce the model's life.

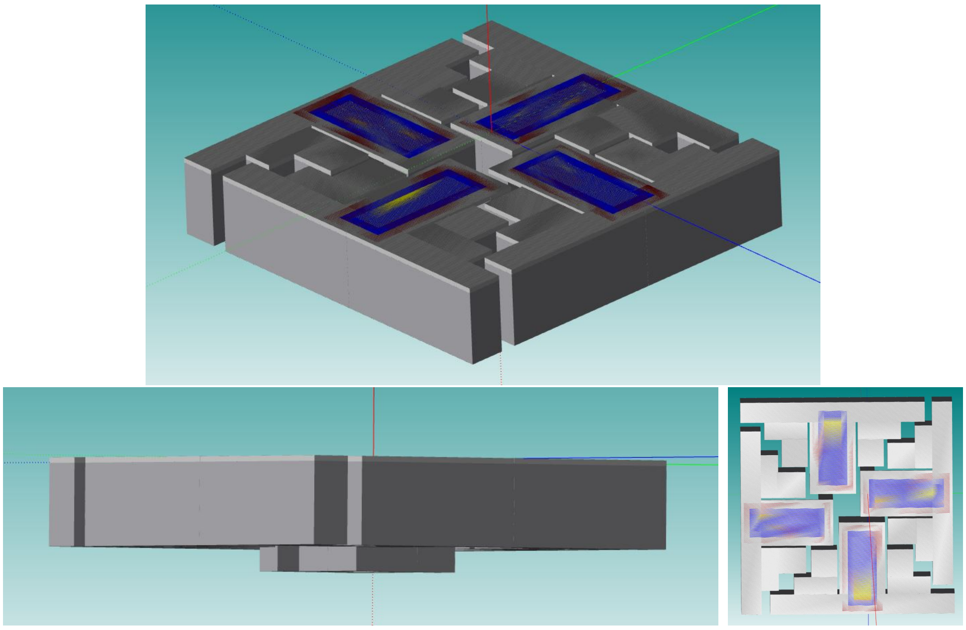

Figure 4.14: 3mm*3mm MEMS piezoelectric energy harvester matrix in MEMS+.

Figure 4.15 shows a single 3mm*3mm MEMS piezoelectric energy harvester in MEMS+. After the model in Figure 4.14 is designed first, the simulation and analysis of a separate energy harvesting cantilever are done. It can be seen from the figure that in order to have a lower resonance frequency and better energy harvesting performance within the design range of 3mm*3mm, when the length of the cantilever has been maximized, the remaining space is designed so that MASS can Try to increase the volume, and then increase the weight. It is hoped that the resonance frequency can be reduced as much as possible. Figure 4.16 shows the single 3mm*3mm MEMS piezoelectric energy harvester at the resonance frequency of 4093 Hz.

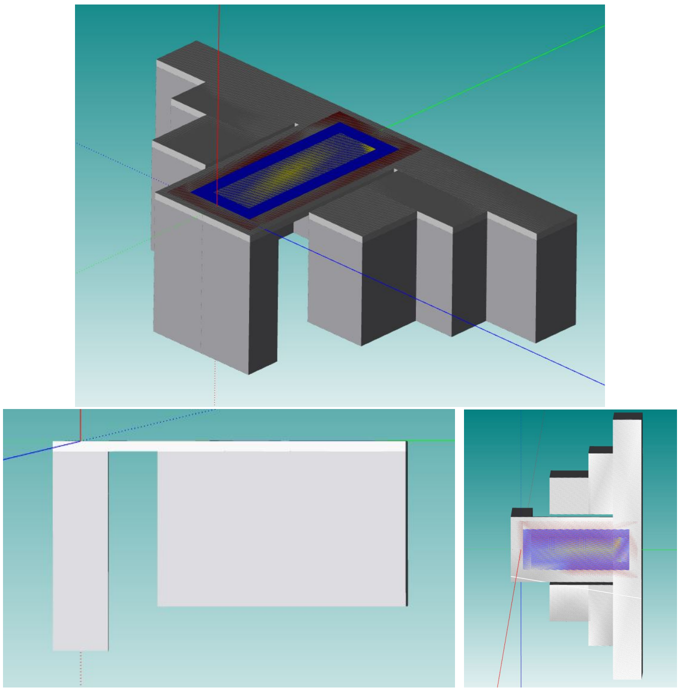

Figure 4.15: Single 3mm*3mm MEMS piezoelectric energy harvester in MEMS+.

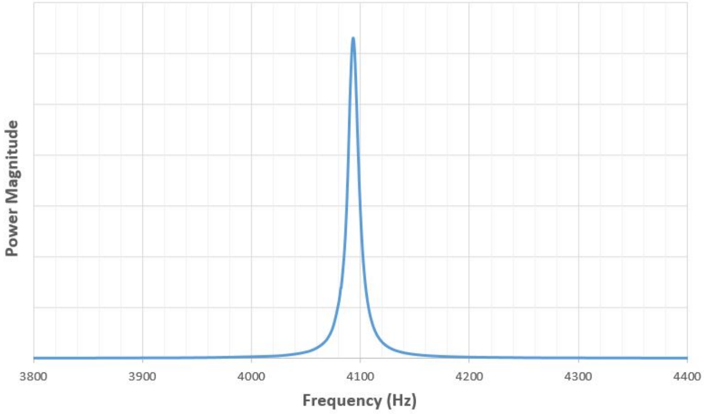

Figure 4.16: Single 3mm*3mm MEMS piezoelectric energy harvester at a resonance frequency of 4093 Hz.

4.3 Implementation process with Cadence

Export the MEMS piezoelectric energy harvesting model to Cadence, and perform further energy management design and simulation on the piezoelectric energy harvesting model. Figure 4.17 is the schematic diagram of the MEMS 3mm*3mm piezoelectric energy harvesting matrix in Cadence. Figure 4.18 is the schematic diagram of MEMS signal 3mm*3mm piezoelectric energy harvesting in Cadence. The schematic diagram will be used for the circuit layout. The symbol uses a simple equivalent model to replace the piezoelectric energy harvesting model, convenient for designing energy management circuits. The operation principle and usage method will be described in more detail in the following experiments.

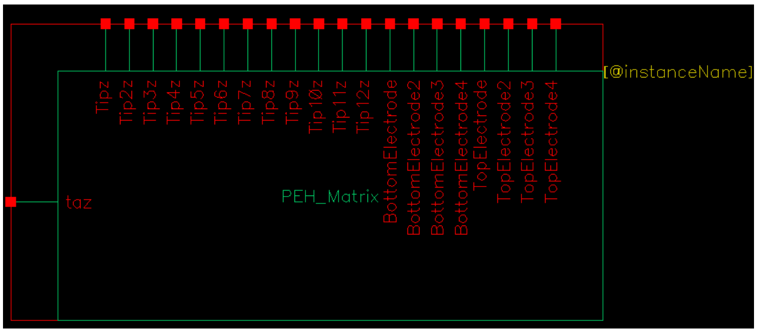

Figure 4.17: Schematic diagram of the MEMS 3mm*3mm piezoelectric energy harvesting matrix in Cadence.

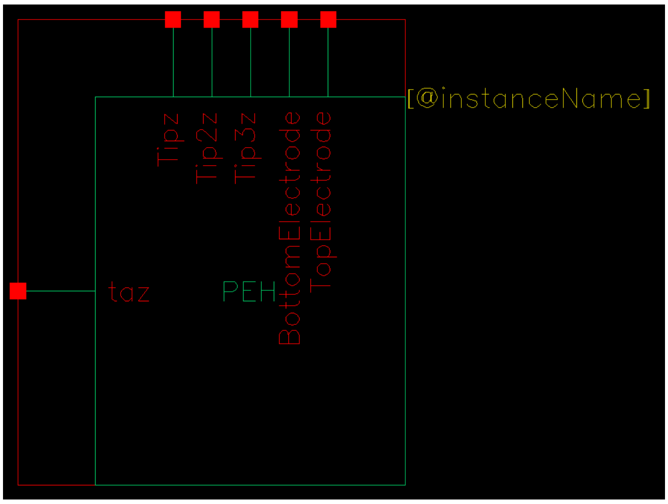

Figure 4.18: Schematic diagram of MEMS signal 3mm*3mm piezoelectric energy harvesting in Cadence.

Figure 4.19 shows schematic diagram of a boost converter with MPPT for energy harvesting power conversion in Cadence. In the early development, the original experiment wanted to use a boost converter with MPPT to track the output voltage. The voltage output will not change with the change of the vibration scene. However, let the voltage maintain a stable output because this experiment focuses on designing a specific frequency and maintaining the same vibration scene. In this application scenario, the boost converter with MPPT is not as effective as the charge pump. Therefore, this framework will not be used for experimental purposes anymore. However, in some applications, it is necessary to respond to the different outputs generated by energy harvesting, and this architecture will be required to track and correct so that the final converted voltage can be supplied stably.

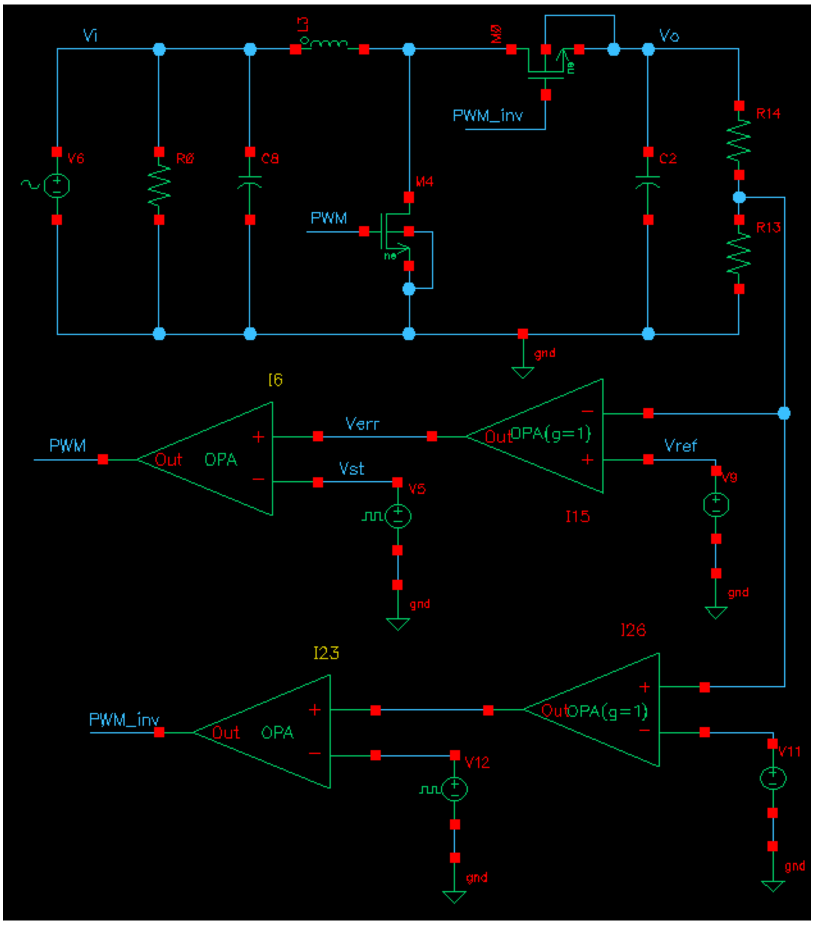

Figure 4.19: Schematic diagram of boost converter wih MPPT for energy harvesting power conversion in Cadence.

Following the experiment, the boost converter will be adjusted to a DC-DC converter architecture with a charge pump as the circuit. It is precisely the boost converter or the charge pump that requires an external control signal to operate the circuit. The boost converter uses a fixed PWM to control the switching of the switches in the circuit, or the boost converter uses the output feedback circuit to track and correct the output, and the PWM output of the feedback circuit is connected in series to control the switching of the switch. In order to ensure the normal operation of the circuit, the charge pump allows each stage in the circuit. Figure 4.20 is a schematic diagram of a Vpulse generator composed of a ring oscillator in Cadence. Since it cannot be operated with a simple signal source as in simulation, these additional control signals must be executed through Cadence's circuit production. The asynchronous resonator is composed of multi-stage inverters in series. The inverter characteristics are used to generate the control signal number—the lower the frequency generated by the cascaded multi-stage inverter. The number of series can be determined according to the application. Finally, a buffer is connected in series so that the control signal can be amplified and the signal can drive the components of the circuit.

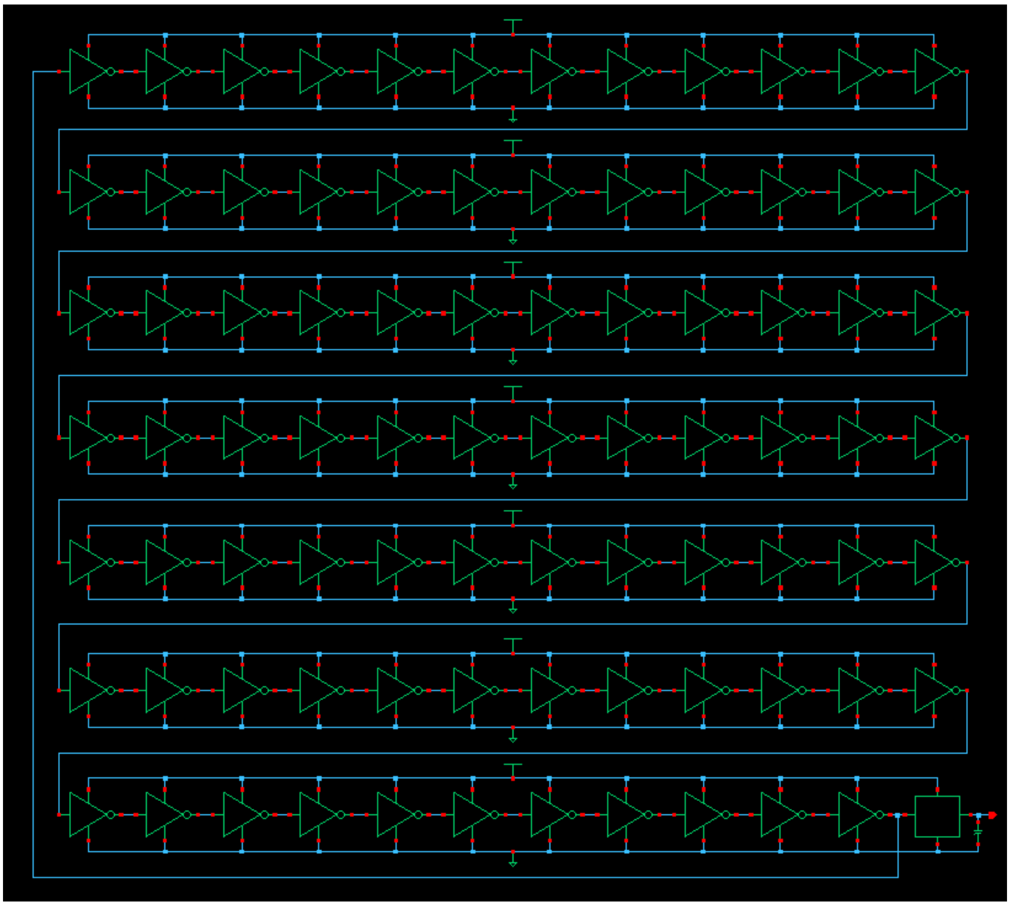

Figure 4.20: Schematic diagram of Vpulse generator composed of ring oscillator in Cadence.

The circuit design of a single PEH first can make the circuit design of the PEH matrix smoother. Figure 4.21 shows the schematic diagram of a single PEH with an energy management circuit in Cadence. The experiment consists of a single PEH and energy management circuit. The taz of PEH is to simulate the vibration acceleration harvested into the environment and then connect to a source of simulated given acceleration value V0. The output of PEH only needs to deal with the charge on both ends of the charged plates (BottomElectrode and TopElectrode), and the voltage in response to harvesting vibration energy is alternating current. To connect both ends of the PEH charge plates to a full-bridge full-wave rectifier to convert alternating current into pulsed direct current. Since the output energy of energy harvesting is low, it is necessary to reduce the energy loss on the circuit as much as possible when converting electric energy so that the output electric power is not too small to be used.

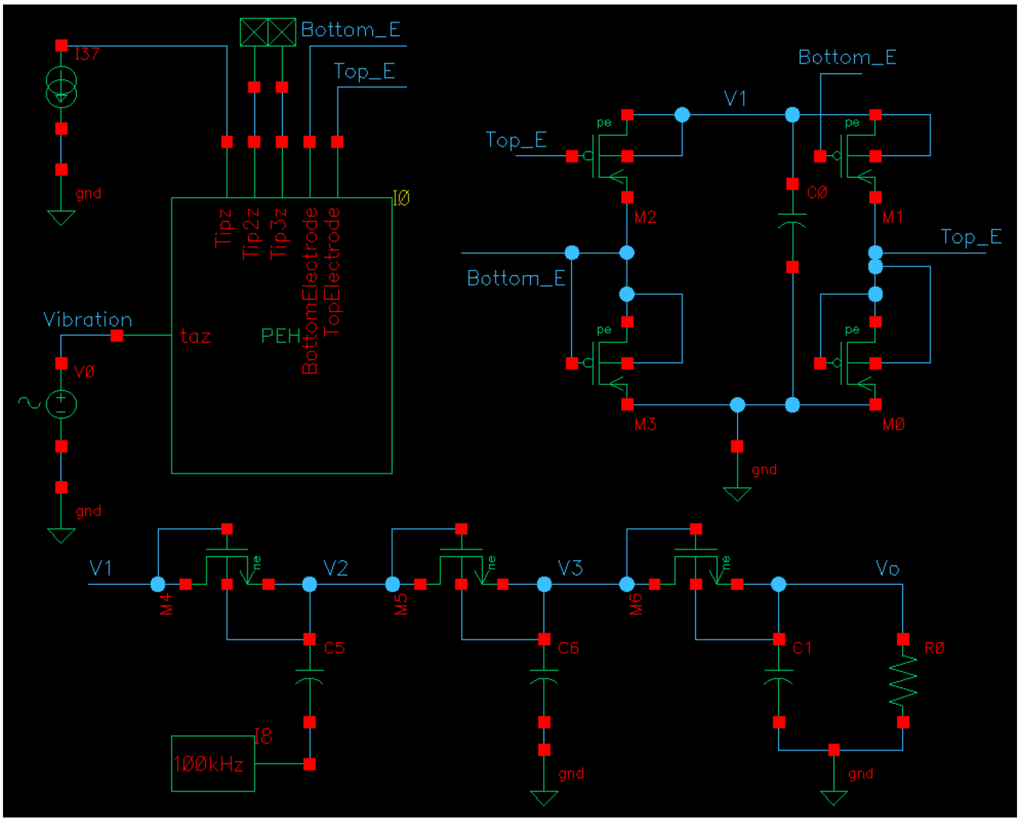

Figure 4.21: Schematic diagram of single PEH with energy management circuit in Cadence.

To reduce the loss of the experiment, the commonly used diode structure of the circuit is replaced with a transistor. The advantage is that the voltage drop of the diode conduction can be reduced so that the voltage output from the PEH will not be reduced too much. The capacitor C0 is used to convert the pulsed DC output from the full-wave rectification into a more stable DC.

Then output the direct current V1 to the charge pump for boosting. Since the experiment is only used to test the correctness of ideas and practices, only a small number of stages are used for boosting. If in order to achieve different application voltages, the boosting multiple can be adjusted according to the target voltage. For the charge pump to work typically, different clocks must be connected to the two adjacent stages, and the signal used in the experiment is the 100khz Vpulse and ground signal generated by the ring oscillator. In order to maintain the normal operation of the circuit, it is recommended that the operating frequency be higher than the resonant frequency of energy harvesting. You can use different signal sources according to your design. Finally, a transistors to simulate the diodes and capacitor filter are used to supply the output V3 of the charge pump to Vo of the final simulated load R. This is a complete energy management circuit for energy harvesting.

Figure 4.22 is the schematic diagram of PEH matrix with energy management in Cadence. It is to change the single PEH in Figure 4.21 to the PEH matrix. The experiment consists of PEH matrix and energy management circuits. Since the matrix comprises four single PEHs, four sets of full-bridge rectifier circuits and capacitor filtering are required to first convert the individual AC power of the four sets of PEHs into stable DC. Then connect these four groups of direct current series transistors to simulate the diodes, and then connect these four groups of power supplies in parallel so that the vibration energy in different directions can be collected more effectively. Finally, a charge pump is used to complete the boost output.

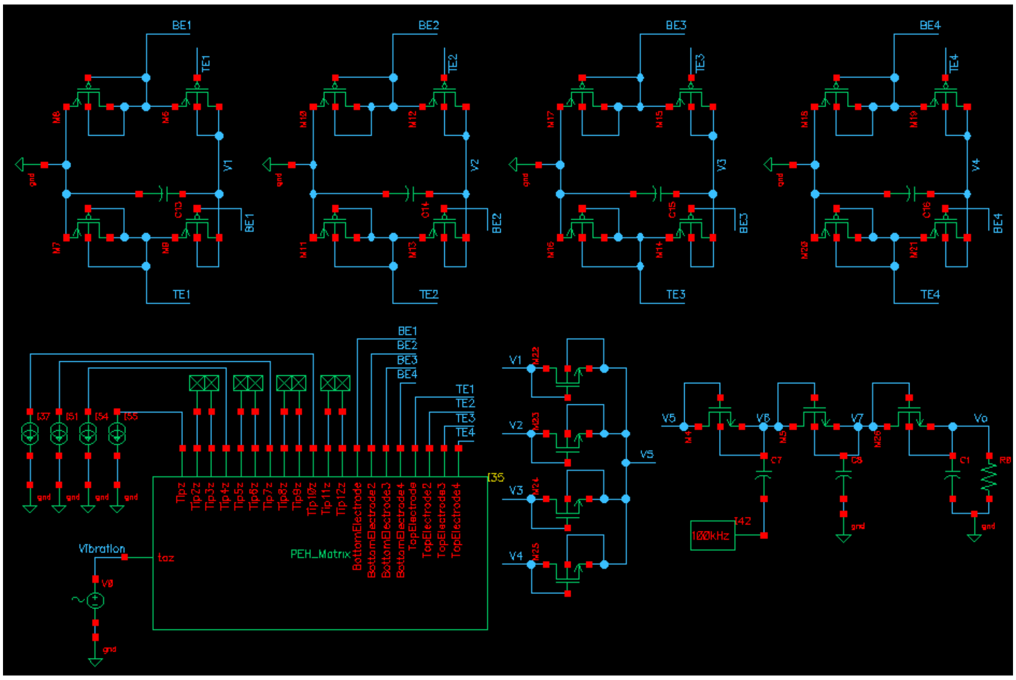

Figure 4.22: Schematic diagram of PEH matrix with energy management circuit in Cadence.

Figure 4.23 shows the output voltage waveform of PEH Bottom Electrode and Top Electrode and the final output voltage waveform after conversion in Cadence(0ms to 7ms). It can be observed from the figure that the output voltage is being established for 0 to 4ms at the beginning. After 4ms, the output voltage is established and can be maintained at about 620mV. If you want to increase the voltage more, you can use more charge pump boost. The output voltage waveform of PEH's Bottom Electrode and Top Electrode shows an AC voltage of 4093Hz.

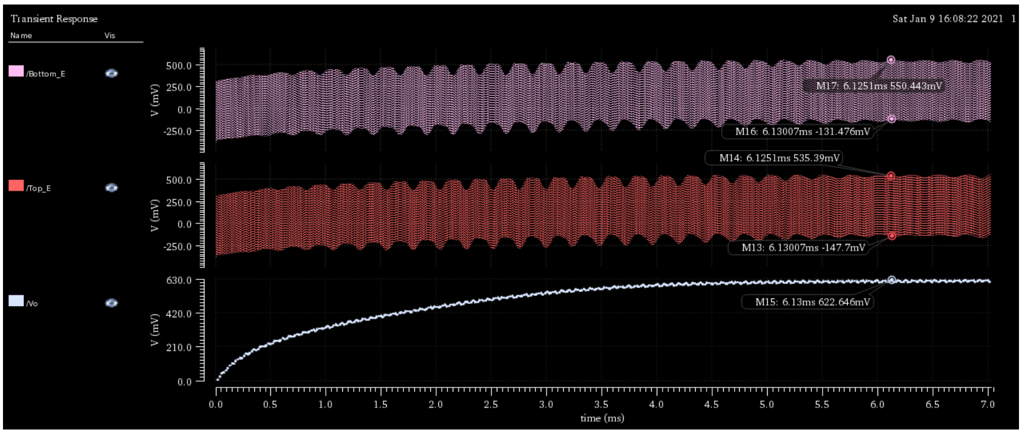

Figure 4.23: The output voltage waveform of PEH's Bottom Electrode and Top Electrode and the final output voltage waveform after conversion in Cadence(0ms to 7ms).

Figure 4.24 shows zoom in the final output voltage waveform after conversion in Cadence(6ms to 6.12ms). As you can see a ripple voltage of 16mV in this circuit architecture. The ripple voltage is 2.6% of the output voltage, which is within the usable range.

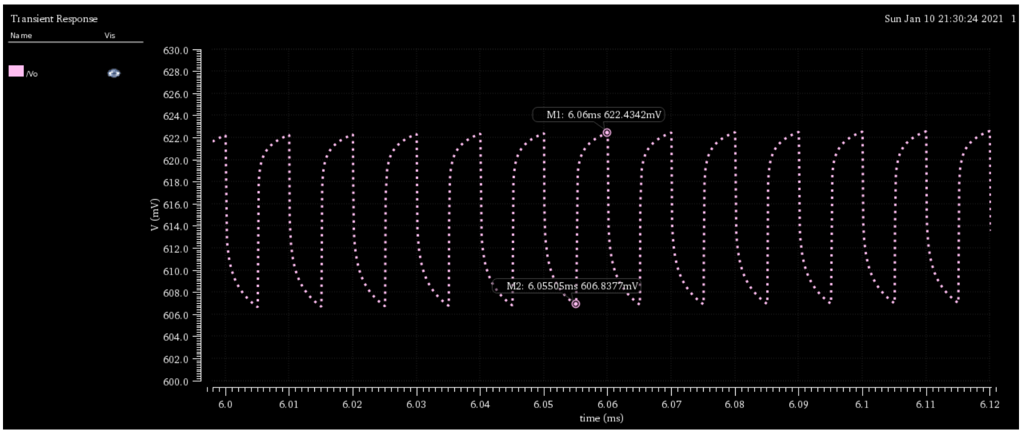

Figure 4.24: Zoom in the final output voltage waveform after conversion in Cadence(6ms to 6.12ms).

Figure 4.25 shows the 2.5mm*1.5mm IC layout diagram of the entire energy management circuit in Cadence. After the entire circuit design is completed, Cadence's IC layout can be carried out. Present the designed circuit in the form of an IC layout. In this process, component placement planning and circuit connection are required after continuous correction and testing. Finally, the IC chip can be made with this IC layout.

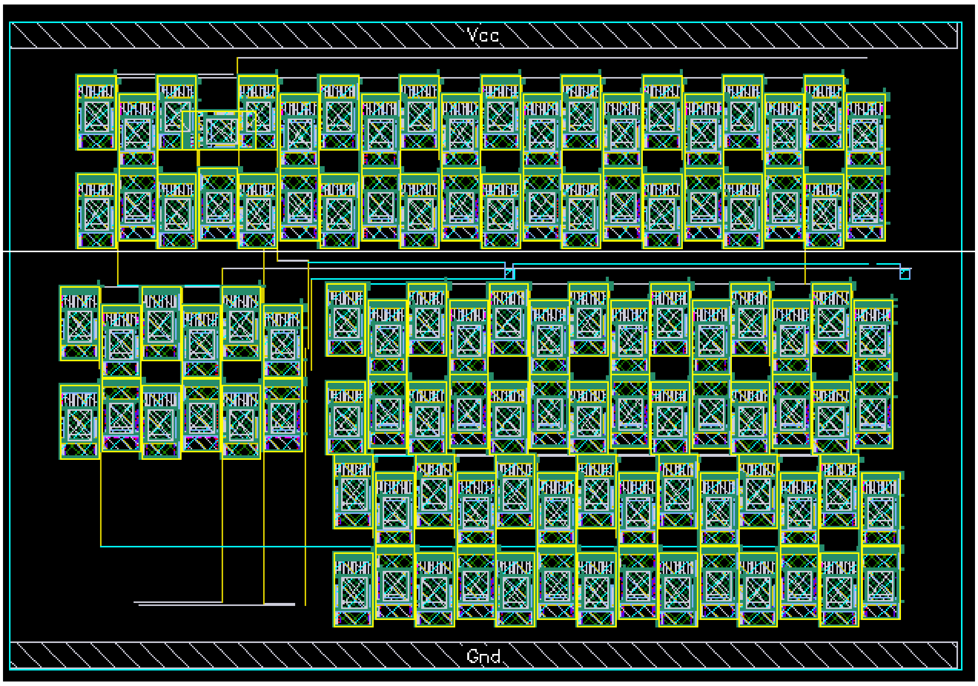

Figure 4.25: 2.5mm*1.5mm IC layout diagram of the entire energy management circuit in Cadence.

Chapter 5

Results and Discussion

Table 5.1 shows the comparison of the energy harvesting model results between this work and other work. Since this work's piezoelectric energy harvesting model is a piezoelectric energy harvesting matrix composed of four identical piezoelectric energy harvesting models, the area is larger than other jobs. Nevertheless, if it is measured separately, it can be measured that this model's size is not larger than other models. In terms of acceleration, the parameters used in each experiment are different. This will depend on the purpose of the experiment. The application scenario determines the design of this acceleration, and the acceleration also determines the amount of energy collected. When the acceleration is larger, it can be known from the formula that the corresponding harvested energy will be larger, and the acceleration is positively correlated with the harvested energy. The application scenario set in this experiment focuses on collecting small vibrations, so the energy harvested by the setting will be relatively small. However, if the operation is at a higher acceleration and the designed resonance frequency, the power harvested will also increase. You need to pay attention when the acceleration starts to cause the piezoelectric energy harvesting cantilever to collide with other surfaces. That is the acceleration limit that this model can respond to.

Table 5.1: Comparison of this work with other paper of MEMS PEH

Ref.	Power[uW]	Freq.[Hz]	Material	Area[mm^2]	Acceleration[g]
[132]	1.01	13900	d_{33} PZT	0.0442^a	13.2^a
[133]	2.16	608	d_{31} PZT	2.65^a	1
[134]	2	1368	d_{31} AIN	0.96^a	4.0
[135]	40	1800	d_{31} PZT	7.5^a	1.9^a
[136]	2.15	462.5	d_{31} PZT	2.65^a	2.0
[137]	1.1	528	d_{31} PZT	1.8	0.39
[138]	2^a	3688	d_{31} AIN	1	2
This	1.26	3094	d_{31} PZT	2^a	2.45

Even after many experiments and attempts, there is still much room for improvement and ways to try this work. For example: In this experiment, the height is limited to less than 1mm, but if there is no such height limit, MEMS+ can be used to increase the height when making piezoelectric energy harvesting so that the model has more space to accommodate mass and can effectively reduce the resonance frequency. Alternatively, when the height is increased, another set of piezoelectric energy harvesting cantilever with resonance frequency can be made on the original cantilever. This can make this model have a wider resonance frequency and can respond to more application scenarios. If the height limit is not very strict, more groups of piezoelectric energy harvesting cantilevers with different resonance frequencies can be added, which can be discussed again. You can also experiment to compare the 9mm*9mm model with the 9 3mm*3mm models used this time, and then explore the difference in the two's characteristics under the same space. In-depth review of the flexibility and convenience of using small model overlays and the effectiveness of using a single large model. In terms of materials and technology, you can try different combinations and compare each in-depth advantages and disadvantages.

Chapter 6

Conclusion

Energy consumption is increasing every day, and the sources of energy production are also decreasing, so new sources of energy must be found. Generally, energy harvesting can be defined as obtaining energy from a useful work source. In order to harvest energy, it needs to be captured and stored to minimize losses.

View energy available from various sources, such as mechanical vibration, light, wind, temperature, and electromagnetic changes. The collection process converts environmental energy into electrical energy. By eliminating the need for additional batteries or replacement batteries, energy harvesting can maximize device performance and lifespan.

The number of IoT devices will grow rapidly in the future, and managing these devices has become the biggest problem. Nevertheless, there is corresponding energy harvesting so that the power system of the device can be self-sufficient. It can greatly reduce the management cost of the device.

In this article, energy harvesting is discussed based on techniques for harvesting vibration energy. A review of the extensive enhancement and development of energy harvesting research in the literature shows the importance of this research in improving energy harvesting in different fields. This article reviews the technologies related to energy vibration harvesting based on previous studies' system analysis, including piezoelectric energy harvesting and electrostatic energy harvesting. There is a more in-depth discussion of piezoelectric energy harvesting. After collecting energy, there is more introduction to the related management of output energy.

In terms of this work, it was demonstrated that after completing the piezoelectric energy collection model using CoventorMP and Cadence's collaboration, the model-related simulation and analysis were performed. Furthermore, this process of making energy harvesting greatly reduces the production cost of engineers. After familiarizing with this set of procedures, in practice, adjust and improve the model's parameters to achieve better performance of the energy harvesting device.

Both piezoelectric and electrostatic are in the early stages of development and may be added in future applications. In the future, more energy can also be concentrated on integrating multiple energy harvesting and power generation technologies into a single system to take advantage of their respective advantages and develop new innovative applications in the future.

Bibliography

[1] Yildiz, F.. “Potential Ambient Energy-Harvesting Sources and Techniques.” The Journal of Technology Studies 35 (2009): 40-48. Last seen date: Oct. 2020

[2] Runar Finanger, "What is energy harvesting?", ONiN, 2020. Last seen date: Dec. 2020

[3] Joseph Davidson, Changki Mo, "Recent Advances in Energy Harvesting Technologies for Structural Health Monitoring Applications", Smart Materials Research, vol. 2014, Article ID 410316, 14 pages, 2014. Last seen date: Oct. 2020

[4] "Thermoelectric Energy Harvesting", II-VI. Last seen date: Oct. 2020

[5] Batra, Ashok Aggarwal, Mohan. (2013). Pyroelectric materials: Infrared detectors, particle accelerators and energy harvesters. 10.1117/3.1000982. Last seen date: Oct. 2020

[6] Frank Schmidt, Enocean Gmbh, "Current and future possibilities with wireless energy harvesting", Embedded Computing Design, 2016. Last seen date: Oct. 2020

[7] Amos Kingatua, "The How and Why of Energy Harvesting for Low-Power Applications", All About Circuits, 2016. Last seen date: Oct. 2020

[8] Dragoslav Grbovic, Sebastian Osswald, "Harvesting and Storage", Naval Postgraduate School, 2011. Last seen date: Oct. 2020

[9] "Energy harvesting trends and the important role of battery technology", ilika, 2016. Last seen date: Oct. 2020

[10] "E-PEAS TCT Demonstrate Inductive Energy Harvesting", EEJournal, 2020. Last seen date: Dec. 2020

[11] Maija Palmer, "The tiny Dutch startup solving the IoT industry’s battery problem", sifted, 2019. Last seen date: Oct. 2020

[12] Paul Shepard, "New Process Technology Eliminates the Need for Batteries to Power IoT Devices", EE Power, 2018. Last seen date: Oct. 2020

[13] Action Nechibvute, Albert Chawanda, Pearson Luhanga, "Piezoelectric Energy Harvesting Devices: An Alternative Energy Source for Wireless Sensors", Smart Materials Research, vol. 2012, Article ID 853481, 13 pages, 2012. Last seen date: Oct. 2020

[14] "CEA-Leti's Energy-Harvesting ICs Point the Way To Battery-Free Sensor Systems in Humans Or in Harsh Environments", Leti Cea tech, 2020. Last seen date: Dec. 2020

[15] Jeffrey Briner, "Energy Harvesting for IoT Devices", Leverege, 2019. Last seen date: Oct. 2020

[16] Srinivas Pattamatta, "How Energy Harvesting is Enabling New Possibilities for Medical Wearable Devices", Embedded Computing Design, 2020. Last seen date: Dec. 2020

[17] Frederik Dostal, "New Advances in Energy Harvesting Power Conversion", Analog Dialogue, Vol. 49, 2015. Last seen date: Oct. 2020

[18] J. Huang, Y. Zhou, Z. Ning and H. Gharavi, "Wireless Power Transfer and Energy Harvesting: Current Status and Future Prospects," in IEEE Wireless Communications, vol. 26, no. 4, pp. 163-169, August 2019, doi: 10.1109/MWC.2019.1800378. Last seen date: Oct. 2020

[19] Ecn Staff, "Brainstorm: Where Will Energy Harvesting Make Its Greatest Impact?", EE world Online, 2019. Last seen date: Oct. 2020

[20] "Energy harvesting", Wikipedia. Last seen date: Oct. 2020

[21] "Here's why energy-harvesting trumps batteries", ONiN, 2020. Last seen date: Dec. 2020

[22] S.P. Beeby, Z. Cao, A. Almussallam, "Kinetic, thermoelectric and solar energy harvesting technologies for smart textiles", Woodhead Publishing, 2013, Pages 306-328, ISBN 9780857093424. Last seen date: Oct. 2020

[23] "IoT Devices Harvest Their Own Energy", aeris. Last seen date: Oct. 2020

[24] "Energy Harvesting and the Energy Grid", Mithras. Last seen date: Oct. 2020

[25] Peter Cleaveland, "How does energy harvesting enable the IoT?", Enterprise iot Insights, 2018. Last seen date: Oct. 2020

[26] Ed Sperling and Kevin Fogarty, "The Limits Of Energy Harvesting", Semiconductor Engineering, 2019. Last seen date: Oct. 2020

[27] *Z*astrow, Mark. (2019). Energy harvesters pick up power. Nature. 576. S38-S39. 10.1038/d41586-019-03767-y. Last seen date: Oct. 2020

[28] *C*hristian Pennisi, "Energy Harvesting's Emerging Role in a 'Smarter' World", Tech Briefs, 2016. Last seen date: Oct. 2020

[29] *P*atrick Moorhead, "No More Batteries, No More Cords: The Perks Of IoT Energy Harvesting", Forbes, 2020. Last seen date: Dec. 2020

[30] ″Wireless power energizes wireless sensor networks", Industrial Embedded Systems, 2009. Last seen date: Oct. 2020

[31] *Z*hang, Fan Zhang, Yanqing Silver, Jason Shakhsheer, Yousef Nagaraju, Manohar Klinefelter, Alicia Pandey, Jagdish Boley, James Carlson, Eric Shrivastava, Aatmesh Otis, Brian Calhoun, Benton. (2012). A batteryless 19W MICS/ISM-band energy harvesting body area sensor node SoC. 55. 298-300. 10.1109/ISSCC.2012.6177004. Last seen date: Oct. 2020

[32] *J*eff Shepard, "Design challenges when using energy harvesting – Virtual Roundtable", Power Electronic Tips, 2020. Last seen date: Dec. 2020

[33] *S*teven Mill, "Latest Energy Harvesting Systems that will replace Batteries", Electrical Equipment. Last seen date: Oct. 2020

[34] *J*abbar, Hamid Song, Young Jeong, Taikyeong. (2010). RF Energy Harvesting System and Circuits for Charging of Mobile Devices. Consumer Electronics, IEEE Transactions on. 56. 247 - 253. 10.1109/TCE.2010.5439152. Last seen date: Oct. 2020

[35] *S* Roundy, PK Wright (2004) A piezoelectric vibration based generator for wireless electronics. Smart materials and structures 13:1131. Last seen date: Oct. 2020

[36] *Y*oung-Man Choi, "Future Directions in High-Power Wearable Biomechanical Energy Harvesting Technologies", Eyvor, 2018. Last seen date: Oct. 2020

[37] *R*ajesh Uppal, "Soldiers employing human energy harvesting technologies including backpack, knee kinetic and heel-strike to power devices on the battlefield", IDST, 2020. Last seen date: Dec. 2020

[38] *B*ai Yang, Jantunen Heli, Juuti Jari, "Hybrid, Multi-Source, and Integrated Energy Harvesters", Frontiers in Materials, Vol. 5, 2018, DOI=10.3389/fmats.2018.00065. Last seen date: Oct. 2020

[39] *Z*hang Yangyang, Lu Bingwei, Lü Chaofeng and Feng Xue 2017Theory of energy harvesting from heartbeat including the effects of pleural cavity and respirationProc. R. Soc. A.47320170615. Last seen date: Oct. 2020

[40] *A*lice Matthews, "Energy harvester produces power from local environment", electronic specifier, 2017. Last seen date: Oct. 2020

[41] Canan Dagdeviren, Byung Duk Yang, Yewang Su, Phat L. Tran, Pauline Joe, Eric Anderson, Jing Xia, Vijay Doraiswamy, Behrooz Dehdashti, Xue Feng, Bingwei Lu, Robert Poston, Zain Khalpey, Roozbeh Ghaffari, Yonggang Huang, Marvin J. Slepian, John A. Rogers, "Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm", Proceedings of the National Academy of Sciences Feb 2014, 111 (5) 1927-1932; DOI: 10.1073/pnas.1317233111. Last seen date: Oct. 2020

[42] Pradeesh, E.L., Udhayakumar, S. Sathishkumar, C. Investigation on various beam geometries for piezoelectric energy harvester with two serially mounted piezoelectric materials. SN Appl. Sci. 1, 1648 (2019). Last seen date: Oct. 2020

[43] Bakytbekov, A, Nguyen, TQ, Li, W, et al. Multi-source ambient energy harvester based on RF and thermal energy: Design, testing, and IoT application. Energy Sci Eng. 2020; 8: 3883– 3897. Last seen date: Dec. 2020

[44] C. Gould and R. Edwards, "Review on micro-energy harvesting technologies," 2016 51st International Universities Power Engineering Conference (UPEC), Coimbra, 2016, pp. 1-5. Last seen date: Oct. 2020

[45] Conferences of Energy Harvesting Storage, IDTechEx, 2009. Last seen date: Oct. 2020

[46] Wang, W., V. Cionca, Ningning Wang, M. Hayes, B. O'Flynn and C. O'Mathúna. "Thermoelectric Energy Harvesting for Building Energy Management Wireless Sensor Networks." International Journal of Distributed Sensor Networks 9 (2013): n. pag. Last seen date: Oct. 2020

[47] Morteza Ghorbani, Ali Mohammadi, Ahmad Reza Motezakker, Luis Guillermo Villanueva, Yusuf Leblebici, and Ali Koşar, "Energy Harvesting in Microscale with Cavitating Flows", ACS Omega 2017 2 (10), 6870-6877, DOI: 10.1021/acsomega.7b01204. Last seen date: Oct. 2020

[48] Chin-Chung Chen, Tien-Kan Chung, Chi-Cheng Cheng, Chia-Yuan Tseng, "A novel miniature thermomagnetic energy harvester," Proc. SPIE 9057, Active and Passive Smart Structures and Integrated Systems 2014, 90570X (9 March 2014). Last seen date: Oct. 2020

[49] Ying Gong, Zhengbao Yang, Xiaobiao Shan, Yubiao Sun, Tao Xie and Yunlong Zi, "Capturing Flow Energy from Ocean and Wind", Energies 2019, 12(11), 2184. Last seen date: Oct. 2020

[50] Elizabeth Montalbano, "Energy Harvester Specifically for Nano-Devices Developed", Design News, 2017. Last seen date: Oct. 2020

[51] Shin, Youn-Hwan Choi, Jaehoon Kim, Seong Kim, Sangtae Maurya, Deepam Sung, Tae-Hyun Priya, S.Jeba Kang, Chong-Yun Song,

Hyun-Cheol. (2020). Automatic resonance tuning mechanism for ultra-wide bandwidth mechanical energy harvesting. Nano Energy. 77. 104986. 10.1016/j.nanoen.2020.104986. Last seen date: Dec. 2020

[52] *R*obert Henson, "Smart infrastructure | Vibration energy", New Civil Engineer, 2016. Last seen date: Oct. 2020

[53] *W*illiams CB and Yates RB (1996) Analysis of a micro-electric generator for microsystems. Sensors and Actuators A: Physical 52(1): 8–11. Last seen date: Oct. 2020

[54] *J*ia, Yu. “Review of Nonlinear Vibration Energy Harvesting: Duffing, Bistability, Parametric, Stochastic and Others.” Journal of Intelligent Material Systems and Structures 31, no. 7 (April 2020): 921–44. Last seen date: Oct. 2020

[55] *F*arid Ullah Khan, Iftikhar Ahmad, "Review of Energy Harvesters Utilizing Bridge Vibrations", Shock and Vibration, vol. 2016, Article ID 1340402, 21 pages, 2016. Last seen date: Oct. 2020

[56] *J*ohan Pedersen, "Vibrations power tomorrow’s IoT devices", Force Technology. Last seen date: Oct. 2020

[57] *F*rancesco Orfei, "Introduction to Vibration Energy Harvesting", All About Circuits, 2019. Last seen date: Nov. 2020

[58] *L*en Calderone, "Producing Energy from Vibrations", altenergymag, altenergymag, 2020. Last seen date: Dec. 2020

[59] *C*hengkuo Lee, et al., "Power MEMS Energy Harvesters", NUS Lab of Sensors, MEMS and NEMS. Last seen date: Nov. 2020

[60] *R*uize Xu, Haluk Akay, and Sang-Gook Kim, "Buckled MEMS Beams for Energy Harvesting from Low Frequency Vibrations", Massachusetts Institute of Technology, Mechanical Engineering Department, Cambridge, MA 02139, USA. Last seen date: Nov. 2020

[61] *E*ghbali, Pejman Farhangdoust, Saman Younesian, Davood. (2020). Railway vehicle vibration energy harvesting using nonlinear resonators. 3. 10.1117/12.2559329. Last seen date: Dec. 2020

[62] *P*edchenko, Alexander Vadimovich, "The Power Harvesting Ratio: Design and Power Estimation of Vibration Energy Harvesters", Vanderbilt University Institutional Repository, 2015. Last seen date: Nov. 2020

[63] ″Compact vibration harvester power supply with highest efficiency", IDTechEx, 2014. Last seen date: Nov. 2020

[64] *C*hris Ludlow, "Can I Power my Smart Phone with Vibration Energy Harvesting?", Piezo.com blog. Last seen date: Nov. 2020

[65] Ardito Raffaele, Corigliano Alberto, Gafforelli Giacomo, Valzasina Carlo, Procopio Francesco,and Zafalon Roberto, "Advanced Model for Fast Assessment of Piezoelectric Micro Energy Harvesters", Frontiers in Material, Volum 3, 2016. Last seen date: Nov. 2020

[66] Miller, L. M. (2012). Micro-scale piezoelectric vibration energy harvesting: from fixed-frequency to adaptable-frequency devices. UC Berkeley. Merritt ID: ark:/13030/m56q2259. Last seen date: Nov. 2020

[67] John Donovan, "New Applications for Energy Harvesting", Mouser Electronics. Last seen date: Nov. 2020

[68] Paul Ahern "Good Vibrations: Piezoelectric Energy Harvesting", EE535 Renewable Energy Systems, 2012. Last seen date: Nov. 2020

[69] Bhosale Arun, Anderson Arul, Deshmukh P. Suhas Voltage enhancing using multi-magnetic arrangement for low frequency vibrational energy harvesting. Journal of Vibroengineering, Vol. 20, Issue 4, 2018, p. 1720-1732. Last seen date: Nov. 2020

[70] "Vibration-powered generator", Wikipedia. Last seen date: Nov. 2020

[71] Namita Shah, "Piezoelectric Energy Harvesting from Vehicle Wheels", Longdom, 2020, ISSN: 2167-7670. Last seen date: Dec. 2020

[72] Imran Patel, "Ceramic Based Intelligent Piezoelectric Energy Harvesting Device", IntechOpen, 2010, DOI: 10.5772/19189. Last seen date: Nov. 2020

[73] Fuhong Dai and Diankun Pan, "Piezoelectric Energy Harvesting Based on Bi-Stable Composite Laminate", IntechOpen, 2018, DOI: 10.5772/intechopen.76193. Last seen date: Nov. 2020

[74] Shashank Priya and Robert D. Myers, "Piezoelectric energy harvester", Hilti AG University of Texas System, 2008. Last seen date: Nov. 2020

[75] Matthew Zelisko Kimberly Anderson, "Hands-on Activity: Building a Piezoelectric Generator", Teach Engineering, 2020. Last seen date: Dec. 2020

[76] Fu, Hailing Chen, Guangzhu Bai, Nan. (2018). Electrode Coverage Optimization for Piezoelectric Energy Harvesting from Tip Excitation. Last seen date: Nov. 2020

[77] P. J. Cornwell, J. Goethal, J. Kowko, M. Damianakis, "Enhancing power harvesting using a tuned auxiliary structure", Journal of Intelligent Material Systems and Structures, vol. 16, pp. 825-834, 2005. Last seen date: Nov. 2020

[78] Y. Liu, K. L. Ren, H. F. Hofmann, Q. Zhang, "Investigation of Electrostrictive Polymers for Energy Harvesting", IEEE Transactions on Ultrasonics ferroelectrics and Frequency control, vol. 52, no. 12, pp. 2411-2417, December 2005. Last seen date: Nov. 2020

[79] P. D. Mitcheson, T. C. Green, E. M. Yeatman, A. S. Holmes, "Architectures for Vibration-Driven Micro-Power Generators", IEEE Journal of Microelectromechanical Systems, vol. 13, pp. 429-440, 2004. Last seen date: Nov. 2020

[80] N. M. White, P. Glynne-Jones, S. Beeby, "A novel thick-film piezoelectric micro-generator", Smart Material Structures, vol. 10, pp. 850-852, August 2001. Last seen date: Nov. 2020

[81] Michael Berger, "Designing nanogenerators for large-scale energy harvesting", nanowerk, 2013. Last seen date: Nov. 2020

[82] Kempitiya, A. (2012). Low power interface IC's for electrostatic energy harvesting applications (Order No. 3514768). . (1022175958). Last seen date: Nov. 2020

[83] Varpula, A., Laakso, S., Havia, T. et al. Harvesting Vibrational Energy Using Material Work Functions. Sci Rep 4, 6799 (2014). Last seen date: Nov. 2020

[84] "The Electrostatic Energy Harvesting Engineering Essay." UKEssays. ukessays.com, November 2018. Last seen date: Nov. 2020

[85] Sang Woo KIM, Keun Young LEE, and Seong Su KIM, "Electrosratic Energy-Harvesting Device Having 3-Dimensional Cone Shape" Justia Patents, 2015. Last seen date: Nov. 2020

[86] Clara Lagomarsini, Achraf Kachroudi, Skandar Basrour, Claire Jean-Mistral, Alain Sylvestre, "Autonomous electrostatic generator for energy harvesting applications under inertial load," Proc. SPIE 10594, Electroactive Polymer Actuators and Devices (EAPAD) XX, 105941Q (27 March 2018). Last seen date: Nov. 2020

[87] Ji-Tzuoh Lin, "SBIR Phase I: Ultra Low Power Electrostatic Switch Relay for Vibration Energy Harvesting", 2012. Last seen date: Nov. 2020

[88] S. Boisseau, G. Despesse and B. Ahmed Seddik, "Electrostatic Conversion for Vibration Energy Harvesting", IntechOpen, 2012, DOI: 10.5772/51360. Last seen date: Nov. 2020

[89] Miljkovic N, Preston DJ, Enright R, Wang EN. Jumping-droplet electrostatic energy harvesting. Applied Physics Letters. 2014 Jul 7;105(1). 013111. Last seen date: Nov. 2020

[90] Kubba, Ali Jiang, K.C.. (2014). A Comprehensive Study on Technologies of Tyre Monitoring Systems and Possible Energy Solutions. Last seen date: Nov. 2020

[91] V. Janicek, M. Husak, J. Jakovenko, J. Formanek, "Design and Fabrication of 3D Electrostatic Energy Harvester", Radio Engineering, vol. 21, no. 1, pp. 231-238, 2012. Last seen date: Nov. 2020

[92] V. Janicek, "Energy harvesting in 3D," The Tenth International Conference on Advanced Semiconductor Devices and Microsystems, Smolenice, 2014, pp. 1-4. Last seen date: Nov. 2020

[93] V. Janicek, "3D energy harvester with tunable resonant frequency," 2016 11th International Conference on Advanced Semiconductor Devices Microsystems (ASDAM), Smolenice, 2016, pp. 97-100. Last seen date: Nov. 2020

[94] W. Ali and S. Ibrahim, "Power Analysis for Piezoelectric Energy Harvester," Energy and Power Engineering, Vol. 4 No. 6, 2012, pp. 496-505. doi: 10.4236/epe.2012.46063. Last seen date: Nov. 2020

[95] A. Safari and A. E. Korary, "Piezoelectric and Acoustic Materials for Transducer Applications," Springer, Berlin, Heidelberg, 2010. Last seen date: Nov. 2020

[96] W. Heywang, K. Lubitz and W. Wersing, "Piezoelectricity Evolution and Future of a Technology," Springer, Berlin, Heidelberg, 2008. Last seen date: Nov. 2020

[97] A. Arnau, "Piezoelectric Transducers and Applications," Springer, Berlin, Heidelberg, 2008. Last seen date: Nov. 2020

[98] H. A. Sodano and D. J. Inman, "Comparison of Piezoelectric Energy Harvesting Devices for Recharging Batteries," Journal of Intelligent Material Systems and Structures, Vol. 16, No. 10, 2005, pp. 799-807. doi:10.1177/1045389X05056681 [Citation Time(s):1]. Last seen date: Nov. 2020

[99] K. A. Cook-Chennault, N. Thambi and A. M. Sastry, "Powering MEMS Portable Devices—A Review of Non-Regenerative and Regenerative Power Supply Systems with Special Emphasis on Piezoelectric Energy Harvesting Systems," Smart Materials and Structures, Vol. 17, No. 4, 2008. doi:10.1088/0964-1726/17/4/043001 [Citation Time(s):1]. Last seen date: Nov. 2020

[100] Jafri, Hasnain Mehdi. (2020). Re: What is the difference between d33, d31, d32 component of piezoelectric coefficient?. Retrieved from: https://www.researchgate.net/post/What-is-the-difference-between-d33-d31-d32-component-of-piezoelectric-coefficient/5ec4d2f66ed41c7f3f1ced42/citation/download. Last seen date: Dec. 2020

[101] C. B. Williams and R. B. Yates, "Analysis of MicroElectric Generator for Microsystems," Sensors and Actuators A: Physical, Vol. 52, No. 1-3,

1996, pp. 8-11. doi:10.1016/0924-4247(96)80118-X [Citation Time(s):2]. Last seen date: Nov. 2020

[102] T. J. Kazmierski and S. Beeby, “Energy Harvesting Systems: Principles, Modeling and Applications,” Springer Science, Berlin, Heidelberg, 2011. [Citation Time(s):2]. Last seen date: Nov. 2020

[103] Yongke Yan Deepam Maurya, "Principles of Piezoelectric Energy Harvesting", APC International, 2015. Last seen date: Nov. 2020

[104] Andrius Čeponis, Dalius Mažeika, "Investigation of Multifrequency Piezoelectric Energy Harvester", Shock and Vibration, vol. 2017, Article ID 8703680, 13 pages, 2017. Last seen date: Nov. 2020

[105] Eghbali, P., Younesian, D., Moayedizadeh, A. et al. Study in circular auxetic structures for efficiency enhancement in piezoelectric vibration energy harvesting. Sci Rep 10, 16338 (2020). Last seen date: Dec. 2020

[106] Li Chuan, Hong Daewoong, Kwon Kwang-Ho, Jeong Jaehwa Enhancement of energy harvesting performance for a piezoelectric cantilever using a spring mass suspension. Journal of Vibroengineering, Vol. 16, Issue 1, 2014, p. 116-125. Last seen date: Nov. 2020

[107] Yabin Liao, Huanyu Cheng, "An integrated design approach of piezoelectric vibration energy harvesters," Proc. SPIE 11376, Active and Passive Smart Structures and Integrated Systems XIV, 1137608 (22 April 2020). Last seen date: Nov. 2020

[108] Chris Ludlow, "Four Steps to Selecting a Piezoelectric Energy Harvesting Device", Piezo.com Blog. Last seen date: Nov. 2020

[109] B. Ahmed Seddik, G. Despesse, S. Boisseau and E. Defay (October 31st 2012). Strategies for Wideband Mechanical Energy Harvester, Small-Scale Energy Harvesting, Mickael Lallart, IntechOpen, DOI: 10.5772/51898. Last seen date: Nov. 2020

[110] Peyman Hajheidari, Ion Stiharu Rama Bhat (2020) Performance enhancement of cantilever piezoelectric energy harvesters by sizing analysis, International Journal of Smart and Nano Materials, 11:2, 93-116, DOI: 10.1080/19475411.2020.1751743. Last seen date: Dec. 2020

[111] Patel, Rupesh (2013) Modelling analysis and optimisation of cantilever piezoelectric energy harvesters. PhD thesis, University of Nottingham. Last seen date: Nov. 2020

[112] Abhay Khalatkar, V. K. Gupta, Ankit Agrawal, "Analytical, FEA, and Experimental Comparisons of Piezoelectric Energy Harvesting Using Engine Vibrations", Smart Materials Research, vol. 2014, Article ID 741280, 8 pages, 2014. Last seen date: Nov. 2020

[113] Saman Farhangdoust, "Auxetic cantilever beam energy harvester," Proc. SPIE 11382, Smart Structures and NDE for Industry 4.0, Smart Cities, and Energy Systems, 113820V (22 April 2020). Last seen date: Nov. 2020

[114] Sharpes, N., Abdelkefi, A., Priya, S. (2014). Comparative Analysis of One-Dimensional and Two-Dimensional Cantilever Piezoelectric Energy Harvesters, Energy Harvesting and Systems, 1(3-4), 209-216. Last seen date: Nov. 2020

[115] Warda Saeed, Nosherwan Shoaib, Hammad M. Cheema, and Muhammad U. Khan, "RF Energy Harvesting for Ubiquitous, Zero Power Wireless Sensors", Hindawi, International Journal of Antennas and Propagation, Volume 2018, Article ID 8903139, 16 pages. Last seen date: Nov. 2020

[116] Maurizio Di Paolo Emilio, "Circuits for RF Energy Harvesting", Planet Analog, 2019. Last seen date: Nov. 2020

[117] A. Savanth, A. S. Weddell, J. Myers, D. Flynn and B. M. Al-Hashimi, "Integrated Reciprocal Conversion With Selective Direct Operation for Energy Harvesting Systems," in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 64, no. 9, pp. 2370-2379, Sept. 2017, doi: 10.1109/TCSI.2017.2707304. Last seen date: Nov. 2020

[118] "Energy Harvesting by Means of Low Power Conversion", iEN.eu, 2015. Last seen date: Dec. 2020

[119] O'Connor, Thomas Joseph III, "Power Converter Design for Maximum Power Transfer and Battery Management for Vibration-Based Energy Harvesting on Commercial Railcars", Virginia Polytechnic Institute and State University, 2015. Last seen date: Dec. 2020

[120] Nguyen, Cong-Long and Tartakovsky, Boris and Woodward, Lyne, "Harvesting Energy from Multiple Microbial Fuel Cells with a High-Conversion Efficiency Power Management System", ACS Omega, Vol. 4, no. 21, pp. 18978-18986, 2019. DOI = 10.1021/acsomega.9b01854. Last seen date: Dec. 2020

[121] R.J.M Vullers et al., "Micropower energy harvesting", Solid-State Electronics, vol. 53, no. 7, pp. 684-693, Jul 2009. Last seen date: Dec. 2020

[122] "DC/DC converter with energy harvesting battery charger", Linear Technology Corporation, 2014. Last seen date: Dec. 2020

[123] Liu, Haili, Rui Hua, Yang Lu, Ya Wang, Emre Salman, and Junrui Liang. "Boosting the Efficiency of a Footstep Piezoelectric-Stack Energy Harvester Using the Synchronized Switch Technology." Journal of Intelligent Material Systems and Structures 30, no. 6 (April 2019): 813–22. Last seen date: Dec. 2020

[124] *V.* E and R. S, “Performance improvement of piezoelectric materials in energy harvesting in recent days – a review,” Journal of Vibroengineering, vol. 20, no. 7, pp. 2632–2650, Nov. 2018. Last seen date: Dec. 2020

[125] ″New Wearable Piezoelectric Device Harvests Energy from Low-Frequency Vibrations", Sci News, 2018. Last seen date: Dec. 2020

[126] *E*ltamaly, Ali Addoweesh, Khaled. (2016). A Novel Self Power SSHI Circuit for Piezoelectric Energy Harvester. IEEE Transactions on Power Electronics. PP. 1-1. 10.1109/TPEL.2016.2636903. Last seen date: Dec. 2020

[127] *D.* Newell and M. Duffy, "Review of Power Conversion and Energy Management for Low-Power, Low-Voltage Energy Harvesting Powered Wireless Sensors," in IEEE Transactions on Power Electronics, vol. 34, no. 10, pp. 9794-9805, Oct. 2019. Last seen date: Dec. 2020

[128] *K*umar, Saurabh Kumar, Rajat Singh, Dr. Navdeep. (2017). Performance of closed loop SEPIC converter with DC-DC converter for solar energy system. 10.1109/ICPCES.2017.8117668. Last seen date: Dec. 2020

[129] ″Charge pump", Wikipedia. Last seen date: Dec. 2020

[130] ″MEMS+IC Co-Simulation at Circuit Level", Coventor, form: https://www.coventor.com/products/coventormp/mems-plus/cadence-integration/. Last seen date: Dec. 2020

[131] ″MEMS Energy Harvesters Design and Simulation", Coventor, form: https://www.coventor.com/mems-solutions/energy-harvesters/. Last seen date: Dec. 2020

[132] *Y.*B. Jeon et al., “MEMS Power Generator with Transverse Mode Thin Film PZT”, Sensors Actuators A, vol. 122, pp. 16–22, 2005. Last seen date: Dec. 2020

[133] *H.*-B. Fang, J.-Q. Liu, Z.-Y. Xu, L. Dong, L. Wang, D. Chen, B.-C. Chai, and Y. Liu, "Fabrication and Performance of MEMS-based Piezoelectric Power Generator for Vibration Energy Harvester,” Microelectron. J., vol. 37, pp. 1280-1284, 2006. Last seen date: Dec. 2020

[134] *M.* Marzencki, Y. Ammar, and S. Basrour, “Integrated Power Harvesting System Including a MEMS Generator and A Power Management Circuit,” in Proc. Int. Conf. on Solid-State Sensors, Actuators and Microsystems, Lyon, 2007, pp. 887-890. Last seen date: Dec. 2020

[135] *M.* Renaud, T. Sterken, A. Schmitz, P. Fiorini, C. Van Hoof, and R. Puers, “Piezoelectric Harvesters and MEMS Technology: Fabrication, Modeling and Measurements,” in Proc. Int. Conf. on Solid-State Sensors, Actuators and Microsystems, Lyon, 2007, pp. 891-894. Last seen date: Jan. 2021

[136] *D*. Shen, J.-H. Park, J. Ajitsaria, S.-Y. Choe, H. C. Wikle III, and D.-J. Kim, “The Design, Fabrication and Evaluation of A MEMS PZT Cantilever with An Integrated Si Proof Mass for Vibration Energy Harvesting,” J. Micromech. Microeng., vol. 18, pp. 1-7, 2008. Last seen date: Jan. 2021

[137] *J*. C. Park, D. H. Lee, J. Y. Park, Y. S. Chang and Y. P. Lee, "High performance piezoelectric MEMS energy harvester based on D33 mode of PZT thin film on buffer-layer with PBTIO3 inter-layer," TRANSDUCERS 2009 - 2009 International Solid-State Sensors, Actuators and Microsystems Conference, Denver, CO, 2009, pp. 517-520, doi: 10.1109/SENSOR.2009.5285375. Last seen date: Jan. 2021

[138] *J*ia, Y., Seshia, A.A. Five topologies of cantilever-based MEMS piezoelectric vibration energy harvesters: a numerical and experimental comparison. Microsyst Technol 22, 2841–2852 (2016). Last seen date: Jan. 2021

[139] *B*allo, Andrea Grasso, Alfio Palumbo, Gaetano. (2019). A Review of Charge Pump Topologies for the Power Management of IoT Nodes. Electronics. 8. 10.3390/electronics8050480. Last seen date: Jan. 2021

[140] *T*akei, Ryohei Okada, Hiroyuki Noda, Daiji Ohta, Ryo Takeshita, Toshihiro Itoh, Toshihiro Kobayashi, Takeshi. (2017). High-efficiency MOSFET bridge rectifier for AlN MEMS cantilever vibration energy harvester. Japanese Journal of Applied Physics. 56. 04CC03. 10.7567/JJAP.56.04CC03. Last seen date: Jan. 2021

[141] *P*eter Spies, Loreto Mateu, Markus Pollak, "Handbook of energy harvesting power supplies and applications-CRC Press", 2015, ISBN-13: 978-981-4303-06-4. Last seen date: Jan. 2021

[142] *C*MOS Circuits for Piezoelectric Energy Harvesters: Efficient Power Extraction, Interface Modeling and Loss Analysis, ISBN-13: 978-9401792875. Last seen date: Jan. 2021

[143] *N*anostructured Piezoelectric Energy Harvesters, ISBN-13: 978-3319096315. Last seen date: Jan. 2021

[144] *C*oventor Tutorials, from: www.coventor.com. Last seen date: Jan. 2021

[145] *C*adence Design Tutorials, from: www.cadence.com. Last seen date: Jan. 2021