Energy Harvesting for IoT Sensors

Parvathi Shenoy Kasargod

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Energy Harvesting for IOT Sensors

By

Parvathi Shenoy Kasargod

A Thesis
Submitted to the Faculty of Graduate Studies
to the Department of Electrical and Computer Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2017

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Energy Harvesting for IOT Sensors

by

Parvathi Shenoy Kasargod

APPROVED BY:

______________________________
Dr. Riahi Reza
Mechanical, Automotive & Materials Engineering

______________________________
Dr. Roberto Muscedere
Electrical and Computer Engineering

______________________________
Dr. Majid Ahmadi, Co-Advisor
Electrical and Computer Engineering

______________________________
Dr. Rashid Rashidzadeh, Co-Advisor
Electrical and Computer Engineering

January 23, 2017
DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATION

I. Co-Authorship Declaration

I hereby declare that this dissertation incorporates material that is the result of research conducted under the supervision of my supervisors, Dr. Rashid Rashidzadeh and Dr. Majid Ahmadi. I am aware of the University of Windsor's Senate Policy on Authorship and I certify that I have properly acknowledged the contributions of other researchers to my dissertation, and I have obtained written permission from my co-authors to include the aforementioned materials in my dissertation. I certify that this dissertation and the research results to which it refers are the product of my own work.

II. Declaration of Previous Publication

This dissertation includes three original papers that have been previously published/submitted for publication in peer reviewed journals, as follows:

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ABSTRACT

The growing need for alternative energy sources for sensors and portable devices has led to many energy-harvesting solutions. As the technology scales down and the supply voltage drops, the complexity of designing energy harvesting circuits increases. In this work, a vibrational energy harvester using Microelectromechanical systems (MEMS) based switches is proposed. The MEMS switches are used instead of diodes to design a high efficiency rectifier. The voltage drop across diodes in conventional rectifiers reduces the efficiency of energy harvesters. The operation of the MEMS switches in the proposed rectifier is similar to the commutators in DC motor where alternating current is converted to direct current through mechanical switches rather than diodes. In the proposed rectifier, the MEMS switches are automatically activated in the presence of mechanical vibrations. An increased in efficiency of 30% is observed by utilizing MEMS switches compared to a conventional diode based energy harvester using an input source of 1V. This thesis also presents a direct AC-DC power converter using a slotted MEMS structure. The MEMS switches were designed and simulated using Intellisuite software package.
DEDICATION

I would like to thank my wonderful family – parents, grandparents, Vishnu Rao and Vivek Rao for their encouragement and support.
ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS/SYMBOLS

MEMS – Microelectromechanical systems.

EH- Energy harvester.

DCM- Discontinues conduction mode.

CCM -Continuous conduction mode.

PZD -Piezoelectric device

FBR – Full bridge rectifier.
Chapter -1

Introduction

It is predicted that more than 25 billion sensors will be used by 2020 as part of the Internet of Things (IoT). With the recent advances in wireless sensors such as medical implants and animal tracking devices where battery replacement may be difficult or impossible to achieve the need for energy harvesting systems has become more evident. Battery free sensors is gaining popularity in the market. Fig.1 shows applications of IoT in day-to-day activities.

1.1 Motivation -Beyond Battery

Harvesting energy is a process of obtaining ambient energy from environment, converting it into electricity to power up electronic devices [1]. Most popularly used energy sources are Light, Mechanical, Thermal, Electromagnetic and Chemical. These energy sources are commonly utilized to power up automation systems, watches, mobile charging devices, artificial pacemakers etc.

Fig. 2 shows the block diagram for rechargeable batteries using ambient energy sources, a generator and a temporary storage system. The energy from the temporary storage system like rechargeable batteries and ultra-capacitors can be used to power up electronic devices. With the technology scale down, ultra-low power sensors can be designed [1] where the ambient energy sources can be used to replace the battery.

Donelan [2] described how body energy can be used as an alternative source for battery. Walking, pushing a button, squeezing hand can generate electrical energy that can be harvested. A biomechanical energy harvester was fabricated in [2], this device was attached to knees to generate electricity during walking.

The conversion of mechanical energy from periodic or non-periodic vibrations to electrical energy is of particular interest. A new methodology using Micro electro mechanical sensors
(MEMS) has been described in this work to harvest energy from mechanical vibrations. This Chapter provides an overview of vibrational energy harvesting.

1.2 Vibrational Energy harvesting as a potential solution
Harvesting energy from vibrational sources can be classified as shown in Fig.3.
Where,

- Electrostatic energy harvesters make use of parallel plate capacitors which helps to generate electricity from relative motion between two plates as shown in Fig. 4a.
- Electromagnetic energy harvesters generate charges through a phenomenon explained by Lenz's law [3] which involves relative motion between a mass (coil) and a magnet as shown in Fig. 4b.
- Piezoelectric energy harvesters: When a piezoelectric material is subjected to stress or strain it can generate electricity. Fig. 4c shows a piezoelectric material as a part of cantilever beam. The in depth principle of operation for vibrational energy harvesters is explained in chapter-2.

1.3 Comparison of Vibrational energy harvesters

A brief summary about the advantages and disadvantages of vibrational energy harvesters is as shown in Table-1. Piezoelectric and electrostatic devices can be used for small-scale energy harvesting as they can be integrated with MEMS structures. Due to the bulky size of magnets, electromagnetic harvesters are suitable for larger sized devices [4].

This thesis mainly focuses on conversion techniques of electrostatic and piezoelectric energy harvesting devices as it can be conveniently integrated with MEMS technology.
Figure 4(a) Electrostatic energy harvesters (b) Electromagnetic Energy harvesters (C) Piezoelectric energy harvesters [8].

Table 1: Comparison of Vibrational Energy harvesters

<table>
<thead>
<tr>
<th>Piezoelectric Devices</th>
<th>Electro Magnetic Devices</th>
<th>Electro Static Devices</th>
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<tbody>
<tr>
<td>Compatible with MEMS</td>
<td>Not Compatible with MEMS</td>
<td>Compatible with MEMS</td>
</tr>
<tr>
<td>Bulky size magnets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No external Voltage source required for operation</td>
<td>No external Voltage source required for operation</td>
<td>External Voltage source is required for operation</td>
</tr>
<tr>
<td>Voltage from 1-10V are generated</td>
<td>Maximum Voltage generated is 1V</td>
<td>Voltage from 2-10V are generated</td>
</tr>
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</table>
1.4 Micro Electro Mechanical (MEMS) Technology

MEMS devices are attractive for many applications due to their small footprint, low cost and easy integration with available fabrication technologies. Fig. 5 shows various applications of MEMS devices. On chip integration of electromechanical systems and electrical circuitry is a major advantage of using MEMS technology over alternative solutions. MEMS fabrication with integrated circuits improves reliability and reduces manufacturing costs [5]. The use of MEMS structure in power harvesting is gaining popularity as it overcomes the drawback of threshold voltage issues present in diodes which will be explained in detail in chapter 2.

![MEMS & Sensors](image)

Figure- 5 Shows the development of MEMS sensor [8]

1.5 Utilizing MEMS Technology for Vibrational Energy Harvesting

MEMS is considered to be an attractive technology for small amplitude vibrations. Various techniques are used to integrate mechanical components with electrical components. Fabrication techniques for MEMS devices are [6]:

1. Surface Micromachining
2. Bulk micromachining
3. Molding

The MEMS devices used in this thesis are modelled using Intellisuite software design tools. Simulations were carried out using 0.18µm technology in Cadence environment. Intellisuite was mainly used to create the 3D design of the harvesting structures. Chapter -3 presents Electrostatic energy harvester utilizing a MEMS variable capacitor and MEMS switches for low power energy harvesting. Chapter-4 provides the details of MEMS rectification technique which is used to extract energy from a piezoelectric energy harvester. Chapter-5 provides a slotted MEMS comb-drive used to implement a direct AC-DC boost converter.

1.6 Research Objectives

The objective of this research is to improve the efficiency of energy harvesters using MEMS technology. The major focus is on modeling a MEMS rectifier, super diode and direct AC to DC MEMS boost converter to increase the efficiency.

The research contributions of this thesis have been summarized below:

1. An electrostatic transducer utilizing MEMS variable capacitor, switch and super diode is presented. This approach eliminates the need for clock synchronization, which is commonly required for transistor based electrostatic energy harvesters. The simulation results of the proposed transducer compared to the transistor based harvesters indicate an increase in efficiency by more than 25%.

2. An electronic interface is designed between harvester and load. A full bridge rectifier was implemented using MEMS switches. The efficiency improvement of MEMS based rectifier over the diode based rectifier is investigated. It is shown in chapter 4 that the efficiency increase by about 30%, if MEMS switches are used instead of diodes for rectification.

3. Integration of MEMS rectifier with a boost converter improves the performance which is verified through simulations in Cadence environment using 0.18µm CMOS technology.
1.7 Thesis Overview

This thesis is organized as follows:

Chapter-1 gives a brief description of main topics and research objectives.

Chapter -2 provides in-depth literature reviews of vibrational energy harvesting. It also provides details of different rectification techniques used to convert the AC input to a DC output. Two stage power conversion technique for harvesting energy is also described in this chapter.

Chapter-3 presents detail about electrostatic energy harvesters. It also provides details of constant charge and constant voltage electrostatic harvesting techniques. This chapter further introduces the concept of super diode which is used to increase the efficiency of electrostatic energy harvester by 25% at 1V Vibrational input.

Chapter-4 explains the MEMS based rectification techniques to avoid the problem of voltage drop across diodes. In this chapter the mathematical explanation of the proposed technique is presented which indicate that the use of MEMS switches for rectification increase the efficiency of energy harvester by more than 30% at 1V, low voltage vibrational input.

In chapter-5 a direct AC to DC MEMS boost converter is presented, where slotted MEMS switch and split capacitor technology is used for rectification and power conversion stages. This integration method of power converter reduces component count in the harvester.

Chapter-6 covers conclusion and future works.

1.8 References


Chapter -2
Literature Review

Low-level vibrations can be found in environments such as machinery, vehicles, human walking. The vibrational energy from these sources can be converted into an AC signal. The AC signal is then converted into a DC signal by a rectifier. Based on the vibration frequency, harvesters can be divided into two groups (a) non-resonant and (b) resonant energy harvesters. In a non-resonant energy harvester, the input contains very low frequency (< 100 Hz) and has inconsistent and discontinuous vibrations. Such vibration is generated by the motion of human body. On the other hand, resonant energy harvesters contain vibrations of constant amplitude and higher frequency (>100Hz). To convert the energy obtained from the vibrational energy harvesters into electricity, three mechanisms of Electromagnetic, Electrostatic and Piezoelectric are discussed in this chapter.

2.1 Electromagnetic Energy Harvesting

Electromagnetic energy harvesting works based on the principle of Lenz law. When a coil is moved in a magnetic field, current is generated [1]. Without the provision of external voltage source, vibrations can be converted to electricity. In this process of energy harvesting a permanent magnet is needed to create a magnetic field. As electromagnetic harvester makes use of magnet, it is bulky in size, it’s hard to integrate electromagnetic harvester with the MEMS technology. Moreover, the maximum voltage generated by the electromagnetic harvesters is limited and commonly it is around 1V. Therefore, additional transformer is needed to transform voltage to higher levels [2] for certain applications.

In [2] the authors presented a fabricated model of electromagnetic harvester. The mathematical model of the harvester can be developed using mass spring damper system. Based on the mathematical model it can be found that the output power of the generator is proportional to the cube of vibrational frequency. Which indicates that the mass should be as high as possible to generate more current. For an electromagnetic generator of the size
5mm × 5mm × 1mm, with the input vibrational frequency of 70Hz, the estimated output is around 1μW [2].

2.2 Electrostatic Energy Harvester

Electrostatic Energy harvesting system is also known as capacitive energy harvester [3]. In this energy harvesting system, vibrational energy is converted into electricity based on capacitance variation of variable capacitors. A variable capacitor consists of two conductors separated by a dielectric material. Vibration creates change of capacitance and allows mechanical energy to be converted to electrical energy using the principle of constant charge conversion. The major drawback in this system is a constant voltage source is required to provide an electric field [3]. This type of harvester uses a capacitor which can be integrated with MEMS devices [3]. In [4] authors fabricated an electrostatic energy harvester and reported the total useable power of 5.6μW out of the total harvested power of 8.6μW. A permanently charged dielectric for constant charge supply is reported in [5] where there is no need for separate voltage supply. The drawback of this solution is limited lifetime as the dielectric discharges over time. Electrostatic energy harvester based on the position and the structure of the electrodes can be classified into three types [5]:

(a) In plane overlap converter: Comb-drive structure with variable overlap of fingers moving in the perpendicular plane of comb-drive as shown in Fig. 6a.
(b) In plane gap closing: Comb-drive structure with variable gaps between fingers moving in the plane of the comb-drive as seen in Fig. 6b.
(c) Out of plane gap closing: Planar structure with a variable air gap between plates and the movement of the structure is perpendicular to the plane of comb-drive as seen in Fig. 6c.
Piezoelectric energy harvesting is a material based energy harvester for motion driven power scavenging. The piezoelectric effect is displayed in certain class of materials like ceramics, crystals, Polyvinylidene fluoride (PVDF) [6]. When mechanical strain is applied on the piezoelectric material few materials show electric polarization which is proportional to the applied strain. Piezoelectric elements have different geometries. But the most popular one is the cantilever and comb-drive structure [7]. This configuration has an added advantage that can be easily integrated with MEMS structure. Furthermore, it has the most efficient conversion mechanism [8]. No separate voltage source is required as in the case of electrostatic transducers. The output voltage generated varies from 3V to 8V [8]. The energy density of piezoelectric materials is three times higher than electromagnetic and electrostatic energy harvester [8]. The major drawback of this system is that it is more complex to integrate piezoelectric materials into the microsystems. As the integration needs strong electric field and high temperature (365°C) [8]. The integration can be simplified by using thin film piezoelectric configuration, which requires a lower voltage of

![Image](image.png)

Figure- 6 (a) In plane overlap converter (b) In plane gap closing converter (c) out of plane gap closing converter [5].

2.3 Piezoelectric Energy harvester
200 V for 127µm thick film [9]. High temperature is not required in the integration of thin film piezoelectric materials with IC.

The signal generated by electrostatic, electromagnetic and piezoelectric energy harvesters are in the form of an AC signal. To convert the AC input into a DC output, different types of rectification techniques are employed as explained in section 2.4.

2.4 Rectification Techniques

The output of Vibrational energy transducers is in AC form. However, most of the portable devices requires DC power supply to operate. Therefore, a rectifier circuit is essential to convert the AC output of transducers to DC signal. AC to DC rectifiers utilizing diodes are widely used to convert an input AC to a DC output. Conventional rectification techniques such as full bridge rectifier, MOSFET bridge rectifier are discussed below and their limitations for energy harvesting have been presented.

2.4.1 Full Bridge rectifier

In the case of conventional full bridge rectifier which consists of four junction based diodes [10] (Schottky or PN). The forward bias voltage for junctions based diodes is 0.1V or higher [10]. For low power applications, the voltage drop due to forward bias leads to poor efficiency. If the input to the vibrational energy harvester is around 1V because of the voltage drop of 0.1V there is at least 40% power loss in a full bridge rectifier. As a result, diode based full bridge rectifier are not efficient in low power energy harvesting system. Fig. 7 represents the electrical equivalent of a piezoelectric generator. Fig. 8a shows the circuit diagram of a full bridge rectifier. Where, \( V_{\text{piezo}} \) indicates piezoelectric vibrational output signal, \( R_{\text{piezo}} \) represents the dielectric loss due to the piezoelectric material and \( C_{\text{piezo}} \) depicts the loss due to self-capacitance of the piezoelectric material. During the positive cycle of vibration, diode \( D_1 \) and \( D_2 \) are forward bias and during the negative cycle \( D_3 \) and \( D_4 \) conduct the current.
2.4.2 Voltage Doubler

Voltage doubler circuit was introduced for low power application to overcome the problem of low level output voltage of bridge wave rectifier. Fig. 8b shows the circuit of a typical voltage doubler. During the positive half cycle of the piezoelectric signal, D₂ is forward biased and D₁ is reverse biased. Where as in the case of negative half cycle D₂ is reverse biased and D₁ is forward biased. The major drawback of this circuit is power delivered to the output is low, this is due to the fact that the power is delivered only during one half cycle of the input alternating voltage. This reduces efficiency of the harvester by 50% in low power applications [10].

2.4.3 MOSFET Bridge rectifier

The rectifier in Fig. 8c consists of MOSFETS connected on bridge topology. [10] Here large sized MOSFETS with aspect ratio of 751/1 µm are used to reduce the turn on resistance. So that the voltage drop and power consumption of the rectifier can be minimized. As MOSFETs are utilized instead of diodes, the problem of threshold voltage of diodes is replaced by the on resistance of switches. Fig. 8c shows the bridge wave rectifier during positive cycle where MOSFETs M₃ and M₄ act as conducting switches and M₁ and M₂ act as non-conducting switches. Similarly, during the negative half cycle M₁ and M₂ act as conducting switches and M₃ and M₄ act as non-conducting switches. The main drawback of MOSFET bridge rectifier is that the ON time and the OFF time of NMOS and PMOS transistors have to be accurately controlled. Therefore, a synchronization circuit is needed to properly control the switch time of MOSFETs.

The changing trend for components to rectify low voltage signal is shown in Fig. 9. In this thesis to overcome the threshold voltage drop issues of diodes and R_{on} resistance of MOSFETs, mechanical rectification suitable for low voltage applications is presented in chapter-4.
Figure- 7 Electrical equivalent of piezoelectric energy harvester.

Figure- 8 (a) Full Bridge rectifier. (b) Voltage Doubler. (c) MOSFET bridge rectifier.
2.5 Conventional Interface circuit between energy harvester and load

A two stage power converter is as shown in Fig. 10. The power converter mainly consists of a front end bridge rectifier and a DC-DC converter which is generally a buck or boost converter [11]. The major drawbacks of two stage power converters are: The threshold voltage of diodes and the ON resistance of MOSFET reduce the efficiency significantly at low input voltage. The output of a rectifier is nonlinear, so a DC-DC converter is required. As the rectifier and the converter require a minimum number of five diodes this leads to decrease in efficiency by 75% for low power applications [12]. Instead of using two stages of power conversion, researches have integrated the AC to DC and boost converters to increase the efficiency. In [12] a dual polarity boost converter topology for direct AC to DC boost converter topology is implemented. Where the converter utilizes two inductors and the output power harvested is stored in a series of split two capacitors. Each capacitor is charged in one-half operating cycle of AC input. In this approach the main drawback is that, the direct converter requires some synchronization circuits. Slotted MEMS direct DC-DC converter improves efficiency by more than 25% when compared to conventional boost converters will be explained in detail in chapter 5. This chapter presents a solution utilizing a direct AC to DC MEMS boost converter to address and overcome the above stated issues.
2.6 References


Chapter -3
Design and Development of High Performance Electrostatic Energy harvester

3.1 Introduction

Internet of Things (IoT) is gaining popularity and billions of sensors are expected to be deployed by 2020. Powering up the sensors to allow communication between a vast numbers of sensors will soon become a major challenge. The need for battery free sensors is growing. An emerging solution is to make use of energy that is available in the environment to power the circuit without the need of battery. Electrostatic transducer is one such transducer, which powers up sensors and extends the battery life of wireless sensors. In this chapter we are focusing on powering up sensors during human walking. Piezoelectric energy harvester takes the advantage of rearrangement of dipoles in the piezoelectric materials. So, when this material is subjected to strain the dipole undergoes polarization effect and arranges itself to convert vibrational energy into electricity. The materials that follow this arrangement are polycrystalline ferroelectric ceramics such as barium titanate (BaTiO3) and lead zirconatetitanate (PZT) [1]. A piezoelectric energy harvester has a high energy density [2]. Methods such as parametric frequency generators have been proposed to improve the efficiency of piezoelectric based energy harvesters [3]. Implementation of this technique is not suitable for harvesting energy generated through human walking. Furthermore, Piezoelectric and electromagnetic transducer cannot be readily used as they are relatively complicated to fabricate them particularly at dimensions desired for body implementations [4]. Basic configuration for electrostatic energy harvester is shown in Fig.11.
Fig. 12 [5] shows the life cycle of an energy harvesting system, which involves two phases: (a) pre-charge (b) harvest. In the pre-charge phase of operation, the variable capacitor $C_1$ is charged to the input voltage and then in the harvesting phase the charges stored in $C_1$ is transferred to $C_2$. Two types of electrostatic transducers are presented in the literature [7] (a) Constant Voltage electrostatic transducer and (b) Constant charge electrostatic transducer. As the name indicates in constant charge electrostatic transducers, the charge is kept constant and the voltage is varied to convert the mechanical input to an electrical output. Similarly, in the case of constant voltage the voltage is kept at a constant value and charge is varied.

Figure- 11 (a) Ideal Electrostatic energy harvester (b) Electrostatic energy harvester using diodes [1]
Constant charge harvesters present higher efficiency by 22% compared to the constant voltage harvesters. [6]. In the process of constant charge harvesters, initially as shown in Fig. 11(a) SW1 is closed and the variable capacitor, C1, is charged. Then SW1 is turned off and the distance between the capacitance plates increases due to vibration. As the distance between the plates increases, the value of C1 falls and the voltage across the capacitor rises [7]. Finally, SW2 is closed and the charge is transferred from C1 to CL. The switches in Fig. 11 can be implemented using CMOS technology. However, CMOS switches have on resistance and as a result there is energy loss. Moreover, a reference clock is needed for synchronization of the transistors. This synchronization consumes power from the harvested energy and decreases the efficiency of the harvester circuit. To overcome this problem few researches [7], made use of Schottky and PN junction diodes as shown in Fig. 11b. However, these diodes require the input to exceed the threshold voltage to operate and for low power applications, this reduces the efficiency considerably. In the proposed solution, we are using mechanical switches to replace SW1 and SW2 as shown in Fig. 11a.
It should be noted that the efficiency of diode and CMOS transistor based transducers falls sharply for a supply voltage lower than one volt. The variable capacitor to extract vibrational energy can be implemented using a MEMS actuator. In this chapter, a new transducer circuit utilizing a MEMS actuator and a MEMS switch together with a super-diode is presented that can operate with low supply voltages. It is shown that the proposed circuit increases the overall power scavenging efficiency by more than 27% [1]. The rest of the chapter is organized as follows: Section 3.2 presents the schematic diagram of the proposed solution with a mathematical model. Section 3.3 discusses the proposed method and the circuit efficiency. Simulation results are presented in section 3.4 and finally conclusions are covered in section 3.5.

3.2 Proposed Solution

The circuit for a basic electrostatic transducer is shown in Fig. 11a. The battery facilitates the conversion of mechanical energy to electrical energy. Assuming ideal components, the mechanical energy converted to electrical energy in each cycle can be determined from

\[ \Delta E = \frac{(1 - N)Q_1^2}{2C_1} \]

where \( Q_1 = C_1V_{in} \) and \( N \) is the ratio of \( C_{1\text{Max}}/C_{1\text{Min}} \). Where, \( C_{1\text{Max}} \) and \( C_{1\text{Min}} \) are the maximum and minimum values of the variable capacitor \( C_1 \) respectively.

![Figure- 13 Super diode [1]](image)

An implementation of the ideal transducer in shown in Fig. 11a. To remove the problem of synchronization among switches in Fig. 11b diodes are used instead of switches [8].

To increase the overall efficiency in this work, \( D_1 \) is implemented using MEMS technology. The use of a MEMS switch instead of \( D_1 \) resolves the threshold related problems. The energy loss of a MEMS switch is negligible due to its mechanical nature.
where actual physical contacts are used as a switch. Moreover, the proposed scheme does not require a synchronization clock or a control voltage to turn it on and off. It is designed to automatically turn-on when the distance between the plates of the variable capacitor becomes minimum. D₂ in Fig. 11b is replaced by a super diode. The super-diode eliminates the need for a synchronization circuit while increasing the efficiency of the transducer circuit. It is clear that D₂ can also be implemented using MEMS technology however; in this case, the vibration has to be strong enough to ensure maximum displacement of the movable plate of C₁. This can limit the circuit efficiency in practice. An implementation of a super diode is shown in Fig. 13. The circuit behaves like an ideal diode without a threshold voltage due to the feedback. The output voltage, \( V_{out} \), becomes equal to the input, \( V_{in} \), in positive cycles without signal loss due to the threshold effect. The implementation of the super-diode requires an op-amp, which consumes power and can negatively affect the efficiency of the circuit. It is shown in chapter 3.4 that the energy consumed by the op-amp in each cycle is lower than the extra energy scavenged due to the use of a super-diode. The following analysis determines the maximum available energy that can be extracted using a super-diode instead of a regular diode [1].

![Figure -14 Pre charge principle for energy harvester][1]

The first phase in the operation of the transducer, Phase 1, is Pre charge. The pre charge phase is represented as shown in Fig.14, where there is transfer of energy from \( V_{in} \) to \( C_1 \) and the switch \( SW_1 \) is closed. In the first phase, the distance between the plates of \( C_1 \)
becomes minimum and the capacitor takes its maximum value of $C_{\text{max}}$. At this instance $SW_1$ turns on and connects $C_1$ to the input voltage source.

![Figure 15. Principal of harvest [1]](image)

The second phase of operation of the transducer, Phase 2, called Harvest phase. Where the energy is transferred from $C_1$ to $C_2$ and $SW_1$ is kept open and $SW_2$ is closed. When Vibrations move the top plate of $C_1$ away from its bottom plate, $C_1$ decreases. The voltage across $C_1$ rises, since the total charge, $Q_1=C_1V_1$, remains unchanged. When the voltage across $C_1$ exceeds the op-amp’s nominal supply voltage, the op-amp turns on. Then charge transfer takes place between $C_1$ and $C_L$ as shown in Fig.15.

Fig.16 shows the proposed electrostatic transducer which utilizes a MEMS variable capacitor, a MEMS switch $SW_1$ and a super diode. Fig.16 shows the proposed electrostatic transducer where diode $D_2$ in Fig.11b is replaced with a super diode.
3.3 Power Consumption of Super diode

Assuming \( C_2 \) is discharged and the voltages across \( C_1 \) is \( V_1 \) as shown in Fig.11a, the equilibrium voltage, \( V_{eq} \), after closing \( SW_2 \) in Fig. 11a is given by \( V_{eq} = C_1 V_1 / (C_1 + C_2) \). The energy transferred to \( C_2 \) in one cycle is given by \( \Delta E_1 = 0.5 C_2 (V_{eq})^2 \). Substituting for \( V_{eq} \), the energy transfers from \( C_1 \) to \( C_2 \) becomes

\[
\Delta E_1 = \frac{1}{2} C_2 \left( \frac{C_1 V_1}{C_1 + C_2} \right)^2
\]

(1)

If instead of \( SW_2 \) a diode with threshold voltage of \( V_{th} \) is used, the energy transferred to \( C_2 \) in one cycle assuming \( V_i > V_{th} \) is calculated from

\[
\Delta E_2 = \frac{1}{2} C_2 \left( \frac{C_1 [V_i - V_{th}]}{C_1 + C_2} \right)^2
\]

(2)

Where the difference between the transferred energy in the above two cases, \( \Delta E_{avl} \), is given by \( \Delta E_{avl} = \Delta E_1 - \Delta E_2 \)
\[ \Delta E_{avf} = \frac{1}{2} C_2 \left( \frac{C_1}{C_1 + C_2} \right)^2 (2V_{th} - V_{th}^2) \]  

(3)

In practice, \( C_2 \) has to be much higher than \( C_1 \) to have enough capacity to store the energy delivered over many cycles. Assuming \( C_2 >> C_1 \), \( \Delta E_{avf} \) is simplified to:

\[ \Delta E_{avf} \approx \frac{1}{2} \frac{C_1^2}{C_2} (2V_{th} - V_{th}^2) \]  

(4)

\( \Delta E_{avf} \) is the available energy used by the op amp in the proposed energy harvester which provides a higher efficiency than using a regular diode to implement switch SW2 used in the conventional harvester. In the above analysis, it is assumed that the initial voltage across \( C_2 \) is zero. For a general case assuming \( V_1 > V_{th} + V_2 \), \( \Delta E_{avf} \) is given by

\[ \Delta E_{avf} = \frac{1}{2} C_2 \left( \frac{C_1}{C_1 + C_2} \right)^2 \left( 2(V_1 - V_2) V_{th} - V_{th}^2 \right) \]  

(6)

Assuming \( C_2 >> C_1 \)

\[ \Delta E_{avf} \approx \frac{1}{2} \frac{C_1^2}{C_2} \left( 2(V_1 - V_2) V_{th} - V_{th}^2 \right) \]  

(7)

Where \( V_1 \) and \( V_2 \) are the voltages across \( C_1 \) and \( C_2 \) respectively. The power consumed by the amplifier, used for implementation of the super diode, has to be less than \( \Delta E_{avf} \) in each cycle to ensure the increased efficiency of the circuit. This requirement is met if low-power op-amp is used to implement the super diode. The op-amp turns on for a short period in each cycle to transfer a minute amount of charge to the output.

### 3.4 Implementation of MEMS Electrostatic Transducer

The schematic diagram of the proposed circuit is shown in Fig. 16. A variable MEMS capacitor, \( C_1 \), was implemented using Intellisuite CAD tools [1]. As shown in Fig. 17, the MEMS capacitor includes a switch, which is used to operate as SW1 in Fig. 11 [1].
It can be seen in Fig. 17a that the MEMS switch closes the path when $C_1$ becomes maximum. The switch opens as soon as the distance between the plates of $C_1$ increases due
to vibration as shown in Fig. 17b. The positive terminal of the op-amp, $V_P$, in Fig. 16 is connected to $V_{in}$, this is to ensure that $C_L$ is charged up to the input voltage.

The circuit operates in two different phases. In the first phase, the distance between $C_1$ plates is minimum and $C_1$ takes its maximum value, $C_{\text{max}}$. As a result, the voltage across $C_1$ becomes minimum; the equivalent circuit of the transducer in this phase is shown in Fig. 14. In the second phase, when vibrations move the top plate of $C_1$ away from its bottom plate, $C_1$ decreases. The voltage across $C_1$ increases since the total charge, $Q_1 = C_1V_1$, remains unchanged. When the voltage across $C_1$ exceeds the op-amp’s nominal supply voltage, the op-amp turns on. The equivalent circuit in this phase is shown in Fig. 15. The charges deposited on $C_L$ by the op-amp are supplied by $C_1$. As the distance between the plates of $C_1$ falls due to vibration, the voltage across $C_1$ decreases and drops below the input voltage. The cycle repeats itself once $C_1$ reaches the maximum value.

### 3.5 Simulation results

The circuit shown in Fig. 16 was implemented in Cadence environment. A commercially available low-power op-amp from Intersil, ISL28194, was used for simulations. It consumes about 330nW at 2V supply and delivers 11mA at the output. The op-amp is designed for single-supply operation from 1.8V to 5.5V. To perform simulations, the op-amp was represented by its Verilog-A model in Cadence design environment. Simulation results for $V_{in}=1V$, $C_1=10\text{pf}$, $C_L=1\text{nf}$ at 1Hz vibration frequency is shown in Fig. 18. Initially, $C_1$ is charged through SW$_1$ up to 1.0V and stores 10 pico-coulombs of charge. When the distance between the plates of $C_1$ increases and the voltage exceeds 1.8V, the op-amp turns on and charges $C_L$. Due to the negative feedback the voltage across $C_L$ tries to follow the voltage at the positive input of the op-amp. The op-amp charges $C_L$ with 11mA drive current. Due to the relatively high output current of the op-amp, the time required to transfer the entire 10 pico-coulombs charge from $C_1$ to $C_L$ in one cycle theoretically is less than one nanosecond. Simulation results indicate that it takes about 10ns for the op-amp to settle down and transfer the charge to $C_L$. The available energy from (4) for $V_{th}=0.6V$ is about $0.7 \times 10^{-13}$ joules per cycle. The op-amp consumes less than 7% of
the available energy in each cycle. Fig. 18a shows the simulated voltage across C₁, V_C1, and the voltage across C_L, V_C_L. It can be seen that C_L is charged in every cycle until its voltage settles at the input voltage. The comparison between the power transferred between the conventional diode based transducer and the proposed transducer is shown in Table 2. As seen from the table, the proposed circuit increases the efficiency significantly when the supply voltage falls below one volt. In fact, the conventional diode based transducer cannot operate when the supply voltage becomes lower than the diode threshold.

Figure- 18 (a) Voltage across input capacitor C1 . (b) Voltage across output capacitance CL

<table>
<thead>
<tr>
<th>Voltage across input capacitance, C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>t (s)</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>2.5</td>
</tr>
<tr>
<td>5.0</td>
</tr>
<tr>
<td>7.5</td>
</tr>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage across output capacitance, CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>t (s)</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>2.5</td>
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<tr>
<td>5.0</td>
</tr>
<tr>
<td>7.5</td>
</tr>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

[1]
The need to find new sources to power up wireless sensors becomes more apparent as the IoT grows and demand for sensors increases. In this work, a new transducer circuit utilizing a MEMS switch and a super-diode is presented to extract power from vibration. The proposed circuit presents a high efficiency where the supply voltage falls below one volt. As compared to the available solutions in the literature, the proposed circuit does not require a clock for synchronization while increasing the efficiency. Simulation results in Cadence environment indicate that the proposed circuit compared to the conventional diode based transducers, increases the efficiency of power scavenging by more than 27% at 1.0V supply voltage.

### 3.6 Conclusion

<table>
<thead>
<tr>
<th>Input Voltage</th>
<th>Power Delivered at the Load</th>
<th>% Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional Transducer (µW)</td>
<td>Proposed Circuit (µW)</td>
</tr>
<tr>
<td>1</td>
<td>0.66</td>
<td>0.84</td>
</tr>
<tr>
<td>2</td>
<td>1.61</td>
<td>1.88</td>
</tr>
<tr>
<td>3</td>
<td>2.98</td>
<td>3.35</td>
</tr>
<tr>
<td>4</td>
<td>4.77</td>
<td>5.24</td>
</tr>
<tr>
<td>5</td>
<td>5.82</td>
<td>6.34</td>
</tr>
</tbody>
</table>

Table 2: Comparison of power transferred in Electrostatic Transducer [1]
3.7 References


Chapter-4
MEMS based Mechanical rectifier for IoT Sensor Nodes

4.1 Introduction

IoT is growing rapidly and expected to have a significant effect on society, business and daily life of individuals. It is forecasted that the number of IoT sensors will exceed 25 billion by 2020. How to power up sensors will become a serious problem. Even though batteries are considered the common source of power for wireless IoT sensors, the limited resources and the need for maintenance have led researcher to look for alternative sources of energy. Power harvesting provides a promising alternative for batteries. For high power, solar and wind energy harvesting, efficient technologies have been implemented [1]. In the past decade, many solutions for micro power harvesting have been developed [2], but a dominant solution has not emerged yet. Vibrational power harvesting is gaining popularity as it can provide power supply solution ranging from microwatts to milliwatts. It has been reported [3,4] that through careful energy budgeting piezoelectric materials can be utilized to implement a viable solution for vibrational energy harvesting. A piezoelectric material under vibration can be represented by an AC source if Thevenin’s equivalent condition is used. The dielectric loss and self-capacitance of piezoelectric material can be modeled by a series resistor $R_{piezo}$ to represent the dielectric loss and a parallel capacitor $C_{piezo}$ representing self-capacitance. Choosing materials with right piezoelectric component plays a critical role in the integration of MEMS and IC processes. A complete energy harvester requires a voltage/current boost, voltage/current rectification, voltage/current regulation and other power management functions for conversion of mechanical energy to electrical energy. The input to these harvesters have challenging operating conditions such as low input voltages, low input power and time varying waveform characteristics.

In a vibrational energy scavenging system, the power management interface circuitry must efficiently function during challenging operating condition, such as low input vibration supplying low input voltage levels to the transducer. Additionally, the circuits should be
compact in size. One of the major challenges in vibrational energy harvesting is ac/dc conversion of low amplitude non-periodic vibrational energy.

Fig. 19 shows the electrical model of piezoelectric transducer with the diode rectification. The proposed MEMS based solution, rectifies the AC input through mechanical switches to eliminate the voltage-drop problem in conventional rectifiers. The idea is similar to the mechanical commutators widely used in motors and generators converting alternating voltage to direct voltage. A MEMS comb-drive with a moving arm and four switches are designed to act as a mechanical rectifier. The switches are connected to a mechanical spring and they are automatically turned on and off based on the applied vibration.

The rest of the chapter is organized as follows. Section 4.2 provides the principle of operation for the proposed MEMS based rectifier. Section 4.3 explains the MEMS design of the mechanical rectifier. Section 4.4 presents the Maximum power point tracking for micro input vibrational power harvester. Section 4.5 explains measurement results and presents comparison with the reported works and conclusions are presented in Section 4.6.

![Figure- 19 Diode based rectification with a piezoelectric input power generator.](image)

**4.2 Rectification Using MEMS switches**

Fig. 20 shows the conceptual diagram of the proposed mechanical rectifier in which a basic MEMS comb-drive [6] is used. The comb-drive has a moving arm, which actuates with vibration. At the steady state when there is no vibration, the switches are off as shown in Fig. 20a. When the movable arm is displaced due to positive vibration, it will turn on SW1 and when the vibration is applied in the negative direction SW3 is activated.
Vibrations turn on SW1 or SW3 depending on the direction of the movement as shown in Fig. 20b and Fig. 20c.

To implement a full bridge rectifier instead of one switch for each half cycle of movement, two switches are needed. Fig. 21 shows the schematic diagram of the proposed full bridge rectifier using four MEMS switches. During the positive cycle of vibration, $S_1$ and $S_4$ switches are closed simultaneously as shown in Fig. 22a. Similarly, in the negative cycle of vibration $S_2$ and $S_3$ are activated as shown in Fig. 22b. MEMS switches have the capability to allow the current to flow in the forward direction, but they don’t block the reverse flow of current. To prevent the storage capacitor $C_{rect}$ from being discharged and to make the harvester to operate in discontinuous conduction mode (DCM) a diode with low threshold voltage is needed as shown in Fig. 21. Adding a conventional diode to the circuit can reduce the efficiency. In the proposed rectifier an active diode, in which the voltage drop across the diode is negligible, is used to eliminate the effect of voltage drop across the diode. Fig. 22 shows the rectification technique during positive and negative cycles of vibration. The details of the implemented active diode are covered in section 4.3.

![Figure -20 Conceptual diagram of the proposed mechanical rectifier](image_url)

(a) Steady state where both SW1 and SW3 are off. (b) When the moving arm travels toward the fixed arm closing SW1 and turning SW3 off. (c) When the moving arm travels away from the fixed arm opening SW1 and closing SW3.
Figure-21 Building block of the proposed harvester.

Figure -22 MEMS based rectifier. (a) Positive cycle where S1 and S4 are closed. (b) Negative cycle where S2 and S3 are closed.
4.3 Efficiency analysis of the proposed MEMS rectifier

For a conventional diode based rectifier, the voltage across the storage capacitor, $V_{\text{Crect}}$, in a diode based rectifier can be determined from the difference between the voltage across the piezoelectric element, $V_{\text{piezo}}$, and the voltage drop across the conducting diodes, $V_t$, in the bridge rectifier.

$$V_{\text{Crect}} = |V_{\text{piezo}} - 2V_t| \quad (8)$$

The total available energy harvested from the piezoelectric transducer can be calculated from

$$E_{\text{avl}} = \int V_{\text{piezo}} I_{\text{eq}} dt \quad (9)$$

The current source $I_{\text{eq}}$ is proportional to the vibration velocity $I_{\text{eq}}=au$ [5], where $\alpha$ is the force factor of the piezoelectric element and $u$ represents the displacement speed. Assuming $u_P$ and $u_N$ are the speed of motion in the positive and the negative directions respectively, the total available energy across the piezoelectric element is given by

$$E_{\text{avl}} = \alpha V_{\text{piezo}} [u_P - u_N] \quad (10)$$

Variations of the voltage (V) across the piezoelectric actuator with respect to the displacement can be represented as follow,

$$V = \frac{\alpha}{C_0} u + A \quad (11)$$

Where A is the integration constant and $C_0$ represents the blocking capacitance of the piezoelectric element [6]. During the negative cycle, the voltage across the piezoelectric actuator, $V_{\text{piezo}}$, can be rewritten as

$$-V_{\text{piezo}} = \frac{-\alpha}{C_0} u_N + A \quad (12)$$
\[ A = \frac{\alpha}{C_0} u_N - V_{\text{piezo}} \]  

(13)

For the positive cycle, (11) can be represented as

\[ V_{\text{piezo}} = \frac{\alpha}{C_0} u_p + A \]  

(14)

\[ u_p = \frac{C_0}{\alpha}[V_{\text{piezo}} - A] \]  

(15)

Substituting 13 in 15 we obtain

\[ u_p = 2\frac{C_0}{\alpha} V_{\text{piezo}} - u_N \]  

(16)

Substituting 15 in 10 we obtain

\[ E_{\text{avl}} = 2C_0 V_{\text{piezo}}^2 - 2\alpha u_N V_{\text{piezo}} \]  

(17)

The total available energy at the storage capacitor \( C_{\text{rect}} \) is equal to the energy across the piezoelectric element presented in (17). For the case of conventional rectifiers, the available energy across \( C_{\text{rect}} \) is given by

\[ E_{\text{avl}} = 2C_{\text{rect}} V_{\text{rect}}^2 - 2\alpha u_N V_{\text{rect}} \]  

(18)

Considering the fact that the voltage across the output capacitor, \( V_{\text{rect}} \), is much lower than the voltage across the piezoelectric generator, \( V_{\text{piezo}} = |V_{\text{piezo}} - 2V_f| \), the reduction in the harvested energy can be significant.

### 4.4 Implemented MEMS Actuator

Fig. 23. shows the designed MEMS comb-drive with four switches. A folded flexure [8] spring is used to implement the MEMS structure to support uniform displacement and synchronization among the MEMS switches. From Fig. 24, we can find that the
displacement of the comb fingers is non uniform and the comb fingers are not moving in the desired direction. This problem was fixed using folded flexure type of spring. As shown in Fig. 25, the displacements of fingers become uniform throughout the comb-drive. The motion of fingers of the comb-drive was observed in the desirable direction. In the presence of vibration, $S_1$ and $S_4$ turn on in the positive cycle of motion and $S_2$ and $S_3$ are activated in the negative cycle.

Figure -23 Implementation MEMS structure.
Figure 24: Comb-drive without the use of folded flexure beam

Figure 25: Comb-drive using folded flexure beam
4.5 Active diode

The proposed MEMS based rectifier has the capability to allow the current in the forward direction. But it does not have the capacity to block reverse current. To block current in the reverse direction an active diode is used. Energy harvesting circuits can operate in two modes (a) continuous conduction mode (CCM) and (b) discontinuous conduction mode (DCM). In the CCM mode of operation, if the potential across $C_{\text{rect}}$ becomes higher than the piezoelectric element $v_{\text{piezo}}$, the current flows in the backward direction and the storage capacitor is discharged. To prevent the loss of harvested energy due to discharge, the circuit has to operate in the DCM mode in which the storage capacitor $C_{\text{rect}}$ is prevented from being discharged.

This can be achieved by placing a diode between the rectifier and the storage capacitor $C_{\text{rect}}$. However, adding a diode reduces the harvested energy due to the voltage drop across the diode. To reduce the loss of energy two conditions, have to be satisfied (a) the diode has to have a low forward conduction drop and (b) the reverse leakage current of the diode has to be negligible. To satisfy these conditions, in the proposed solution an active diode is used between the output of the rectifier and the storage capacitor $C_{\text{rect}}$. The active diode is implemented using a comparator and a PMOS transistor to minimize the bias voltage as shown in Fig. 26a. The conditions for operation of the PMOS transistor are stated in equation (20). Where, $V_a$ and $V_c$ are the voltages across the terminals of the active diode.

$$En= \begin{cases} \text{Low, If } V_a>V_c, \text{ Turns on the PMOS} \\ \text{High, If } V_a<V_c, \text{ Turns off the PMOS} \end{cases} \quad (20)$$

The transistor in the active diode operates in the deep triode region in one direction and the sub threshold region in the opposite direction. All the transistors used in the active diode are biased in sub threshold region so that it consumes as low power as possible. The schematic diagram of the comparator used in the active diode is shown in Fig. 26. (b). Comparator used to implement the active diode requires some ambient energy to power-up. However, the power consumed by the comparator is much lower than the energy harvested in (19). The current consumption of the comparator is less than 22.91nA at one-volt supply voltage with switching frequency less than 100 Hz. A bias voltage of 300mV
is needed in the comparator to operate. The variation of the output terminal voltage for a typical low power IoT sensor node is negligible and hence no additional DC-DC regulation stage is needed for rectification.

\[ \text{Active Diode} \]

(a) Figure -26(a) Active diode. (b) Schematic diagram of the comparator used to implement the active diode.
4.6 Efficient DC-DC converter

![Diagram of a DC-DC converter](image)

Voltage across storage capacitor after rectification should be passed through a converter to provide a stable DC voltage to the load. The voltage across $C_{\text{rect}}$ can be represented by a DC input $V_{\text{battery}}$ as shown in Fig. 27. $V_{\text{ac}}$ and $R_s$ represent the small amount of ripple on the DC signal and the source resistance respectively. Two major types of DC-to-DC converters are reported in the literature [11].

1) Boost converter: Boost converters are used to increase the output voltage to meet the voltage requirement of the load.

2) Buck converter: Buck converters are used to reduce voltage to meet the lower voltage requirement of the load.

A DC-to-DC up converter is commonly used in energy harvesting circuits to ensure a high efficiency. A conventional boost converter, which is widely used, is shown in Fig. 28a. It includes a transistor which acts as an electronic switch and a diode which provide a path for the current flowing through the inductor when the transistor turns off. The use of the transistor and the diode reduce the overall efficiency of the energy harvester due to the voltage drop across the diode and the nonlinearity of the electronic switch. In the proposed converter the diode and the electronic switch have been replaced with a single MEMS switch. The MEMS switch is mechanically positioned to become synchronized with the input vibration as result no synchronization circuit is need. Fig. 28b shows the proposed circuit when the input voltage rises due to vibration. In this phase the energy is extracted from the input source. Fig. 28c indicates the second phase where the input source is not
connected to the circuit and the magnetic energy stored in the inductor, $L_1$, is transferred to the output load.

![Diagram](image)

(a)

(b)

(c)

Figure 28 (a) Boost converter with electronic switch. (b) MEMS switch connected to piezoelectric input. (c) MEMS switch position to charge the storage capacitor $C_{load}$. 
4.7 Simulation Result

The power harvester circuit in Fig. 22 was implemented using 0.18µm CMOS process. The MEMS comb-drive and the switches in Fig. 23 were implemented using Intellisuite CAD tools. Simulations were carried out over the frequency range of 60-100 Hz. At 1g vibrational over the frequency range of 60 to 100 Hz the open circuit voltage becomes maximum at 83Hz of frequency as shown in Fig. 29. Simulation results in Fig. 30 indicate that the voltage across the load decrease when the load impedance falls below 48KΩ.

The maximum extracted power of 52.5µW at 100Hz is obtained. In the presence of continuous mechanical excitation with the input voltage of 1V supplied by the piezoelectric component, the voltage across the load rises to about 900mV as indicated in Fig. 31. The comparison between the voltages across a conventional diode versus the voltage across the implemented active diode is shown in Fig. 32. The variation of the output power with frequency for the proposed power harvester and the conventional diode based harvester is shown in Fig. 33. Table-3 shows the energy delivered to the load for the proposed energy harvester compared to the conventional diode based harvester. At 1V transducer output voltage, the energy delivered to the load by the proposed harvester rises by 30% compared to the conventional harvester. This is mainly due the fact that the voltage across the piezoelectric transducer is not much higher than the threshold voltage of the diodes. As the voltage across the piezoelectric transducer increases, the difference between the efficiency falls. This is an expected outcome. At the higher transducer voltages, the effect of diodes forward bias drop on the efficiency becomes insignificant. Table-4 shows the comparison between the proposed energy harvester and the reported works in the literature. It can be seen that, using a MEMS rectifier improve the overall performance.
Table 3: Comparison of power transferred in Piezoelectric transducer

<table>
<thead>
<tr>
<th>Piezoelectric Input voltage (V)</th>
<th>Power Delivered to the Load</th>
<th>% Increase</th>
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</thead>
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<tr>
<td></td>
<td>Conventional Transducer (µW) [10]</td>
<td>Proposed Circuit (µW)</td>
</tr>
<tr>
<td>1</td>
<td>40</td>
<td>52.5</td>
</tr>
<tr>
<td>2</td>
<td>46.24</td>
<td>57.62</td>
</tr>
<tr>
<td>3</td>
<td>55.71</td>
<td>64.29</td>
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<tr>
<td>4</td>
<td>66.59</td>
<td>73.12</td>
</tr>
<tr>
<td>5</td>
<td>79.56</td>
<td>84.5</td>
</tr>
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</table>

Table 4: Comparison of works of piezoelectric harvester

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<th></th>
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<tbody>
<tr>
<td>Process</td>
<td>0.35µm</td>
<td>0.18µm</td>
<td>0.18µm</td>
</tr>
<tr>
<td>External power</td>
<td>2µW</td>
<td>0.5µW</td>
<td>0.3µW</td>
</tr>
<tr>
<td>Output power</td>
<td>32.5µW</td>
<td>40µW</td>
<td>52.5µW</td>
</tr>
<tr>
<td>Conversion Architecture</td>
<td>Schottky bridge rectifier</td>
<td>Bridge rectifier using CMOS</td>
<td>MEMS bridge rectifier</td>
</tr>
</tbody>
</table>
Figure- 29 Open circuit voltage for frequency range of 60Hz to 100Hz for 1g vibrational frequency.

Figure -30 Variation of output voltage with the load impedance.
Figure 31: Voltage across the load

Figure 32: Forward bias voltage across a conventional diode and the implemented active diode.
Figure- 33 Harvested output power using the proposed MEMS based rectifier and a conventional diode based rectifier.

4.8 Conclusion
In this work a new technique utilizing MEMS technology for vibrational power harvesting is presented. MEMS switches are used to convert AC current to DC current similar to commutators in motors and generators. The proposed method eliminates the power loss due to the threshold voltage of diodes in conventional rectifiers. Simulation results indicate that the use of MEMS switches in the proposed energy harvester compared to the conventional diode based rectifiers increases the efficiency by maximum of 31.3%.

4.9 Reference


Chapter-5

Direct AC-DC MEMS Boost Converter for Low Voltage Application

5.1 Introduction
Recently, step-up DC–DC converters that consume low power have been used for many energy-harvesting applications. Enabling these boost converters to operate without the use of external batteries have been a research focus for many years [1]. Fig. 34a depicts a two stage power conversion device which utilizes a rectifier and a DC to DC converter. To have the desired voltage level at the load, DC converters are required. Diodes used in rectifiers and converters cause voltage drop, which is limits the efficiency of energy harvesters in low voltage applications. A non-linear load used in rectifiers makes the converter 63% less efficient for energy harvesting [1]. To increase the efficiency of the output of the rectifier, a power converter is required. Power converter mainly consists of a π or T controller with a comparator. It is used to maintain the rectified output to a stable DC value and to offer an adjustable resistive load. This is not feasible in low power applications. In [2] a rectifier and DC to DC converter were integrated using two inductors and two capacitors. Each capacitor is charged only in one half cycle of AC voltage. The voltage across the capacitor was discharged to load causing large voltage drop. The efficiency of this technique is reported to be 15%. In [3] a bidirectional MOSFET is used for direct AC to DC, conversion utilizing a single inductor. For low voltage application this technique is difficult to realize. Fig. 35 shows a direct AC to DC converter where the rectifier and the boost converter are integrated in one stage. In this approach a controller circuit is used to turn on and off MOSFET, M1. A split capacitor is used and each capacitor is charged in one half cycle of the AC input. C1 and C2 have small storage capacity of 4.7µF and Cload has a capacity of 22µF.

Component count should be kept as low as possible to obtain high end to end efficiency. Many research groups have worked on planarization and interconnection of MEMS CMOS structure [4]. In this chapter, an open loop control structure for low power systems (in the range of milliwatts) is presented. The method is best suited for systems where the energy is consistently present and provides a simple MEMS control strategy for energy harvesting and output voltage regulation. With the elimination of the rectifier in the front end and with
the use of active diodes the efficiency of the harvester increases. The MEMS vibration switches use a slotted comb-drive. Each comb-drive finger has ten slots. The use of a slotted comb-drive eliminates the need for bidirectional switches. Two possible energy harvesting scenario is discussed in literature. One, in which the converter is controlled to harvest maximum power available from the vibrational energy harvester and store it in energy storage component like battery at the output. In this case, the output voltage is mainly decided by the characteristics of the energy storage component. In the second case, the converter is controlled to harvest the amount of power demanded by the load while maintaining the desired output voltage. In this chapter second technique is used for direct AC-DC power conversion. This increases the harvester efficiency by 25.3%. Slotted MEMS switch is used to replace the functionality of controller circuit. As this system works based on mechanical synchronization technique additional power managing systems are not required. Section 5.2 highlights the proposed direct AC to DC converter design. Section 5.3 deals with modeling and analysis of the slotted comb-drive structure along with active diode. Section 5.4 presents simulation results and Section 5.5 provides conclusions.

Figure- 34  (a) Two stage piezoelectric harvester. (b) The equivalent circuit for a piezoelectric generator
Figure 35 Conventional single stage boost converter

Figure 36 Schematic diagram of the proposed harvester
5.2 AC to DC converter design

Van Dyke model [5] is an approximate model for piezoelectric generators which is represented as shown in Fig. 34b. Where $C_{\text{piezo}}$ and $R_{\text{piezo}}$ represent loses in the piezoelectric material. The equivalent of piezoelectric generator as shown in Fig. 34b is used in Fig. 35. SW$_1$ in Fig.36 is a micro electro mechanical switch which is activated in the presence of vibration.

The operation of energy harvesting is completed in two phases. During the first phase in the presence of vibration, the inductor current raises and reaches the maximum value. $C_{\text{load}}$ is discharged through $R_{\text{load}}$ as shown in Fig. 37a.

In the second phase, in the absence of vibration SW$_1$ is turned off, the inductor discharges through capacitor C$_1$. During the positive cycle capacitor C$_1$ is charged as shown in Fig.37b.

In the negative cycle, the same two phases of operation are performed.

In first phase, the SW$_1$ is closed to allow the inductor current to increase in the negative direction as shown in Fig. 37c.

In the second phase, the inductor current charges C$_2$ as shown in Fig.37d through diode D$_2$.

The temporary storage capacitors C$_1$ and C$_2$ have small storage capacity to avoid voltage ripple and large voltage drops [6].
5.3 Modeling and analysis of Mechanical switch and active diode

Figure- 37 (a) (c) Working of direct AC to DC converter when SW1 is on (b)(d) SW1 is off during the positive half cycle.
5.3.1. Mechanical switch analysis

Consider the MEMS switch SW1 in the closed position, when the switch is closed the inductor current \(i_L\) across L builds up. The peak value of the inductor current \(i_p\) can be represented by:

\[
i_p = m_1 DT = \frac{V_{\text{piezo}} DT}{L}
\]

(21)

Where, \(D\) is the duty cycle of the boost converter. With switching period represented as \(T\) as shown in Fig. 38. \(V_{\text{piezo}}\) represents the voltage across the energy harvester with amplitude \(V_{\text{piezo}}\) and \(m_1\) represents the slope of the inductor rise time. When MEMS switch SW1 is in open position the inductor current fall-time can be represented by:

\[
dT = \frac{i_p}{m_2} = \frac{i_p L}{V_{\text{out}} - V_{\text{piezo}}}
\]

(22)

Where, \(m_2\) represents the slope of the inductor current fall-time and \(d\) is the duty cycle during fall time of the inductor current. \(T\) represents switching period of the boost converter as shown in Fig.38. During \(n^{th}\) switching cycle the total energy \(E_n\) transferred from the energy harvester to the load can be represented as:

\[
E_n = \frac{V_{\text{piezo}} i_p (D + d)T}{2}
\]

(23)

As the total energy transfer is dependent on the input voltage \(V_{\text{piezo}}\). The total loss due to the threshold of diodes and power consumption of controller circuit in the conventional converter can be represented by:

\[
E_n = \frac{(V_{\text{out}} - V_t - V_c) i_p (D + d)T}{2}
\]

(24)

Where \(V_t\) represents the threshold voltage of diodes. \(V_c\) represents voltage across the controller circuit. The MEMS switches and the active diode used in the proposed converter as shown in Fig. 36 allows the entire piezoelectric input to be delivered to the output. This is due to the fact that the active diode used in the proposed converter has zero threshold
and the controller circuit uses mechanical MEMS switch which requires no forward bias voltage like diodes. The total energy available at the output can be represented by

$$ E_n = \frac{V_{out} i_r (D + d) T}{2} $$  

(25)

From (24) we can see that $V_{piezok} = |V_{out} - V_T - V_c|$ the input voltage of the micro generator is delivered to the output $V_{out}$ without any loss as shown in (25).

![Figure- 38 Inductor current](image)

5.3.2. Design of Active Diode

From Fig. 36 in the positive cycle the equilibrium voltage $V_{eq}$ can be represented as (26)

$$ V_{eq} = \frac{CV_1}{C_1 + C_2} $$  

(26)

Where, $V_1$ is the voltage across capacitor $C_1$. Total power transferred to $R_{load}$ can be represented as

$$ P_{positive} = \frac{1}{R_{load}} \left( \frac{CV_1}{C_1 + C_2} \right)^2 $$  

(27)
Power transfer during the negative cycle can be represented by (28)

$$P_{\text{negative}} = \frac{1}{R_{\text{load}}} \left( \frac{C_2 V_2}{C_1 + C_2} \right)^2$$

(28)

Where, \( V_2 \) is the voltage across capacitor \( C_2 \). Total power transferred during both positive and negative cycle to \( R_{\text{load}} \) can be represented as \( \Delta P_{\text{total}} = \Delta P_{\text{positive}} + \Delta P_{\text{negative}} \)

$$\Delta P_{\text{total}} = \frac{1}{R_{\text{load}}} \left[ \left( \frac{C_1 V_1}{C_1 + C_2} \right)^2 + \left( \frac{C_2 V_2}{C_1 + C_2} \right)^2 \right]$$

(29)

Voltage across capacitor \( C_1 \) and \( C_2 \) can be represented as the difference between the positive \( V_{ip} \) or negative \( V_{in} \) input voltage with \( V_{th} \) threshold voltage of the diode as represented in (30)

$$\Delta P_{\text{total}} = \frac{1}{R_{\text{load}} (C_1 + C_2)^2} \left[ C_1^2 (V_{ip} - V_{th})^2 + C_2^2 (V_{in} - V_{th})^2 \right]$$

(30)

Since we are using active diodes instead of conventional diodes the threshold voltage can be ignored. So the total power harvested can be represented as (31).

$$\Delta P_{\text{total}} = \frac{1}{R_{\text{load}} (C_1 + C_2)^2} \left[ C_1^2 V_{ip}^2 + C_2^2 V_{in}^2 \right]$$

(31)

The total power consumed by the active diode should be less than the power harvested by the harvester as shown in (31). The variation of output power for different amplitudes of vibration for active diode and diode is shown in Fig. 39.
5.3.3 Slotted MEMS switch

The structure of the proposed MEMS comb-drive is shown in Fig. 40. The expanded view of slots of comb fingers is shown in Fig. 40b. Depending on the vibration across the comb-drive, the comb fingers interact. It is observed in [7] that comb-drive without spring does not show uniform displacement. So comb-drive with spring structure is used as shown in Fig. 40. If the vibrational intensity across the slotted MEMS switch is low, the comb fingers overlap in the first slot. If the vibrational intensity across comb fingers is high, then comb fingers overlap in the 5\textsuperscript{th} slot as shown in Fig. 40b.

5.4 Simulation Results

The proposed circuit in Fig.36 was implemented in Cadence using 0.18µm CMOS technology. The MEMS switch SW\textsubscript{1} of Fig. 36 was implemented using Intellisuite as shown in Fig. 40. The simulations were carried out at a frequency of 100Hz which is considered as the frequency of human walking. For a low input vibration of 0.3V and 0.5V the variations of $V_{out}$ versus different load $R_{load}$ are determined. It can be observed from Fig.41.that, the increase in the input voltage increases the output voltage. This is due to the fact that an increase in input voltage decreases the current flowing in the circuit and hence
the losses are reduced. For different low power inputs, the constant output voltage \( V_{out} \) presents at load 35 K\( \Omega \). The voltage across the temporary storage capacitor \( C_1 \) and \( C_2 \) and permanent storage capacitor \( C_{load} \) is shown in Fig. 42. Table -1 shows the comparison of the proposed method with the available techniques. The simulation was performed for a constant load of 35 K\( \Omega \). It can be observed that the efficiency of the converter increases with increase in the input voltage. At higher input voltages it is observed that there will not be a significant increase in efficiency as the voltage drop across the diode does not play a significant role.
Figure -40 (a) Proposed MEMS comb-drive (b) Expanded view of slotted MEMS finger
Figure 41 Variation of output voltage with respect to load.

Figure 42 $V_{\text{piezo}}$ harvested input and voltage across $C_{\text{load}}$ after conversion.
Table 5: Comparison of MEMS Direct AC to DC converter with two stage approach

<table>
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<tr>
<th>Input Voltage</th>
<th>Power Delivered at the load</th>
<th>% Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional transducer(µW) [8]</td>
<td>Proposed Transducer(µW)</td>
</tr>
<tr>
<td>0.5</td>
<td>3.71</td>
<td>4.35</td>
</tr>
<tr>
<td>0.75</td>
<td>8.83</td>
<td>10.661</td>
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<tr>
<td>1</td>
<td>15.55</td>
<td>19.48</td>
</tr>
<tr>
<td>1.5</td>
<td>24.38</td>
<td>29.79</td>
</tr>
</tbody>
</table>

5.5 Conclusion
This chapter presents study of vibration activated slotted MEMS switch which is used to charge a constant load of 35KΩ. This method presents a direct MEMS AC- DC power conversion unit which increases the efficiency of the harvester by 25.3%.

5.6 References


Chapter -6

Conclusions and future work

6.1 Conclusions
Ambient vibrations represent one of the promising energy sources for energy harvesting. Most vibrational energy sources are inconsistent and have low energy. To increase the efficiency of vibrational harvesters the concept of MEMS switches, super diode and slotted MEMS actuators are proposed in this thesis. New techniques to design energy harvesters utilizing MEMS technology are also presented. A piezoelectric based vibrational harvester and an electrostatic based harvester were designed and simulated to validate the proposed design techniques.

Micromechanical switches using MEMS technology are utilized to design rectifiers. The MEMS based rectifiers do not suffer from the energy loss due to the forward bias of conventional rectifiers using diodes. Simulation results show that using MEMS switches instead of diodes in a conventional piezoelectric energy harvester increases the efficiency by more than 30%.

A super diode with MEMS switch were used in an electrostatic energy harvester. The use of MEMS switches in the electrostatic energy harvester eliminated the need of synchronization and increased the efficiency of the harvester by 24%. A slotted MEMS switch direct AC to DC converter was also proposed in this thesis to integrate the rectification and boost power converter in one stage.
6.2 Future Works
In this thesis, a resistive load is used to determine the power generated by different energy harvesters. The effects of variation in the load can be explored in the future. The storage of the harvested energy can be further investigated. In some applications, the generated energy may be low in magnitude, in such cases the energy stored over time can be investigated.

Vibrations generated during human walking is inconsistent. Study of Hybrid energy scavenging using MEMS technology can be investigated in the future.

A MEMS based electromagnetic generators can be designed. However, the coil of a micro-scale generator may not be large enough to produce good magnetic field. Muti-layer coils with small air gap, may result in a high magnetic field density for low amplitude vibrations. Methods of producing efficient MEMS permanent magnets must be developed. Similar to the current inexpensive magnetic generator techniques.

The active and super diode used in this thesis requires a bias voltage of 300mV to start, advanced design technique can be used to reduce the bias voltage in the future.
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VITA AUCTORIS

NAME: Parvathi Shenoy Kasargod

PLACE OF BIRTH: Bangalore, India

YEAR OF BIRTH: 1992

Education:

Master of Applied Science (Electrical and Computer)  
University of Windsor  
Jan 2017  
Windsor, ON

Master of Engineering (Electrical and Computer)  
University of Windsor  
Aug 2015  
Windsor, ON

Bachelor of Engineering (Telecommunication)  
B.N.M Institute of Technology  
Aug 2014  
Bangalore

Publications:

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<td>P. S. Kasargod, R. Rashidzadeh, M. Ahmadi, “A direct AC to DC boost converter for low voltage application,”</td>
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