A GREEN HYBRID ENERGY HARVESTING SYSTEM FOR ROTATIONAL MOTION

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Abstract

This thesis describes a novel, innovative high power density electromagnetic energy harvester device powered by rotational motion. The primary aim of the thesis was to develop high power density energy scavenging device extracting power from rotational motion. In this thesis, a novel permanent magnet array based energy harvesting device is developed and a charging circuit was prototyped to extract the power generated by energy harvester and deliver it to battery. The design of the rotational energy harvester improves the performance, and the use of the axial flux permanent magnets enables inducing strong magnetic field in the coil, which resulted in large induced voltage.

Most of the research work published in the scientific journals has used ambient vibrations in the environment as the energy source. These devices have not achieved the desired power levels, which can enable their practical real life implantations as reliable energy harvesting sources. Most of the rotational motion energy harvesters published in the scientific journals also have not been able to achieve high power density levels. The rotational motion energy harvesters have very important applications such as tire pressure sensing, and MEMS sensors in the automobile, as wells as flywheel rotating mechanisms. In this work, it is demonstrated that in many applications, a rotational energy harvester can offer significant improvements in power density over its vibration-driven counterparts.

In thesis, using axial flux permanent magnet arrays, a prototype of rotational electromagnetic energy harvester was developed. The rotational motion was coupled to rotor in the laboratory to generate the rotational torque. This creates a relative angular speed between rotor and stator, which enable the power to be generated. The novel approach used in the design enables magneto static coupling between coils and permanent magnets that leads to higher flux change and greater induced voltage, which eventually lead to high power output. The detailed analysis of the magnetic material and air gap flux density distribution is conducted in the thesis work.

The detailed analytical model of the rotational energy harvested was created and implement using Matlab™. The FEM modeling of the rotational motion energy harvester was created in FEM simulation software ANSYS Maxwell™. The result of both analytical and FEM simulation matched well with the experimental data collected on the generator. A detailed optimization procedure of boost converter was implemented using Matlab™ in order to maximize the power in the circuit. Using a novel approach to reduce the transformer losses in the boost converter was developed which reduced the circuit losses. The final charging circuit tests were conducted on the energy harvester. The power output of 2.5 Watts was calculated from a single harvester. The device generated open circuit voltage of 6.3V and short circuit current of 0.355 A at 2200 RPMs. Under maximum power transfer a single harvester delivered 0.6 W of power to load resistance of 18.2 ohms.
To my Mom and Dad, family and friends

I always wanted to live a genuine innovative life

and this thesis is testament to who I am

and my values.
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Yours Sincerely,

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INTRODUCTION

1.1 Introduction

Energy harvesting technologies are gathering much interest both from academia and industry in the last decades. In recent years energy harvesting technologies are developing rapidly and have shown great potential in many real applications. However, these applications are limited due to amount of power that can be harvested. By achieving a high power and power density, the wide range of applications can be implemented. In the last decade, several energy harvesting technologies such as piezo-electric, vibrations, thermo-electric, and rotational motion energy harvesting technologies have been tested. Several technologies are being developed and demonstrated with a common goal of replacing battery operated systems. In the recent years, research groups all over the world have certainly increased the power density of this energy harvesting devices.

1.2 Energy Harvesting: Overview

The wheel has been always been perceived as a greatest discoveries known to the man. The invention of the wheel has played a significant role in the evolution of human civilization. It has always been a source of inspiration, and has enabled engineers, scientists, entrepreneurs and opportunists alike, to envision and create many another great inventions from the original concept and purpose of the wheel’s inventions. Today’s modern society has been derived from agrarian society of medieval and ancient times, and this has been only possible because of series of inventions tapping energy from rotation of wheel. The industrial revolution of 18th century was based on coal-powered steam engines, whose main energy transduction mechanics, was based on rotational motion of cogs and flywheels used in it. During, medieval times, much before the industrial revolution, the wheel had significant applications like wind mills which was used to
grind wheat into flour, and water wheels which were used as irrigation system. This two applications show how man used the ambient source energy to his advantage (Fig. 1.1). Another application of harnessing energy from ambient source is sailing, which has contributed to many sea voyages, and it had permanently changed the geo-political demographics of the world.

![Image](image-url)

(a) Photography of a medieval windmill in Greetseil, Germany, reproduced from [1].
(b) Illustration of a water wheel (right) powering a metallurgy foundry (left), which was used for casting iron in 31 AD China, reproduced from [2].

*Figure 1.1 The early forms of energy harvesting techniques from ambient sources of the energy: the windmill and water wheel.*

In the medieval times, windmills and water wheels were commonly used as instruments for grinding or crushing the grains to make the flour, and sometimes for the water irrigation. The windmill can be said to be as device that converts the wind energy into electrical energy. However, earlier prototypes of the wind wheel were used to convert wind energy into mechanical energy. The windmill resembles a rotating wheel with sails or fans (similar to the spokes of a modern car wheel), which is connected to the central shaft of the wheel. As the wind blows into the windmill, the energy of the wind propels the fans to rotate in circular motion. This circular motion is then converted to mechanical energy through gears, which are connected to the central shaft of the windmill. As the wind propels the sail in to a circular motion, the shaft would rotate...
which sets the milling plant in the operation or in the water irrigation system. Some water irrigation wheels use the kinetic energy of the moving water stream to propel itself in the rotational motion. Fundamentally, the windmills convert wind energy to mechanical energy and a water wheel as shown in Fig. 1.1(b), uses the kinetic energy of the flowing river water to set continuously opening and closing of metal casting billow [2]. In the both the above cases, the kinetic energy present in air and water in the continuous flow of air and water, were basically idle ambient energy sources, and thus their conversion into mechanical motion can be effectively utilized.

During the eighteenth century, a scientist named Michael Faraday discovered the electricity through magnetic motion. As the civilization progressed, the electricity becomes integral part of the day-to-day lives of the modern society. There aroused an increasing interest in harnessing the power of the nature and transforming the ambient sources of energy in to a usable form of energy like electricity.

![Figure 1.2 Charles Brush’s wind turbine that was built and tested in his backyard, in Cleveland, Ohio reproduced from [3]](image)

In the 1888, American pioneer named Charles Brush built the world’s first automatically operated wind turbine [3]. It was 60 feet tall and had a diameter of 56 feet, weighed 80,000
pounds and had 12 kW DC generator [3]. Figure 1.2 shows the windmill built by Charles Brush. This wind turbine has influenced the modern engineers to design the wind turbines and windmills which are scattered all over the windy locations on the planet. The above examples were the early examples of energy harvesting technologies, and the scale of their size is very large. However, the modern energy harvesting technologies find its influence from the self-powering wristwatches. Japanese company Seiko built range of wristwatches that could generate power on its own. The recent research on energy harvesting devices has been progressing rapidly due to the reductions in the power consumption of the electronics devices, advancement in wireless data transmission and miniaturization of devices through implementation of advance manufacturing process and use of newly develop micro electromechanical systems (MEMS) technologies.

1.3 Wireless Sensor Networks (WSN)

The definition of wireless sensor networks (WSN) is network consisting of a group of sensors located at different locations or host communicating with one another in order to achieve a common goal. An example of a WSN network is the Texas instrument MSP430 Wireless Development Tool that is a simple wireless network of a transmitter and receiver [4]. Now a day’s sensors are ubiquitously used to monitor the conditions of machinery, environment and structures, and in the military applications where they are used to transmit critical information. Recent advancements in MEMS fabrication technology have resulted in low power, low-cost digital signal processing (DSP) chips and RF electronics have enabled to manufacture commercially viable and inexpensive WSN devices [5]. This WSN networks often have limited lifetime due to the batteries being the primary energy source. The advancement in the battery technologies is not able to match to match the development in MEMS fabrication technologies. As a result, now energy-harvesting devices are used to replace the batteries used in WSN networks, since the sensors and power management electronics have power dissipation. There are two major concerns when using the WSN: the lifetime and physical size of the battery used to
power these devices. The batteries are a finite source of energy, and they require be replacing or recharging very frequently in order to maintain continuity of the WSN operation [6]. The WSN have wide range of applications, and it is very difficult to replace battery used in the WSN device in some cases [7]. Shad Roundy in his PhD thesis [8] made a comparison of the average power density against the lifetimes for various battery technologies with that from the solar and vibration based energy harvesters, which is shown in Fig. 1.3. The graph in Fig. 1.3 clearly shows that both the vibration and solar energy harvester can provide uniform power density for a long period of time.

![Figure 1.3 The comparison of average power density/cm\(^3\) from battery technologies and from vibration and solar-based energy harvesters, reproduced from [8]](image)

However, the power density of energy harvesters depends on the operating conditions. The batteries on the other hand are capable of delivering high power density, but they can do so only for a short period of time. Under typical indoor conditions, solar energy harvester is capable of generating 10\(\mu\text{W/cm}^3\) to 100\(\mu\text{W/cm}^3\) of the output power, and when the device was used in ample bright solar radiation the output power ranges from: 100\(\mu\text{W/cm}^3\) to 1000\(\mu\text{W/cm}^3\). In the case of vibration energy harvesters, the power density is directly proportional to the vibration
frequencies. Xing et al demonstrated a vibration-driven energy harvester with acceleration of 0.57g at 54 Hz [9]. In Roundy demonstrated a vibration-driven energy harvester with an acceleration of 2.25ms$^{-2}$ at 120 Hz. From Roundy’s analysis the batteries are clearly a good choice for a WSN network, which require a low average power. Based on the analysis presented in Fig. 1.3 the energy harvester offers a long term and stable power solutions to WSN networks. Hence, energy harvesting device can provide a good power solution to any electronics device with a solution that is independent of time.

1.4 Thesis Structure

Most of the motivations of the research work published in different journals are driven directly by using ambient vibration source of energy. These vibration sources are found in most of the structures such as buildings, human body motion, vehicles, and part with rotating machinery. In the applications like tire pressure-sensing systems, the host undergoes through a constant rotational motion. The aim of thesis was to develop and prototype a new energy harvester system which utilizes the rotational motion as direct activation source.

The research objectives can be summarized therefore as follows:

1. Demonstrate an energy harvester powered by a complete rotational motion source.
2. Simulate and design an optimal and efficient energy harvester with application of ultra-efficient magnetic components in the energy harvester.
3. Investigate the behavior of the energy harvester and design a power management circuit with low power losses.

The above objectives for the energy harvester for rotational motion are organized into six chapters.

Chapter 1 gives the general information about the energy harvesting technologies and the historical perspective of energy harvesting technologies, and the reason, which served as motivation for recent research into energy harvesting devices.
Chapter 2 will provide the literature review on the recent research work carried on the energy harvesting systems. The chapter 2 will also discuss about the different mechanism of transductions employed by the different energy harvesting systems.

Chapter 3 discusses about the material used in the electromagnetic energy harvesters. It also discusses about the analysis of the different material that can be implemented for improving the power density of the energy harvester. The different models of the energy harvester will be discussed in detail. Finally the experimental result of the test performed on the harvester will be provided.

Chapter 4 analyses the power electronics circuits used in the energy harvester. The chapter discuss about the recent research on the power management of the different energy harvesting systems.

Chapter 5 discusses in detail the prototype circuit built for interfacing the harvester to load. A detailed analysis and experimental result obtained from the two prototype circuits will be put forth.

Chapter 6 summarizes the work reported in the thesis and suggestions for the future work will be discussed briefly.
A literature review of the different energy harvesting devices and mechanisms is presented in this chapter. This review is divided into several sections with motive to examine on transduction mechanism on kinetic and non-kinetic energy harvesting devices. The basic motive of any typical energy-harvesting device is to utilize an endless source of ambient energy coupled with transduction mechanism in order to deliver usable electrical power. The nature of the source of ambient energy is of two types: kinetic sources and non-kinetic sources. The kinetic energy sources rely exclusively on the motion of the host structures, which can be vibration [10-11], rotation, or a linear motion. On the other hand non-kinetic energy sources include electromagnetic waves from RF or microwave spectrum [12-14] or solar energy from the radiation of sun [15-16] and thermal radiation arising because of presence of thermal gradient in thermally conducting bodies. Typically, most of these energy harvesters scavenge energy from a single ambient source irrespective of its nature.

2.1 Transduction Mechanisms of Kinetic Energy Harvesters

The transduction mechanisms of kinetic energy harvesters will be discussed in this section. A transducer is a device that converts one form of energy into another form of energy. In the energy-harvesting device, the role of transduction mechanism is to convert an ambient source of energy into a usable electrical energy. The kinetic energy harvesters employ various types of transducer or transduction mechanisms such as vibration, electromagnetic, electrostatic and piezoelectric to harvest ambient energy.

2.1.1 Principles of operations

Energy harvesting from ambient motion employ the concept of inertia, i.e. a device with a proof mass suspended in a frame whereby energy is extracted using a transduction mechanism
which dampens the motion of mass which is connected to a damping frame mostly made of springs. These devices are advantageous because they have a single point of attachment, which makes them rely directly on the motion of the source rather than relying on the motion of different moving parts of the host structure. Vibration-based inertial energy harvesters [17] are often modeled as a second order spring-mass-damper system (Fig. 2.1). The Fig. 2.1, show a schematic of an inertial energy harvester [18] using a spring-mass-damper system.

![Figure 2.1: Schematic of a spring-mass-damper representation of inertial energy harvesters, reproduced from [18].](image)

The motion of the frame is represented by \( y(t) \) and if the vibration source is said to be harmonic in the nature, then the amplitude of the source will be given as \( Y_0 \). The displacement of the mass, \( m \) is \( z(t) \) with a maximum limit of \( Z_l \) and \( x(t) \) is the displacement the mass relative to the host structure. The maximum power output occurs at the resonance of the system, and which is given by following expression:

\[
P_{\text{res}} = \frac{1}{2} Y_0 Z_l m \omega^3
\]

It should be noted that the above expression is valid on the following assumptions:

1. The mass had achieved steady state motion.
2. The ambient energy source is not affected by the working of the energy harvester.
3. The choice of the damping factor determines the maximum travel distance of the mass.
2.1.2 Piezoelectric Energy Harvesters

Piezoelectric transducers use the piezoelectric effect as the principle of transductions. The piezoelectric effect is defined as when a mechanical strain is exerted on a piezoelectric material or device, the device will induce the electrical charge on the piezoelectric capacitance, and thus a voltage is formed across the terminals of the device. Conversely, a piezoelectric actuator will experience a mechanical force on it when a voltage is applied across its terminal. This effect is used in piezoelectric energy harvester. Typical piezo-electric energy harvester consist of a cantilever beam deposited with one or two layers of piezoelectric material such as lead zirconate titanate (PZT) and a mass attached to the free end of the beam [19]. The schematic of the piezoelectric energy harvested is shown in Fig. 2.2

![Figure 2.2: a schematic of typical piezoelectric energy harvester](image)

The conversion of the energy is dependent on the piezoelectric coupling coefficient, \( k_{ij} \), and the capacitance of the piezoelectric material, \( C_p \). The polarization of the material in three-dimensional space is denoted by subscripts ‘i’ and ‘j’ in the coupling coefficient. Two modes for piezoelectric materials are 33-mode and 31-mode. In the 33-mode, both the applied field and electric field is in the three directions, whereas in 31-mode the applied strain is 3 directions and electric field is only in the one direction. Since the coupling coefficient is higher in 33-mode, most of the piezoelectric energy harvesters utilize 33-mode in their operations.
2.1.2 Electromagnetic Energy Harvesters

Electromagnetism forms the working principle of the big generators in power plants. Michael Faraday discovered the law of electromagnetic induction, and it forms the working principle of all the electromagnetic generators. It states that when a closed loop coil of conducting material is moved relative to a magnetic field, an electromotive force (EMF) will be induced in the coil and when the coil is connected to the load, a current will follow through it. Thus, Faraday’s laws showed that mechanical motion could be converted into usable electrical energy. Fig. 2.3 shows an electromagnetic energy harvester using moving high power neodymium-iron-boron magnets and a stationary copper coil with 2800 turns [20].

![Figure 2.3: Mark 3 electromagnetic generator reported by Torah et al., reproduced from [20]](image)

2.1.4 Vibration Energy Harvesters

The review of the vibration energy harvester is presented in this section. The focus of this review is more on the publications, which are more elaborate on the design and power management on the harvester. This is of more importance because the work on this thesis is primarily concerned with a rotational energy harvester system that transferred maximum power from the harvester to the load, which can be a battery.
Roundy and Wright reported a piezoelectric vibration generator, which produced a maximum output power of 375 µW into a resistive load from source, which provided excitation of 120 Hz at acceleration of 2.25 m/s² [21]. The dimensions of their reported device are 15 mm × 6.7 mm and 30 mm × 3.6 mm. Both the generators were designed with the objective of keeping the volume of 1 cm³, and their device was used to transmit signals from a custom-made radio operating at 1.9 GHz. The authors modeled the mechanical components of their energy harvester using electrical components. For the example, the mechanical stiffness was represented with a capacitor, mass with an inductor, and the mechanical damping as a resistor. A diode rectifier converted the generator’s output voltage into a DC voltage. This DC voltage charged a storage capacitor. The ‘shunt down control’ was used to determine the charging of the capacitor, which could activate only when the capacitor voltage dropped below a specified level. The maximum power transfer from the generator to the capacitive load was achieved when the storage capacitor’s voltage was half of the open circuit output voltage.

Kim et al. presented a cymbal-shaped piezoelectric energy harvester with DC-DC buck converter in [22-23] and are shown in the Fig. 2.4. A buck converter was used to step down the high output voltage to the maximum value of 25 V, which was dependent on the converter’s output load resistance.

![Figure 2.4: Cymbal-shaped piezoelectric energy harvester reproduced from [22-23]](image)

(a) Dimensions of the cymbal-shaped piezoelectric transducer (b) Experiment setup for the transducer
Their energy harvester consisted of ten PZT layer with thickness of 1 mm stacked under a steel cymbal enclosure. This PZT energy harvester was subjected to vibrations similar to that in a car’s engine. The generator could transfer power of 53 mW to the LED load and the power consumption in the converter was measured to be 5 mW at operating frequency of 1 kHz. Shenck and Paradiso reported shoe-mounted piezoelectric energy harvester. Their device is shown in Fig 2.5.

![Figure 2.5: A shoe mounted piezoelectric energy harvester developed by Shenck and Paradiso, reproduced from [24].](image)

Their first approach used a hexagonal-shaped piezoelectric material to harvest energy from bending motion of the human foot as the person walks. In their second approach, they used bimorph piezoelectric plate positioned under the heel and the person’s heel touches the ground, the PZT plate scavenges the energy from the walking motion. Both approach used the mechanical strain produced while walking. Around 1.3 mW and 8.4 mW of the average power were generated under matched resistive loads for both the methods. They used the harvested energy to power RFID tag, which transmitted a periodic RF signal. The interface electronics for this
harvester was designed to accumulate charge in a storage capacitor, and as the charge is turned to be sufficient enough, a 5 V transmitter was energized. Their piezoelectric energy harvester output voltage ranged from 0 – 170 V-peak, so they used a forward switch mode converter which is much more efficient than low-dropout voltage regulator. Xing et al. [9] built a wideband vibration energy harvester with very high permeability magnetic material. Her device generated maximum power of 74 mW at 54 Hz with the acceleration of 0.57 g. The Xing’s wideband electromagnetic vibration energy harvester is shown in Fig. 2.6

![Wideband vibration energy harvester](image)

**Figure 2.6: Wideband vibration energy harvester reported by Xing and Sun et al. reproduced from [9].**

In resonant energy harvesting systems, the output power is directly proportional to the resonant frequency, which means the power deteriorates, as the excitation frequency deviates from the resonant frequency. This is a severe drawback, which hinders the practical implementation of the vibration based energy harvesters. Over the year, considerable research had been done to make design, which could passively or actively change its resonant frequency according to the fluctuations in the excitation frequency. Ayala et al. published papers on electromagnetic vibration energy harvester a contact-less adaptive resonant frequency tuning mechanism in [25]. He could achieve this by altering the stiffness of a cantilever beam structure housing the electromagnetic energy harvester and adding another tuning magnet to the free end of the beam. The placement of the tuning magnet was made in such a way that there exist a force of attraction between it and the transduction magnets. The resonant frequency of the harvester is 45
Hz. The usage of the tuning mechanism could make it possible to vary resonant frequency from 64 Hz -78 Hz, thus improving the bandwidth of the harvester by 54 times the standalone device.

A schematic and experimental setup of the device is shown in Fig. 2.7

![Image of schematic and experimental setup](image)

**Figure 2.7: Tuned Electromagnetic energy harvester reported by Ayala et al. reproduced from [25].**

Leland and Wright developed tunable vibration-driven piezoelectric energy harvester whose resonance was made tunable by applying an axial preload on the device [26]. A schematic of their device is shown in Fig. 2.8.

![Image of schematic](image)

**Figure 2.8: Schematic of tunable vibration-driven piezoelectric energy harvester reported by Leland and Wright, reproduced from [26].**

The application of the load increases the stiffness in the beam, and thus it alters the resonant frequency of the harvester. The authors cite that the piezoelectric beam being brittle in nature is the main reason that tensile load cannot be used for frequency tuning of the piezoelectric energy harvesters. The authors reported of generating 300 µW – 400 µW across a source excitation frequency range of 200 Hz – 250 Hz when a 7 g proof mass was used. On the other hand, a 12 g...
mass resulted in a larger output power from 360 µW – 650 µW between frequencies of 160 Hz – 195 Hz.

Mitcheson et al. [17] produced a detailed analysis of three types of energy harvester architectures; namely: velocity damped resonant generator, coulomb damped resonant generator and coulomb-force parametric generator. The authors cite the parasitic damping effects on the overall damping co-efficient of the generator, and if this factor’s influence is very significant then author suggested the re-optimization of the harvester design should be done. The electrical damping should be matched with the parasitic damping in order to increase the efficiency of the energy harvesters.

2.1.5 Fluid Flow Energy Harvesters

Presently most of the reported rotational energy harvesters are based on the mm-scale alternating (AC) machines that convert energy in fluid flow into electrical power. A paper published by Arnold [27] reviews the different types of magnetic based power generators that have been research in the past decade. These generators can be classified in to following categories: Hybrid, Oscillatory and rotational generators. The hybrid generator is the generator that converted linear motion into rotational motion. Arnold pointed out several difficulties in the improvement of power densities of these generators. The power density is defined as ratio of maximum output power to the volume of active electromagnetic components.

The use of high flux density materials like neodymium iron boron (NdFeB) magnets in present day micro-fabrication process requires use of high temperature process. High temperature processes are not good for the magnetic properties of these materials. Thus, the magnetic properties of this power generator are often sub-optimal compared to when they are bulk-manufactured. Also these magnetic generators rely on the rotational motion of rotor and stator part, which arouses the problem of the friction between these moving parts. Arnold et al. [28] reported a second-generation axial flux PM generator with copper stator windings and an 8-pole PM rotor. The author cites the two advantages of using axial flux machine is that the orientation
of flux in axial direction enables it to integrate in standard MEMS fabrication process and magnetic field of PM magnets becomes independent of the generator dimensions. As a result, the current induced in the coils will increase even with use of small magnets. Their work reported 30% increase in the power densities when the first and second-generation devices were compared. They could generate power of 8 W at rotation of 305 kRPM and the device volume was 136 mm$^3$.

In [29] Holmes et al. report a MEMS-based axial flux permanent energy harvester with a diameter of 7.5 mm, delivering an output power of 1.1 mW per stator rotating at 30 kRPM (Fig. 2.9). The device has two silicon stators located above and below the permanent magnet rotor. The authors concluded that a reduction in PM generator size will reduce the output power drastically unless the rotation speed is significantly increased.

![Image](image.png)

*Figure 2.9: A MEMS-based axial flux permanent magnet energy harvester, reproduced from [29].*

In [30], Raisigel et al. reported an 8 mm diameter axial flux permanent magnet harvester with a stator that consisted of three phase planar coils. The micro generator (shown in Fig. 2.10) produced a maximum electrical output power of 5W per stator at 380 kRPM. The author reported that if the DC resistance of the stator coils were reduced it would lead into higher electrical efficiencies.
C. T. Pan and Wu [31] developed a planar electromagnetic generator, which could produce power of 0.412 mW on a load resistor measuring 30 Ω, at a rotation speed of 2240 RPM (shown in Fig. 2.11). The device volume was 50 mm$^3$.

2.1.6 Electrostatic Energy Harvesters

An electrostatic energy harvester consists of a capacitor whose plate move in relation to the mechanical movements. These types of energy harvesting devices utilize the excitation of electrostatic force, and work done against the force is the energy harvested.
An example of electrostatic energy harvester is shown in the Fig. 2.12. The device consists of three parts: a bottom plate holding charging contacts, discharge contacts are placed on the top plate and middle plate is the proof mass. The ambient mechanical motion displaces the middle plate in such a way that it moves between the top plate and the bottom plate. Thus a charge difference is developed because of the movement of the middle plate.

2.1.6 Discussion

The review of the different energy harvesters and their working principles presented in the above sections has served as a guideline for the work undertaken in this research thesis. The following conclusion can be drawn which are follows: The impedance matching between the input of the load electronics and output impedance of the harvester would transfer maximum power to the load. The electrical damping of the energy harvesting system should be set in such a way that it matches with the parasitic damping of the harvester. Energy storage elements are fundamental requirement in the energy harvesting systems, as the ambient excitations are not always continuous. Cascading the several energy harvesters could lead to greater voltages and thus would be able to supply sufficient power to the electronic circuitry connected at its output. The frequency spectrum for the energy harvesters should be very wide and the recent research
works have delivered different ways to tune the energy harvesters. The size of rotational motion-based electromagnetic generator is very critical to its power density, and scaling in the size should be compensated with increasing the rotational speed.

2.2 Rotational Energy Harvesters

Various vibration based energy harvester have been used to power sensor by converting the vibrations into rotational motions. The PMG FSH vibration-driven energy harvesters developed by Perpetuum Corporation [33] have been used extensively by the transportation industry. The device is capable of supplying 20 mW (5V at 4 mA) for input excitation of up to 0.5 g applied at the tuned resonant frequency. The VEH-460 electromagnetic energy harvester from Mide [34] is capable of providing 5.2 mW of the rectified DC power at an input acceleration of 0.1 g at 60 Hz. Gu and Livermore present experimental results of a passive self-tuning piezoelectric beam that harvest energy from rotational motion [35]. The PZT beam was aligned radially on the rotating host with the fixed point of the beam positioned at distance $r$ from the axis of the rotation. The authors reported that when the beam experiences the centrifugal force, the beam stiffness and resonant frequency changes. By varying the beam length and beam positions, the author reported to being able to tune the resonant frequency of the harvesters. The frequency range of the their harvester was reported to be from 0 Hz – 21Hz, with maximum frequency mismatch of 0.5 Hz at 6.2 Hz. The tuned rotational motion energy harvester achieved a maximum power of 0.7 mW at a source frequency of 13.2 Hz, which is equivalent to 920 RPM. There has been an extensive amount of the published work on using vibration from rotating structures. However, these systems don’t scavenge energy directly from the rotational motion. The major drawback of this energy harvester is the source vibration has fixed frequency and amplitude. These harvesters have maximum efficiency only at their resonant frequency. Also the vibrations from the rotating machinery are not very strong and are just the by-product of rotation.
2.4 Conclusions

With MEMS fabrication technologies advancing at rapid pace, miniaturization of energy harvesting device looks promising. The miniaturization of the electrostatic energy harvesting is most promising of the energy harvesters. The scaling laws are more promising for the electrostatic energy harvesting devices. The electromagnetic energy harvesters are affected very drastically by scaling laws. The magnetic properties are at rate sub-optimal range when compared with the bulk level. The efficiency of an energy harvester depends on the both the mechanical and electrical efficiencies. The overall efficiency of any energy harvesting system also largely depends on the power management electronics. The interface electronics should be designed in such a way that the power loss in it is extremely minimal. Typically the interface electronics consist of a diode bridge rectifier or an adaptive dual polarity switch mode power converter. The dual polarity switch mode power converter has three significant advantages over diodes:

1. Voltage step up can be achieved during the positive and negative half cycles of the AC input signals.
2. An impedance matching can be achieved by controlling the duty cycle of the converter.
3. The diode voltage drop is less compared to the diode bridge rectifier.

This chapter has provided following guideline for the research work done in this thesis. The energy harvesting power density can be increased to significant extent by direct utilization of rotational motion as an excitation source. The impedance matching between the harvester output and the load electronics input leads to maximum power transfer to the load. The application of materials with better magnetic properties will lead to higher power output. The Chapter 3 discuss about the details of the materials used in the energy harvester. The working principles used in the energy harvester will be presented, followed by experimental result from the energy harvester.
3.1 Introduction

The main motivation of this study concentrates on the axial flux permanent magnet machines with one-rotor – two-stator configuration. This configuration is used in building the prototype of the energy harvester. The chapter focuses on the advantage of this configuration as it proves to be the adequate structure for target applications with low speed and high torque. The advantage of using this topology is that the handling of the coils in stator becomes easy. The one-rotor – two-stator topology can work in the conditions even when one of the stator coils is electrically discontinued, and the axial load is relatively small because of the internal rotor. The several generations of electrical engineers have designed, constructed and improved the electrical machines. Yet the electrical machines are under constant improvement and development, because of the improvement in the magnetic materials and interfacing power electronics. The development of the permanent neodymium-iron-boron-magnet since it invention in 1983 have enabled to develop electrical generator for low speed applications. The main research objective covered in this chapter focuses on the materials that can be used to build energy harvester with better magnetic properties, and developing the analytical design of the harvester.

3.1 Axial-flux permanent magnet generators

The history of the electrical generator shows that the early generator was built as axial flux generators. The first one, which was invented by Michael Faraday in 1821, was a practically primitive type of an axial flux permanent magnet generator. In the field of energy harvesting where the volume and dimensions constraints are very tight, the use of axial flux permanent magnet array can be attractive, as it enables to obtain a neat axial length. There are several configurations of axial flux permanent magnet generators with regards to the arrangement of the
stator positions and rotor positions. The Fig. 3.1 depicts the possible configuration in the axial flux generators.

![Axial flux generator configurations](image)

**Figure 3.1:** Axial flux generator configurations reproduced from [36]

Fig 3.1 a) Single rotor - single stator structure. (b) Two rotors - single stator structure. (c) Single rotor - two stators structure. (d) Multistage rotor and stator configuration.

The single rotor and single stator structure is the simplest axial flux configuration. This structure suffers from the unbalanced axial force between the rotor and the stator. This topology requires complex bearings. The one-stator – two-rotor structure as illustrated in Fig. 1.3 (b) is also slightly disadvantageous, because the fixing of the stator in the frame is very complex. However, this configuration improves the machine efficiency and power density. In a single rotor – two stators structures, the permanent magnets may be located on the surface of the rotor or they can
be embedded into the rotor disk shown in Fig. 3.1. Therefore, the main flux may flow axially through the rotor or flow circumferentially along the rotor disk.

![Diagram of flux paths](image)

*Figure 3.2: Flux paths in 2D plane for a single – rotor – two – stators structures.*

The surface mounted structure has a very thin rotor, especially if the magnets are installed in a non-ferromagnetic rotor core [37-38]. Another configuration is the structure in which the permanent magnets are buried into the rotor disk. However, this configuration requires much thicker rotor disk, which reduces the power density in the generator. The advantage of the buried structures is that it offers better protection to magnets against mechanical impacts and corrosion.

### 3.2 Radial-flux permanent-magnet generators

Over the period of several decades radial-flux permanent magnet generators have used been used in a wide variety of applications requiring from few watts to two several megawatts of power. The Fig 3.3 illustrates possible radial-flux permanent magnet generator configurations. In contrast to axial flux permanent magnet generators, which are most manufactured as surface mounted magnets; several variations of assembling the magnets into the rotor of the axial flux machines are possible. If the permanent magnets are surface mounted, then the rotation speed of the generator has to be limited, so that the effects of centrifugal force do not break the magnets
glue points. The buried arrangement offers several advantages over the surface mounted configurations. Consequently, the higher rotation speed can be applied. It is possible to achieve nearly sinusoidal distribution of the air gap flux density. The cogging torque is lesser which thus enables improvement in the torque production. The demagnetization risk of the magnet is reduced. Also it protects the magnets from the mechanical wear and tear. However, the disadvantage is that it suffers from leakage flux.

![Image of radial-flux permanent magnet generators]

*Figure 3.3: Radial-flux permanent magnet generators, reproduced from [36]*

### 3.3 Permanent Magnet materials

The systematic study of magnet started around 1880, where new types of alloy were studied. In 1931, T. Mishima patented the first hard magnetic alloy, based on aluminum, nickel and iron. This marked the development of the permanent magnet family called AlNiCo. In the 1950, another permanent magnet family, known as ferrites becomes commercially available. They become extremely popular for DC motors applications because of their better material properties. The development of the rare earth permanent magnet materials started in the 1960’s
with invention of Samarium Cobalt alloy family. The material proper of SmCo\textsubscript{5} and Sm\textsubscript{2}Co\textsubscript{17} made this alloy family extremely popular. In 1983, high performance Neodymium-Iron-Boron permanent magnets were introduced. This family of magnet has very dense magnetic flux, and when compared with SmCo family of the magnets, they are cheaper. A historical development of the rare earth permanent magnets is shown in Fig. 3.4

![Graph showing historical development of various rare earth magnets](image)

*Figure 3.4. Historical Development of various rare earth magnets, reproduced from [39]*

With the development of these very powerful NdFeB magnets, various electromagnetic energy harvesters have incorporated them in their designs. As the design of permanent magnet energy harvester is concerned, it is relevant to understand the properties of them.

### 3.3.1 Magnetization and Coercivity

In classical electromagnetism, **magnetization** or **magnetic polarization** is the vector field that expresses the density of permanent or induced magnetic dipole moments in a magnetic material. It is sum of all the magnetic moments present in the given volume $V$, of the magnetic material.
The Magnetization \( M \) can be defined as

\[
M = \mu_m \Delta V n
\]

where \( \mu_m \) is the magnetic dipole moment.

\( \Delta V \) is the volume,

\( n \) is the number of atoms per unit volume.

In some magnetic materials, these tiny magnetic dipoles align their axis in the one direction due to the force exerted by their own internal field. The magnetic flux density in a magnetic material is given by following relation

\[
\frac{\mu_0 M_{sat}}{2K_{1}}
\]

, where — and \( B_r \) and \( H_c \) are the remnant magnetization.

The magnetic properties of permanent magnets are based on the magneto anisotropy, such as in NdFeB or Sm-Co materials. The Fig. 3.5 shows the simplified magnetic characteristics of the material.

![Diagram](Figure 3.5 Intrinsic characteristics for the elemental volume of magnet. (b) B-H characteristic for the magnet.)

The point in 1 in Fig 3.5 (a) shows a situation in which all the magnetic dipole in a magnetic materials are aligned in the same direction, thus magnetization \( M \) corresponds to the saturation magnetization \( M_{sat} \). Thus the external applied magnetic field strength is equal to zero at point 1. If we continue to apply an increasing external magnetic field strength in the reverse direction, the magnetization \( M \) continues to oppose the increasing \( H \)-field until a point reaches where the
magnetic domains flip and reverse their direction. This occurs at point 2 in the figure. Similarly if the reverse direction is again applied, the magnetization flips over, and the point 3 represents that instant of flip over. Thus the intrinsic coercivity of any magnetic material is the field strength required to change the direction of the magnetization in the material. The intrinsic coercivity is the measure of the permanent magnetism in a material. It is defined by the following formula:

\[ H_{ci} = \frac{2K}{\mu_{M_{sat}}} \]

where \( K \) is the magnetic anisotropy for a magnet element.

The Fig 3.5 (b) shows the relationship between the magnetic flux density \( B \) and magnetic field density. The value of the H-field that is required to reduce the magnetic flux density to zero in a material is called Coercive force or Coercivity \( H_c \). The above equation represents the behavior of idealized permanent magnets. In practice the B-H curves are much smoother than the one shown in Fig. 3.5 (b). The relationship between the magnetism and temperature is neglected.

### 3.3.2 Neodymium-Iron-Boron Permanent Magnets

Since the energy harvester developed in this thesis uses permanent magnets array, the properties of the permanent magnets are discussed in more detail. The NdFeB magnets in the recent years have been able to achieve remnant magnetic flux density greater than 1.5 T and their maximum energy products were reported to be of 440 kJ/m\(^3\) [39]. Hitachi Metals Corporation commercially manufactures several grades of neodymium magnet with \( B_{r_{max}} \) of 1.5 Teslas. The values of these magnets are close to the values of sintered NdFeB. \( \text{Nd}_{1},\text{Fe}_{14},\text{B}_{1} \) grade has maximum energy product of 510 kJ/m\(^3\). The thermal properties of these high performance magnets are extremely poor, and they therefore cannot be used in applications where high temperatures are present. The maximum operating temperatures of this magnet grade is limited to 100 degree Celsius. As the temperature start increasing the magnetization of NdFeB magnets drops very rapidly and they lose all their magnetization by 250 degree Celsius. Some researchers have shown the temperature tolerance can be increased by addition of dysprosium, which is known to increase the coercivity of the magnets to NdFeB alloy. Another approach suggested
addition of cobalt to iron in order to increase the coercivity of the magnetic material. The addition of these materials reduces the maximum energy product of the magnets. The grade N48 and N52 are known to have good thermal tolerance and at the same time having the remnant flux density greater than 1.3 Tesla. The B-H curve of the NdFeB magnet is shown in Fig. 3.6

![B-H curve of the Neodymium-Iron-Boron magnet material.](image)

The intrinsic coercivity $H_{ci}$ is the function of the temperature. As the temperature increases the intrinsic coercivity drop rapidly, this is one of major disadvantage of NdFeB magnets. Fig. 3.6, depicts the second quadrant working permanent magnets. From the figure, the magnet has larger intrinsic coercivity at 20 °C compared to 80 °C and 150 °C. As the temperature increases from 80 °C to 150 °C, the irreversible change in the magnetization starts when the external magnetic demagnetizing field exceeds the value of -400kA/m. Another disadvantage of the NdFeB magnets is their reduced sensitivity to the corrosion. NdFeB magnets are prone to oxidization, when exposed to oxygen, it diffuses into them and causes metallurgical change in the surface. The NdFeB magnet are also sensitive to the humidity, the hydrogen molecules react with Nd , and
destroys the grain structure of the material. Nowadays, NdFeB magnets are coated with a protective layer of aluminum, epoxy to prevent it from corrosion. The NdFeB material is very hard and brittle, so they are prone to cracking due to shocks. The risk of cracking is more in the surface mounted configuration, and they thus require extreme care in handling. The bonded alloy of NdFeB and with polymer matrix has shown some improvement in the mechanical sturdiness of NdFeB magnets. The NdFeB magnets are poor thermal conductors, and hence excessive temperature rise in the magnet is possible. They also suffer from eddy currents, since they are very good conductors at room temperatures.

<table>
<thead>
<tr>
<th></th>
<th>( B_r ) (T)</th>
<th>( BH_{\text{max}} ) (kJ/m³)</th>
<th>( \rho ) (( \mu \Omega )m)</th>
<th>( \mu_r )</th>
<th>( \lambda ) (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NdFeB</td>
<td>1-1.4</td>
<td>190-380</td>
<td>1.5</td>
<td>1.05-1.2</td>
<td>9</td>
</tr>
<tr>
<td>Plastic bonded NdFeB</td>
<td>0.5-0.7</td>
<td>40-90</td>
<td>10-30</td>
<td>1.15-1.2</td>
<td>2</td>
</tr>
</tbody>
</table>

Reproduced from [40]

### 3.4 Soft Magnetic Materials

Soft magnetic materials have played important role in development of the electromagnetic generators. They exhibit magnetic properties only when they are subjected to external magnetic fields. The soft magnetic materials have characteristically a low coercive field, \( H_c < 1 \text{ kA/m} \). Some other magnetic materials have low anisotropy, low magnetostriction, low mechanical hardness and low crystal anisotropy. The different types of soft magnetic components are as follows:

1. Electrical Steels (Non-oriented and Grain Oriented)
2. Nickel-Iron Alloys
3. Soft ferrites (NiZn and MnZn)
4. Amorphous metals
5. SMC (soft magnetic composites)
3.4.1 Soft Magnetic materials for Energy Harvesters

Electrical steel lamination is the most commonly used core material in electrical generators. Electrical steels are classified into two different types: grain-oriented electrical steels and non-oriented electrical steels. However, the core-losses in the electrical steel is very high, so they are mostly used in the power transformer cores. They show reasonable power losses and typical loss values is about 5 Watts per kilogram with 1.5T magnetic flux density for the grade of steel used in the electrical generator at excitation frequency of 50 Hz. As the frequency increases, the core-losses in the electrical steel increases, so in the high frequency application amorphous materials are used. The amorphous materials exhibit low core-losses because of their material structure and the material thickness. The thickness of the amorphous iron ribbon is typically only 20-30 µm. Soft ferrites also show very low eddy current losses, but they suffer from very low saturation flux density, which is range from 0.35 T to 0.5 T. For the electrical steels, the saturation density ranges from 2.0 to 2.2 Tesla. METGLAS™ [41] has a saturation density of 1.8 Tesla. Co-Fe alloys: Permendur™ (Fe49-Co49-2V) has saturation density of 2.34 T. But Co-Fe alloys are very expensive. Soft magnetic composite materials (SMC-materials) are the new type of materials, which are used very extensively. SMC’s are finely grounded iron powder coated with electrical insulating layer. Typically SMC materials were used for high frequency applications, but recent research has shown that they can configure to low-medium frequency operation. The SMC materials are not suitable for energy harvesting application because of the following reasons:

At low frequency, the losses in SMC-materials are higher than the laminated structures. At Low frequency of 50 Hz the power losses in SMC-materials is 15 W/kg at a 1.5 T magnetic flux density. Such high power losses are extremely undesirable for their use in energy harvesting applications.
SMC doesn’t have good thermal characteristic, and they are prone to the rising temperature. Iron losses increase with the increase in temperature. The magnetic properties depend on the SMC powder type and the properties of the insulating layer.

SMC-materials allow 3-dimensional shaping of the components due to the material spatially isotropic magnetic and thermal properties. In laminates the properties are uni or bi-dimensional, for example the thermal conductivity of electrical steels varies typically 32 to about 40 W/mK in the direction of the lamination and is only one tenth, ∼ 4 W/mK, in the perpendicular direction. Fig. 3.7, illustrates the core-losses induced in soft magnetic materials. From the figure, the
METGLAS™ clearly shows good performance characteristics as compared to other soft magnetic materials. Fig. 3.8 illustrates the power losses as function of frequency.

Some other typical properties for the soft magnetic materials are summarized in Table 3.2.

The Fig. 3.8 shows that Permendur™ and METGLAS™ exhibit same characteristics till 1000Hz frequency. The performance of the METGLAS™ drops after 1000 Hz as compared to that of Permendur. Based on the data presented in the Fig. 3.7 and Fig 3.8, the METGLAS™ performance will be better in the energy harvesting applications compared to other ferromagnetic materials.

![Figure 3.9: B-H curves of various soft magnetic materials.](image)

### Table 3.2 Properties of soft magnetic materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>$B_{sat}$ [T]</th>
<th>$\rho$ [µΩm]</th>
<th>$\mu_{max}$</th>
<th>$\lambda$ [W/mK]</th>
<th>$P$ [W/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-oriented electrical steels</td>
<td>2.1</td>
<td>0.4</td>
<td>5000</td>
<td>40</td>
<td>5</td>
</tr>
<tr>
<td>METGLAS™ 2605C</td>
<td>1.8</td>
<td>1.2</td>
<td>400000</td>
<td>9</td>
<td>0.5</td>
</tr>
<tr>
<td>Permendur (Fe49-Co49-2V)</td>
<td>2.34</td>
<td>0.35</td>
<td>50000</td>
<td>12</td>
<td>1.4</td>
</tr>
<tr>
<td>SMC-composite SOMALOY® 500 with 0.5 % KENOLUBE®</td>
<td>2.0</td>
<td>30</td>
<td>500</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>NiZn ferrites</td>
<td>0.35</td>
<td>$1\cdot10^6$</td>
<td>4000</td>
<td>3.5-$10^{-3}$</td>
<td>-</td>
</tr>
<tr>
<td>MnZn ferrites</td>
<td>0.5</td>
<td>$0.2\cdot10^6$</td>
<td>6000</td>
<td>3.5-$10^{-3}$</td>
<td>-</td>
</tr>
<tr>
<td>Chrome Core® 8 Alloy</td>
<td>1.86</td>
<td>0.49</td>
<td>3100</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Core-losses are given at $f = 50$ Hz and flux density of 1 T, reproduced from [36]
Utilizing high permeable cores in the energy harvesters will dramatically increase the magnitude of the magnetic flux through the coils. Thus, a larger flux change through each core results in greater induced voltage. Using the strong magneto-static interaction between magnets and coils with high permeability magnetic material cores, the output of the harvester can be significantly increased.

3.2 Design of Rotational Energy Harvester

The research objective was to build an analytical solution for the energy harvester. This section discusses about the analytical design method and FEA simulation method for determining the air gap flux density in the harvester. As the harvester had 3-dimensional geometry, it became very important to determine the magnetic flux in the harvester. The results from the analytical and FEA simulation were compared with the experimental data obtained from the prototype.

3.2.1 Introduction

The modeling of the energy harvester is determined by the contradictory requirements related to the fastness and the accuracy of the computations. The energy harvester has a 3D geometry. Therefore, the conventional analytical design or 2D finite element analysis would not be accurate. With 3D FEA, it is possible to take into consideration the 3D geometry of the harvester, but the computations are often too time-consuming. A typical axial flux configuration consists of a set of coils that are fixed below and above the rotating multi-pole magnets such that flux has a return path. During the normal operation, the coils are energized by the rotating magnetic flux and this imparts a voltage in the coil. However, given the three dimensional nature of the problem, it is very difficult to obtain the field solution in closed form. Numerical techniques like finite element method are used to calculate the field in the air gap region separating coils and magnets. The approach taken in the modeling the harvester follows closely to that presented by Furlani [42-43]. Such type of the design is called quasi-3D modeling. The
approach used was the energy harvester is a 3D cylinder. The cylinder is unrolled into two-dimensional surface. This is especially advantageous because the harvester inherent 3D problem now turns into 2D problem.

### 3.3.2 Analytical model of Air-gap flux density

However this model is based on the assumption of an ideal permanent magnet following the equation: $\bar{B} = \mu(\bar{M_s} + \bar{H})$ where $\mu = \frac{B_r}{H_c}$ and $B_r$ and $H_c$ are the remnant magnetization and coercivity of the magnet respectively. The above equation takes into the account finite slope of the B-H loop in the second quadrant where the operating points are usually located.

![Figure 3.10 an example of reduced geometry of an axial flux generator.](image)

The two dimensional model is introduced to solve the inherent three-dimensional harvester problem. The harvester can be assumed as solid cylinder with both rotating and stationary part embedded in to it. In the above Fig 3.10, ‘$l$’ is the straightened arc length from the center of the one pole to the next pole at the mean radius. If $R_1$ and $R_2$ represent the inner and outer radius of the permanent magnets and $p$ denotes the number of poles, then

$$l = \frac{\pi(R_1+R_2)}{p}$$

and the variable $x$ is related to the angle between the two poles by following relation:

$$x = \frac{\theta_1 p}{2\pi}$$
The magneto static field equations for regions are as follows:

\[ \nabla \times \vec{H} = 0 \]  \hspace{1cm} (3.5)

and

\[ \nabla \cdot \vec{B} = 0 \]  \hspace{1cm} (3.6)

where \( \vec{H} \) is the magnetic field strength \( \vec{B} \) and \( \Phi \) is the magnetic flux density. The magnetic flux can be given by the equation:

\[ \vec{H} = -\nabla \Phi \]  \hspace{1cm} (3.7)

which can be reduced to second order scalar equation:

\[ \nabla^2 \Phi = \frac{\mu_0}{\mu} \nabla \cdot \vec{M} \]  \hspace{1cm} (3.8)

This equation can be applied to the reduced geometry model described above. The amount of flux passing through the air gap is dependent on the magnetization of the PM magnets. The harvester is divided into the three regions namely, region 1, region 2, region 3. The magnetization vectors in those regions can be defined by following relations:

\[ M'_s = \begin{cases} M_y & \text{(region1)} \\ -M_y & \text{(region2)} \\ 0 & \text{(region3)} \end{cases} \]  \hspace{1cm} (3.9)

Since the magnetization \( M \) is constant, the equation 4 reduces to equation 6 for all the regions.

\[ \nabla^2 \Phi = 0 \]  \hspace{1cm} (3.10)

A) **Boundary conditions:**

The Y-axis, line \( x=l \) and line \( y=h \) represents the line of symmetry for the field, along which the normal component of the H-field will be zero. The tangential component of H-field is continuous at magnet and gap interface.

B) **The Field Formula:** The complete solution for the magnetic flux distributed in the air gap region is given by:

\[ \Phi_{\text{gap}}(x, y) = \frac{4l \mu_0 M_s}{\mu} \sum_{n=1,3,5,\ldots}^{\infty} \frac{(-1)^{n-1/2}}{(n\pi)^2 k(n,h,g,l,\mu)} \times \sinh \left( \frac{n\pi x}{l} \right) \cos \left( \frac{n\pi x}{l} \right) \]  \hspace{1cm} (3.11)
and therefore the axial component of the B-field in the air gap region is given as:

\[ B_{gap}(x, y) = \frac{4\mu_0^2 M_s}{\mu} \sum_{n=1,3,5}^{\infty} \frac{(-1)^{n-1/2}}{(n\pi k(n,l,m))} \times \cosh \left( \frac{n\pi x}{l} \right) \cos \left( \frac{n\pi x}{l} \right) \]  

(3.12)

and \( k \) is given by the following equation is

\[ k(n, h, g, l, \mu) = \frac{-\mu_0}{\mu} \cosh \left( \frac{n\pi g}{l} \right) + \sinh \left( \frac{n\pi g}{l} \right) \coth \left( \frac{n\pi (g-h)}{l} \right) \]  

(3.13)

where \( y \) is the vertical distance from lower plate of the coil and the other variables are as follows:

- \( M_s \) = magnetization (A/m)
- \( g \) = gap (m)
- \( t_m \) = height of magnet (m)
- \( h = g + t_m/2 \) (m)
- \( \mu_0 = 4\pi \times 10^{-7} \) (Wb/A-m) or (T-m/A)
- \( p \) = Number of poles, where \( k(n, h, g, l, \mu) \) is expressed in the equation (3.13) and can be implemented in Matlab software for the given parameters.

### 3.3.3 Computation of no-load voltage

According to the Faraday’s law of electromagnetism, the emf developed across of coil of \( N \) turns is given by:

\[ emf = -N \frac{db}{dt} \]  

(3.14)

The above equation can be further simplified as

\[ E_f = 2\pi f NB_{avg} A \]  

(3.15)

where \( B_{avg} \) is the average magnetic flux density exited per pole by permanent magnets which is given by following relation

\[ B_{avg} = \frac{1}{\pi/p} \int_0^{\pi/p} B_{gap} \sin(p\alpha) d\alpha = \frac{2}{\pi} B_{gap} \]  

(3.16)

where \( B_{gap} \) is the maximum peak density in the air gap region and \( f \) is the electrical frequency of the harvester. So the rms voltage across the \( M \) number of coil connected in series is given as
$E_f = M_{coils} \times \pi \sqrt{2} f N B_{avg} A \tag{3.17}$

where $A$ is the area of the coil.

The equation (14) shows that emf is directly proportional to electrical frequency, which is also dependent on the angular frequency of rotation given by following relation:

$$N_{rev} = \frac{120f}{p} \tag{3.18}$$

where $N_{rev}$ is revolutions per minute.

The angular speed of the harvester is directly proportional to the linear speed by the following relation:

$$v = r \times \omega \tag{3.19}$$

whereas $f$ is the angular speed in rev/seconds. Fig. 3.11 shows the relation between the angular speed and linear velocity.

![Figure 3.11 Angular Speeds versus Linear Speed](image)

Thus, the harvester’s output power is dependent on the linear speed, magnetization of the magnets, air gap, and the coil core characteristics such as hysteresis losses and amount of the magnetic flux present in the coil core.

The total power generated by the harvester is given by following relation:
\[ P_{output} = V_{rms} \times I_{rms} \]  

(3.20)

Thus, the harvester’s output power is dependent on the linear speed, magnetization of the magnets, air gap, and the coil core characteristics such as hysteresis losses and amount of the magnetic flux present in the coil core.

### 3.3.4 Finite element method

For finding the accurate solution of the problem, FEA simulation is a useful tool. At present, several commercial 2D/3D finite element soft wares are available, and can be used for the electromagnetic analysis of the harvester. The FEM method subdivides the described geometry into portions for which a particular equation is valid. Each of these portions is further subdivided into a large amount of smaller elements, called finite elements. Normally, the large geometry is subdivided into a single pole-pair and 2D finite element analysis is used to solve for the field solution. However, the energy harvester had much more complex geometry and hence complete 3D finite element analysis was solved. The 3D FEM takes into account the 3D effects appearing in the electromagnetic simulation. Thus, 3D FEM model is more accurate than 2D simulation. 3D FEA simulation also provides information about flux leakages, which are otherwise difficult to calculate.

![Figure 3.12. Mesh model of the harvester](image-url)
The harvester is modeled in the standard FEA simulation software ANSYS Maxwell™. The advantage of FEA software simulation is as it acts as a powerful tool to understand the transient response of the model. The coil core is modeled with relative permeability $\mu = 1000$, with air gap on both sides fixed to $g = 1.5\text{mm}$. The DC resistance of each coil is set to 1.2ohms. The FEA transient analysis is calculated at different RPM values (500, 1000, 1500 and 2000 RPMs) to check the consistency of theoretical and measured output. The total numbers of Mesh elements in simulation were 82884. The real time for one simulation was 18 minutes and 36 seconds and the total simulation time is 4 hours. The number of coils and coil terminals is 16 and the number of turns in each coil is set to 183 in the simulation. The no load and short circuit tests are used to determine the back-emf and current in the harvester. The results of FEA simulation are described in the experimental results section.

![Magnetic flux density distribution in the harvester.](image)

**Figure 3.13. Magnetic flux density distribution in the harvester.**

### 3.4 Experimental Results

The block diagram of the experimental setup is shown in Fig. 3.14. A milling machine is used to simulate the rotation motion of the wheels. The harvester is fixed to the base, and the wheel of the harvester touches the spindle in such a way that when spindle rotates, it imparts its
rotational motion to the wheel. The milling machine can control the rotation speed of the harvester wheel.

To test the theory, FEA simulation and experimental tests were conducted. The results of theory matched well with FEA and measurement results. The experimental results of the test are described below. Fig. 3.15 indicates the flux linkage in the harvester as a function of time. The flux linkage is calculated by FEA simulation software.

![Figure 3.14. Experimental Setup](image)

![Figure 3.15. Flux linkage versus Time](image)
Fig. 3.16 indicates the comparison of output voltage $V_{\text{rms}}$ of the harvester with different models.

![Figure 3.16 Output Voltage $V_{\text{rms}}$ versus Angular speed](image)

*Figure 3.16 Output Voltage $V_{\text{rms}}$ versus Angular speed*

Both the theoretical and FEA models have shown good agreement with measured results. The device generated maximum voltage of 6 volts at frequency of 100 Hz and achieved maximum output power of 1.992 W. The device generated maximum power of 2.4W at frequency of 110 Hz. Fig. 3.17 shows the relation of output current and angular speed. The harvester achieved 335 mA at frequency of 110 Hz.

![Figure 3.17 Output Current versus Angular speed](image)

*Figure 3.17 Output Current versus Angular speed*
The output current depends on the internal resistance of the coil, which is 1.2Ω. Higher power can be extracted if the DC resistance is further reduced. The total output power is directly proportional to the angular frequency. The average speed of roller skate lies between 11(miles/hour) to 13(miles/hour). The harvester frequency bandwidth lies between 75Hz (1500 RPMs) to 300 Hz (6000 RPMs), depending upon the linear movement of the skate. Fig. 3.18 indicates total power harvested from skate for the frequency ranging from 0 Hz to 110 Hz (2200 RPMs). The harvester units on the each leg are connected in series and the total output power is measured directly by using open circuit no load voltage and short circuit current tests. The FEA simulation that is carried out at higher speed showed that the device has good potential to generate higher amounts of power at higher speeds.

![Figure. 3.18 Total output power versus Angular speed for the all the 4 energy-harvesting units connected in the series combination and Power density present in one of the harvesters](image)

Fig. 3.18 shows the relationship between power density and angular speed. The power density is directly proportional to frequency. The volume of a single harvester is 51.6 cm³, where outer diameter ⌀ is 2.39 cm and inner diameter ⌀ is 1.61 cm and the height of the device is 5.27 cm. A single harvester achieves the power density of 41 mW/cm³ at the rotational frequency of 110
Hz (2200 RPMs) and the power density is 49 mW/cm$^3$ at frequency of 125 Hz (2500 RPMs).

Thus the device achieves a significantly high power density at moderate linear speeds.

![Output voltage waveform](image)

*Figure 3.19 Output voltage waveform at $f = 100$Hz / (2000RPM) / (linear velocity = 9.42 miles/hour).*

The Fig. 3.19 shows the comparison of output waveform measured by oscilloscope and FEA simulation output waveform.

### 3.5. Conclusion

Table 1 is a summary of the published research work in the rotational energy harvesters and micro generators. Clearly, the new magnetic energy harvester demonstrated a very high power density at moderate speeds compared to piezoelectric and other harvesting mechanisms. The proposed new magnetic energy harvesters have great value for practical applications in wireless sensor networks. Further improvement on the performance of our energy harvester design can be achieved with specially designed inductors using highly permeable magnetic cores such as Metglas™ with high quality factors, larger inductance.
### Table 3.3 Comparisons of Rotational Energy Harvesters

<table>
<thead>
<tr>
<th>Rotational Generators</th>
<th>OD(^a) (mm)</th>
<th>ID(^b) (mm)</th>
<th>T(^c) (mm)</th>
<th>Generator Volume (cm(^3))</th>
<th>Rotational Speed (krpm)</th>
<th>No-Load Voltage (V)</th>
<th>Max Power (W)</th>
<th>Power Density (W/cm(^3))</th>
<th>Normalized Power Density (W/cm(^3).krpms(^2))</th>
<th>Refs</th>
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<tr>
<td>Imperial College</td>
<td>7</td>
<td>4</td>
<td>1.6</td>
<td>0.041</td>
<td>30</td>
<td>0.42</td>
<td>0.0011</td>
<td>0.027</td>
<td>2.9 x 10(^{-5})</td>
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<td>Katholieke U. Leuven</td>
<td>16</td>
<td>0</td>
<td>28</td>
<td>5.63</td>
<td>100</td>
<td>--</td>
<td>16</td>
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<td>2.8 x 10(^{-4})</td>
<td>27</td>
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<tr>
<td>Kinetron MG861</td>
<td>8.8</td>
<td>0</td>
<td>2.75</td>
<td>0.167</td>
<td>5</td>
<td>2.1</td>
<td>0.006</td>
<td>0.036</td>
<td>1.4 x 10(^{-3})</td>
<td>27</td>
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<tr>
<td>Kinetron MG204</td>
<td>4.0</td>
<td>0</td>
<td>2.2</td>
<td>0.028</td>
<td>5</td>
<td>1.8</td>
<td>0.010</td>
<td>0.36</td>
<td>1.4 x 10(^{-2})</td>
<td>27</td>
</tr>
<tr>
<td>Kinetron MG401</td>
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<td>4.4</td>
<td>0.142</td>
<td>5</td>
<td>2.1</td>
<td>0.015</td>
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<td>27</td>
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<td>5</td>
<td>5.3</td>
<td>0.110</td>
<td>0.038</td>
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<td>27</td>
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<td>3.3</td>
<td>2.1</td>
<td>0.140</td>
<td>0.049</td>
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</tr>
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<td>UC-Berkeley</td>
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<td>--</td>
<td>1.0</td>
<td>13.3</td>
<td>1.86</td>
<td>3.8 x 10(^{4})</td>
<td>3.8 x 10(^{4})</td>
<td>2.1 x 10(^{-6})</td>
<td>27</td>
</tr>
<tr>
<td>ETH Zurich/ATE</td>
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<td>0</td>
<td>15</td>
<td>3.0</td>
<td>50</td>
<td>1.13</td>
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<td>LEG</td>
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<td>4</td>
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<td>380</td>
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<td>5.0</td>
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<td>3.2</td>
<td>2.3</td>
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<td>0.5</td>
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</tr>
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<td>305</td>
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<td>8.0</td>
<td>59</td>
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<td>27</td>
</tr>
<tr>
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<td>0</td>
<td>2.1</td>
<td>0.0066</td>
<td>392</td>
<td>0.051</td>
<td>0.0036</td>
<td>0.55</td>
<td>3.5 x 10(^{-6})</td>
<td>27</td>
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<tr>
<td>Nat Sun Yat-Sun U.</td>
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<td>2</td>
<td>2</td>
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<td>2.2</td>
<td>0.079</td>
<td>4.1 x 10(^{4})</td>
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<td>Northeastern University</td>
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<td>32.2</td>
<td>52.7</td>
<td>51.6</td>
<td>2.2</td>
<td>6.73</td>
<td>2.53</td>
<td>0.049</td>
<td>1.01 x 10(^{-2})</td>
<td>27</td>
</tr>
</tbody>
</table>

\(^a\)OD = outer diameter, ID = inner diameter, and T = thickness for active generator components
POWER MANAGEMENT ELECTRONICS

4.1 Introduction

In the low power systems like energy harvesting systems, power management is very critical for proper functioning of the device. The power electronics is often a circuit that conditions the output of energy harvester to the load resistance or a battery. The power electronics circuitry should be able to switch on and switch off the device in a low power state, and effectively charge the battery. Therefore, power electronics plays fundamental role in an energy harvesting system, than simply managing a battery and conserving energy. From the review presented in the chapter 2, the power management electronics should serves following purpose:

1) To achieve high output power density, the power electronics circuit should be able to form impedance match between the energy harvester and the electric load.

2) The output voltage of the energy harvester varies very frequently and rarely compatible with load electronics circuit, and hence proper regulation is needed.

3) An intermittent energy source is major requirement for self-sufficient energy harvesting systems.

Typical power processing stages for an energy harvesting systems is shown in the Fig. 4.1.

![Figure. 4.1 Power processing stages in an energy harvesting system](image-url)
4.1.1 Energy Transfer Requirements

In order to ensure the energy produced in the energy harvester is efficiently transferred to the load, there has to be maximum power transfer from the input energy source to the load connected in the output. The fundamental requirement of the maximum power transfer requires the impedance of the input source is matched with the impedance of the load. If the load resistance is very large or greater than the resistance ($R_{source}$), the energy harvester cannot achieve the maximum efficiency. The maximum DC power transfer occurs only when the DC resistance is equal to the source resistance. In the case of the AC voltage source, the load should provide the complex conjugate match to the source. The source impedance will be dependent upon the type of the energy harvester used and the conditions under which it is used.

![Diagram](image)

Figure 4.2 (a) the requirements for the maximum efficiency of energy transfer from the source to load (b) the condition for the maximum power transfer (c) Equivalent model with imaginary and real parts
The efficiency of the energy harvesting is thus dependent on the power transfer in the system, as the source of the energy to the source is limitless, and thus effectively free. This essentially sets the goal of transfer the energy to load more effectively, rather than accomplishing the energy transfer at a high efficiency. In an energy harvesting transducer, the impedance of the source to which load should be matched does not necessarily means the electrical impedance of the source. As the source impedance also varies with the type of the harvesting technology used and the condition of the environment in which the energy harvester is operating. The harvester model is often depicted as an equivalent electrical circuit model. The mechanical components in the harvester are converted to its electrical equivalent. Vibration-driven energy harvester have source models that takes into account the mechanical properties of the system such as mass, spring, and the characteristics of the vibration source.

4.2 Equivalent Circuit models for Motion-Driven Energy Harvesters

The model of energy harvester is essential during the system design. The suitable source model of an energy harvesting system enables to determine an optimal electrical load. The overall aim of an energy harvesting system is to deliver power to an optimal load, it is sensible to build a source model of a motion driven energy harvesting system. The two examples of the equivalent models are shown in Fig. 4.3 [44].

The circuit showed in the Fig. 4.3 shows equivalent models for vibration-driven energy harvester using electromagnetic and piezoelectric damping. The current source in the Fig. 4.3 (a) models the energy from the vibration source feed in to the system. The inductor, capacitor and resistor connected to the primary of the transformer models the mechanics of the vibration energy harvester. The capacitor represents the mass of attached to the energy harvest, the inductor represents the spring, and the resistance depicts the parasitic damping. The voltage source in the Fig. 4.3 (b) represents the vibration source, the inductor represents the mass, the capacitor represents the spring and the resistor represents the parasitic damping. The transformer functions
as coupling between the mechanical and electrical domain. In Fig. 4.3 (a), voltages across the component on the left of primary winding represent the velocity and the current flowing through them represents the force applied to them. Similarly the vice versa is true is for Fig. 4.3 (b). The terminals of the secondary winding of the transformer represent the physical terminals of the energy harvester, to which the interface power electronics circuit can be connected.

The fundamental energy stored in the inductor and capacitor places a limit on the maximum power transferred to the load. The energy stored in the inductor is depends on the self-inductance and the DC resistance of the coils, as result the energy stored in them is always less than the total power extracted by the source. The models represent in Fig. 4.3 are linear circuit model, however the real life energy harvester is non-linear system, mainly because of the inductor and capacitor,
whose inductances and capacitance are not always constant. It is clear that the maximum power transfer will occur only when the circuit is operated on frequency at which the inductor and the capacitor resonates and the load resistance is equal to the parasitic damping of the energy harvester.

Therefore, in order to ensure a maximum efficiency, the power converter connected to the terminal of the energy harvester should feed the energy to load, and at same time maintain its input impedance. The different resistance value exists when the generator operates at frequency different from the resonant frequency, and hence the power converter should be able to present optimal impedance to the electrical terminals of the micro-generator, in all the cases. Fig. 4.4 shows the different power processing stages in the energy harvesting system.

The Fig. 4.5 gives a general idea of the different stages in the energy harvesting systems. Depending on the energy harvesting mechanisms, the power processing stages may vary.

**4.2.1 Electronics for Electromagnetic Harvesters**

The electromagnetic energy harvesters employ the principle of electromagnetism in their operation. The output of the electromagnetic energy harvester can vary from very low AC voltages to very high AC voltages. Therefore, the general requirements for a power electronics circuit interfaced with an electromagnetic energy harvester can be summarized as follows:

1) Voltage step-up capability in case of very low output AC voltages from the harvester.
2) Proper impedance matching between the input of the power circuit and the output of the harvester. Generally, the reactance of the inductive component in the electromagnetic energy harvester is low at very low frequency.

3) Rectification of AC to DC and the output voltage regulation.

The simplest interface for an electromagnetic energy harvester consists of a step-up transformer, which feed a full wave rectifier. Due to the sinusoidal nature of the electromagnetic energy harvester, the output is generally AC, which requires need for a rectifier. Step-up transformer can be used to increase the very low voltage (tens or hundreds of mV) to appropriate level. However, the usage of step-up transformer introduces parasitic resistances and reactance. These parasitic resistive elements further contribute to the losses in the power conversion. The full wave rectifier with Schottky diodes rectifies the stepped up AC voltage to DC power. This technique of using a full wave rectifier is quite prevalent.

![Electromagnetic Harvester Schematic](Image)

*Figure. 4.6 Schematic of an electromagnetic energy harvester with a transformer and rectifier, reproduced from [45]*

In the configuration used in Fig. 4.6, only one diode conducts during the one half cycles of the input AC signal. This particular approach is convenient because using a full wave rectifier, in place of a bridge rectifier nullifies the losses across two more diodes present in the bridge rectifier. However, this configuration does not provide proper impedance matching, and hence
maximum power transform is not achieved. Nevertheless, the approach is very simple in nature, and it is particularly advantageous. Voltage stepping requires a transformer, which induces substantial power loss in the circuit. Given that the harvester generates little power, the introduction of losses is highly undesirable. The addition of power losses in the harvester, significantly decreases the total power available to the load. The transformer losses can be very significant, and it is desirable to avoid rectification stage with step-up transformers. Another approach for stepping up voltages is using a voltage multiplier circuits like Villard multiplier (Fig. 4.7) and the Dickson multipliers. Several voltage multiplier s can be cascaded together to result in desired step voltage. This arrangement has advantage of reducing the parasitic reactance, by not using the magnetic components present in the transformer. This approach also does not provide impedance matching. Mitcheson et al. [46] proposed a dual polarity boost converter that interfaces an electromagnetic generator with potential solution to provide rectification, an impedance match, and voltage step-up and output voltage regulation all in one circuit.

![Figure 4.7 Villard Voltage multiplier used for stepping-up the energy harvester voltage, reproduced from [47]](image)

This converter circuit as shown in Fig. 4.8 could achieve low voltage rectification of the positive and negative half cycles. The boost converters are activated alternatively to rectify AC voltage from the harvester output.
Sun and Lehman et al. [48] showed a new type of boost converter circuit, which could harness power from the harvester without the need of boost inductors. This elimination of the boost inductors reduces the power losses in the boost converter [48]. Additionally, the dual polarity nature of this circuit removes the need of bridge rectifier. Their circuit performs voltage step up, if the input voltage is insufficient to supply a CMOS device directly. The authors proposed the use of Schottky diode to reduce the power loss in the converter. In [49], Maurath et al. reported on an adaptive impedance matching technique, which utilized switched capacitor arrays. Their circuit consumed less than 50 µW of power and showed that self-powered applications for energy harvester can be achieved. Amirtharajah and Chandrakasan develop a digital signal processing (DSP) circuits have a low power voltage regulator which was powered by its own electromagnetic energy harvester [50]. However, this paper does not discuss the concept of the maximum power transfer, and it could potentially hinder performance of the device. From, the review conducted in this section, the power electronics circuits with very good control and precise impedance matching, can increase the efficiency of an electromagnetic energy harvester.
4.2.2 Electronics for Piezoelectric Harvesters

The equivalent circuit of vibration-driven piezoelectric circuit is shown in Fig. 4.3 (b). The maximum power that can be extracted from the circuit in Fig. 4.3 (b) is possible when the power circuit sets its input impedance to $1/D_p$, at the generator’s resonant frequency. The power extraction is however much more complicated, because the capacitance of the piezoelectric energy harvester is not always constant. The shunt capacitance of the piezoelectric harvester should not be neglected in any cases. The conventional approach for impedance matching is utilizing a shunt inductor, which tunes out the parasitic capacitance, thus preventing the proof mass from dissipating energy at the end-stops. The early work on the power management of the piezoelectric harvester made use of this resistive match to maximize the power output. Recent approaches have attempted to overcome this limitation by using timed switch element. The power output of the piezoelectric harvester can be increased by two possible approaches:

1) Applying bias to piezoelectric material before the mechanical work is done.

2) Synchronization of charge extraction from the piezoelectric material instead of continuous extraction.

Bias application can be explained as when a piezoelectric material is strained in one direction, it opposes by applying a force, which tries to move the material back to its original position. So, if a charge is placed on the material then the material is forced to move in other direction by the applied force from strain, hence the material does more mechanical work, as the force exerted by the piezoelectric material has increased substantially, and as a consequence more electrical energy is released. This phenomenon is illustrated in Fig. 4.9.
When the piezoelectric cantilever as shown in figure is upward direction to its maximum possible displacement, a positive charge is generated across it. So, when a negative bias voltage is applied it causes the cantilever to deflect in the direction opposite to its original state. Similarly, the vice-versa is true. Guyomar et al. applied this technique in the low power energy harvesting, and they report an approximately nine fold increase in output power in [52]. The piezoelectric harvester was connected to a bridge rectifier and filtering capacitor, to produce a DC power output. Garbuio et al. present in [53], that by using synchronized switching on inductor with magnetic rectifier (SSHI-MR). Their circuit utilized a transformer with greater turns ratio. The transformer with two anti-parallel windings, allowed the conversion of the AC signal voltage to DC. The switches were used in such a way that when the displacement of piezoelectric material reaches its maximum, and minimum points. The authors reported that switches opened at half of the resonant time period of $\sqrt{LC_0}$, which rises due the series combination of L and $C_0$. 
In the above Fig. 4.11, the transformer is used to lower the threshold at which the diode conducts. The new threshold value for the conduction of diode is $V_0/m$ where $m$ is the turns ratio of the transformer, which thus reduces the threshold of the diode conduction losses, when compared with full diode bridge rectifier. The harvester reported in [53] had diameter of 24 mm and thickness of 0.04 mm. The harvester’s SSHI-MR technique produced 400 $\mu$W of power when the input vibration frequency was set at 1 kHz, and the displacement amplitude at 23 $\mu$m. The author reported that SSHI-MR technique consumed 5% percent of the total power harvested, thus allowing a self-sufficient energy harvesting system. The power from the harvester is 56 times greater than what could have been harvested if a conventional diode bridge rectifier circuit is used.

Dicken et al. presented a new approach of combining synchronous charge extraction circuit and pre-biasing of the piezoelectric element to increase the power harvested from piezoelectric harvesting units [51]. The advantage of this approach is that it isolated the pre-bias and piezoelectric generation cycle from the output side circuitry. The circuit prototype is shown in Fig. 4.12.
In the above circuit, the MOSFET’s 1 and 4 are used for pre-biasing the piezoelectric harvester and power is extracted using MOSFET’s 5 and 6. The main function of the diode is to recover the energy stored in the inductors to the power supply.

Lefeuvre et al. showed a power optimization method using the buck-boost converters to harvest energy from ambient mechanical vibrations [54]. Their circuit included a diode rectifier and smoothing capacitor between the harvester and the buck-boost converter. The advantage of the buck boost converter is that it is capable of stepping up and down the voltages. In the experimental test, the authors were successful in performing an impedance match of 12 kΩ with in a range of -6% to 37%.

4.2.3 Electronics for the Electrostatic Harvesters

The electrostatic energy harvester typically uses a moving plate capacitor in order to convert kinetic energy to electrical energy. Since the value of the capacitor fluctuates a lot, and it is non-constant, it is very difficult to build a linear circuit component model of the electrostatic energy
harvester. The impedance match of an electrostatic energy harvested can be realized by determining the conditions for the optimal operations of the energy harvester from the capacitor voltage. The two main techniques, which have been reported in the research publications, are: switched systems and continuous systems [55]. The switch systems can be further divided into two main types: Constant charge and Constant Voltage.

In constant charge application, the charge across the capacitor remains constant; whereas the voltage across the capacitor varies. In the constant voltage application, the external voltage is permanently connected to the capacitor, as a result the voltage across the capacitor remains constant, and the charge across the capacitor varies in relation to the mechanical vibration subjected to the capacitor.

4.2.3.1 Constant Charge Operation

Mitcheson et al. reported a MEMS-fabricated electrostatic energy harvester in the constant charge operation [56]. The prototype was fabricated using deep reactive-ion etching and the capacitor plate area was 200 mm$^2$. The time for charging the capacitor is 50 ms, and the maximum capacitance occurs at 30 V. As the charge is constant, the voltage across the capacitor varies, as the plates are separated due to the source motion. The generator reported in [56] produce power of 12 µJ from an input motion of 40 Hz and 6 mm displacement amplitude. A power conversion circuit for this generator is half-bridge step down circuit, which was reported by Stark et al [57], shown in Fig. 4.13.
The operation of the above circuit can be explained in three ways: charging of the diode, magnetization of the inductor, and freewheeling through diode. The converter is used in the single-pulse mode operations, because the source is so weak, that it gets discharged in few nanoseconds. When the MOSFET is turned on, the current starts to flow into the diode, and the diode becomes reverse biased, which as consequently reduces the voltage across the MOSFET. During the second phase, the current through the inductor start increasing and hence the voltage across the generator keeps falling until it is completely discharged. In the last stage, the current freewheels through the diode until the inductor is demagnetized.

4.2.3.2 Constant Voltage operations

In this section, charging circuit for the constant voltage electrostatic harvesters will be discussed briefly. The modified charge pump circuit [58] is shown in the Fig. 4.14. The diodes are often having forward conducting losses, and hence they are replaced by the active switches. The load and control electronics consist of a delay-locked-loop (DLL), which enables the energy conversion from the mechanical domain, to the electrical domain. The DLL is capable of synchronizing the energy extraction to the source vibration frequency. The reference clock gets
locked in phase with the motion of the generator’s moving plate, which generates the timing pulse for the MOSFET switches SW1 and SW2. During the discharging, the switching sequence is opposite of the charging one. The Spice simulation of the electrostatic generator was predicted to produce the 8.6 $\mu$W.

![Figure 4.14. A modified charge pump circuit that uses active MOSFET switches, reproduced from [58]](image)

### 4.2.3.3 Continuous Systems

In continuous systems, an electrostatic energy harvester is always connected to the load and voltage source that provides the polarization voltage. The operation of these systems can be explained as follows: When the electrodes of the capacitor are physically moved, the capacitance of the capacitor changes, and hence the charge flows through the electrodes to the load. The continuous system offers an advantage over the switched system in way that the control circuit used for controlling the switches often consumes some of the generated power.

![Figure 4.15. Schematic of a variable capacitance electrostatic harvester, reproduced from [59]](image)
Sterken et al. demonstrated in [59-60] that continuous system could be implement using a variable capacitor. The micro-machined prototype of an area 0.1 cm² electrostatic generator was predicted to be able to generate 50 µW. When an electret charges the moving plate of the capacitor up to 50 V, so that clamp down suspended by meandered beams that perform function of a spring. The displacement of the moving plate changes its capacitance and charge, thus the current flows through the load resistor.

Figure 4.16 Cross section of the electrostatic energy harvester, reproduced from [60].

4.3 Conclusion

The power electronics circuit for the electromagnetic energy harvester has to perform voltage rectification and step–up because of the low AC voltage generated by the harvester. In some recent publication of research work, Schottky diode full wave rectifiers and dual polarity boost converters carried out the rectification. The diode bridge rectifier are not suitable for the energy harvesting applications, as the power loss present in them is high, because of the presence of two
extra diodes. The maximum power transfer for electromagnetic energy harvester requires an impedance matching between the coil and load resistance.

The major work on power electronics circuitry for vibration-driven energy harvester is been on the piezoelectric transducers. The output voltage from the piezoelectric energy harvester is comparatively high, and hence interfacing electronics become very easy. The optimization of the resistive load is very important, and an impedance match in the form of an optimized resistive load will result in maximum power transfer from the harvester to the load. Several tuning can be employed while design the harvester to increase the frequency response of the harvester. The use of pre-biasing and timed switches to synchronously extract the energy increases the output power. The electrostatic energy harvester typically generate high output voltages at low currents, hence the power electronics circuitry for the electrostatic generator require step-down converter. The output impedance of the transducer is determined by the capacitance of the capacitor in the structure. The capacitance of the system varies as function of the mechanical force. In electrostatic energy harvester require pre-charge voltage application for the proper functioning of it. The continuous electrostatic systems are preferred because of their relative simplicity, compared to their switch counterparts.
5.1 Requirements for Power Generation

In this section, the condition for the stable power generation from the energy harvester will be discussed in detail. The proper conditions for determining the amount of the usable power extracted from the energy harvester that can be pushed into an energy storage element or dissipated into a load should be study. The careful consideration should be given to the equivalent electrical circuit of the generator. The DC model of the rotational energy harvester is shown in Fig. 5.1

![Diagram of DC model of the rotational energy harvester](image)

*Figure 5.1 DC model of the rotational energy harvester.*

The rotor of the harvester rotates and thus it generates current in the coils, as the load draws this current when it is connected to the output of the rotational harvester, it acts against the torque
generated the rotor motion, and hence the work is performed against this work. For any particular
generator, the torque is directly proportional to angular frequency. As the load draws more
current form the harvester, it opposes the generator torque, and ultimately, it stops the rotational
motion of the harvester. Hence, the load resistance should be selected such that it ensures
maximum current is drawn from the armature winding or coils in the harvester. The impedance of
the harvester depends on two factors, firstly the DC resistance of the coils, and secondly the
armature reactance or the reactance offered by the inductor used in the coil. But, the energy
harvester often operates at very low frequency, so the armature or inductor reactance is very
small, and it can be neglected. But, as the frequency of the rotation increase, the armature
reactance also increases, and hence it becomes very much essential for the power circuit to
provide good impedance match. The inductor Q factor is another vital factor, which determines
the output power coming out from the rotational energy harvester. However, the control on the Q
factor inductor is very difficult to achieve at such low frequencies. The maximum power transfer
is achieved when the load resistance is equal to the total reactance offered by generator. The
above condition hold true for any given rotation speed and generated voltage $V_G$. Therefore,
power circuits for the rotational energy harvester should satisfy following conditions:

1) It should be able to closely match the load impedance and the harvester impedance.

2) Rectification of AC signals to DC signal.

3) In case of low voltage, power interface circuit should be able to step up the input
   voltages.

4) The power losses in the power circuit should be extremely less.

5) It should provide a regulated output power over wide frequency range.

The following guidelines have served the motivation for the thesis work presented in these
sections. Two different prototype circuits were tested on the rotational energy harvester and their
analysis is discussed in the subsequent sections. The prototype circuits have shown considerable
good improvement in the output power supplied to the load. The prototype circuits have shown good agreement with increasing rotation speeds and under matched load conditions.

### 5.2 Interface Electronics topology

Based on the objectives mentioned in the previous section, the load resistor should be able to adapt itself to dynamically changing host rotation speed and generated voltage. This condition can be accomplished by placing a circuit that could change the load impedance according to the variation in the energy harvester. This interface circuit should guarantee, that maximum energy is transferred under all operating conditions, for a given armature resistance, source rotation speed and setup. The interface circuits often use controlling algorithms, which enable the proper impedance match by controlling the input impedance of the interface circuit. However, it is highly desirable to design an interface circuit, which doesn’t require an external control circuitry.

The output of the interface circuit is connected to the storage element, which acts an intermediate power supply to the external load, which can be a battery, WSN network chip or a microcontroller circuit. The addition of the storage circuit require regulated converter, since the output from any energy harvesting system often fluctuate a lot. The main function of an interface circuit is to provide matched input impedance, and it should be able to push the charge into a storage element very effectively. The topology used in interface electronics is shown in Fig. 5.2.

![Figure 5.2 Topology of the interface electronics for the rotational generator](image-url)
The topology presented in the above is most commonly used. The advantage of using the boost converter is that it is able to smooth the input current, and as a result the input side of the boost converter appears to be resistive. The boost converter also steps up the voltage and the stores the excess energy in the storage elements, which can discharge at the times of low rotation speeds. The main purpose of the storage element is to store energy at time when the harvester is producing sufficiently large power, and utilize that energy when the harvester power output drop to low level. The regulated buck converter can be utilized to provide a constant voltage to the load. The regulator should have very good flexibility in regards to its input parameter, because the output of the storage device changes depending on its charging and discharging cycles.

The rotational generator can generate 500 mW of power under proper matched conditions. The output power is also the fundamental function of the rotation speed. The other factors affecting the amount of total power available is the power losses in the various stages of the interface circuits.

### 5.3 Dual Polarity Boost Converter

The main challenge in designing an electromagnetic energy harvesting system is how to increase the power output and power density. There are two approaches, which can be used to achieve this goal. The first approach is discussed in Chapter 3. The second approach is maximizing the power delivered through by using an efficient interface circuit. The difficulty of extracting the energy from magnetic harvester is that they produce low AC voltages typically in frequency range of 40 Hz to 100 Hz’s. The step up transformer cannot be used in such applications because they induce losses. The size of the transformer is bulky, which increases the volume of the system. The voltage requirement for low power semiconductor devices like Schottky diode is around 0.3 V. Thus, the harvester has to provide at least 0.3 V AC supply to the interface circuit in order to ensure proper functioning of the circuit So, a new dual polarity boost converter was proposed. The approach used in the converter is to utilize the leakage inductance of the inductor coils in the
magnetic energy harvester, and hence the need for external boost inductor is removed. The coils used in the harvester are center-tapped and the output terminal of these coils is fed to two Schottky diodes. The coil inductance is high, and hence the leakage inductance of the inductor is high even at low frequency level. This approach greatly reduces the additional power losses induced in the circuit by addition of the boost inductors, and also there has been decrease in the total device volume, which is very highly desirable. Absence of a Bi-directional switch also further reduces the power losses. The Figure 5.3 shows the equivalent circuit of the inductive magnetic energy harvester [48].

![Figure 5.3 Equivalent model of inductive magnetic energy harvester reproduced from [48] will be discussed in detail in Qian Sun’s upcoming PhD Thesis.](image)

In the above figure [48] \(i_s\) is the current flowing through the source, and \(i_m\) is the excitation current, which flows through the magnetizing inductance. The air gap flux density is not very uniform in the harvesters, and the permeability of the core is also finite. Hence the small amount of leakage flux is present in the inductor. The author reports that the leakage flux depends on the magnetic flux from the magnets flowing through the air gap, and the amount of flux saturating in the core. This leakage flux as modeled as \(L_k\) and \(L_w\). The air gap flux density is not uniform; the leakage flux from magnets is much larger than the leakage flux arising from coils. The resistance \(R_w\) is the winding resistance, and is connected in series with leakage inductance. The output voltage of the harvester is directly proportional to the number of turns in coils, and the resistance \(R_w\) increases as the number of turns increases. The winding resistance value is very large, and
hence it cannot be ignored. The large values of $R_w$ are undesirable, because they affect the efficiency of the harvester. The resistance $R_c$ parallel with $L_m$ represents eddy current loss and hysteresis loss. The core loss was very less and hence they were neglected in the analysis. Thus the values of the leakage inductance affect the operation of the harvester.

5.3.1 Working principle of the prototype converter

The winding resistance of the harvester is significantly large. The optimal operation of the boost converter requires very low winding resistance. The possible approach to reduce the winding resistance is by center tapping the coils. In [48], a new dual polarity boost converter is proposed that utilizes the leakage inductance of these center-tapped coils as the two boost inductors. A full wave rectifier comprising of Schottky diodes is attached to the output terminal of this leakage boost inductors. Since the design has reduced significantly the number of inductor components. This approach significantly removed the power losses in the circuit. The converter circuit is illustrated in Fig. 5.4.

![Dual polarity boost converter prototype circuit](image)

*Figure 5.4 Dual polarity boost converter prototype circuit reproduced from [48].*
Each diode operates during the half cycle of the input AC signal. The external control scheme is applied to the circuit to provide fixed duty cycle signal to the switching element in the circuit. During the positive half cycle the diode D1 and D3 works and thus output of the harvester is connected to the load. During the negative half cycle, the Diode D1 is switched off and Diode D2 is turned off, and hence the output current flows through D2 and D3. The converter circuit can work in the both discontinuous and continuous mode. The converter works in DCM mode when the input voltage is low, and when the input voltage increases, the converter transfers to CCM.

Table 5.1 and Table 5.2 give information about the harvester parameters and circuit parameter and power losses in the converter respectively.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induced Voltage</td>
<td>1 V</td>
</tr>
<tr>
<td>Air gap</td>
<td>3 mm</td>
</tr>
<tr>
<td>Magnet Diameter</td>
<td>7.9 mm</td>
</tr>
<tr>
<td>Number of Coils</td>
<td>4</td>
</tr>
<tr>
<td>Coil Inductance</td>
<td>1 mH</td>
</tr>
<tr>
<td>Coil Resistance</td>
<td>4.5 Ω</td>
</tr>
</tbody>
</table>

The magnetic energy harvester is designed with extreme less air gap, so that flux linkage of the coils and magnets is very high. The reduction in the air gap increases the leakage inductance decreases. The high output power requires very low leakage inductance. However, the harvester converter circuit suffers high power losses when the leakage inductance is small. Hence, maximum power cannot be obtained for both the harvester and converter at the same time $L_k$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Estimated Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage Inductance</td>
<td>2 mH</td>
<td>-</td>
</tr>
<tr>
<td>Winding resistance</td>
<td>4.7 Ω</td>
<td>0.113 mW</td>
</tr>
<tr>
<td>MOSFET</td>
<td>0.22 Ω</td>
<td>0.0045 mW</td>
</tr>
<tr>
<td>Output Capacitor</td>
<td>100 µF</td>
<td>-</td>
</tr>
<tr>
<td>Input Diodes</td>
<td>0.23 V</td>
<td>25.3 mW</td>
</tr>
<tr>
<td>Output Diode</td>
<td></td>
<td>4.5 mW</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>3.3 V</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 Circuit Parameter and Losses in the Converter

Reproduced from [48]. More details will be discussed in Qian Sun’s upcoming PhD thesis.
The main losses in the converter are due to winding resistance of the coils, since the converter does not utilize the external boost inductors and the switching losses in the MOSFET, and the losses due to the voltage drop across the output and input diodes.

5.3.2 Experimental Results

A milling machine is used to simulate the rotation motion of the wheels. The harvester is fixed to the base, and the wheel of the harvester touches the spindle in such a way that when spindle rotates, it imparts its rotational motion to the wheel. The milling machine can control the rotation speed of the harvester wheel. The block diagram of the experimental setup is shown in Fig. 3.14. Fig 5.5 and Fig. 5.6 show the output voltage measured with oscilloscope.

![Figure 5.5](image-url)

*Figure 5.5. Output voltage and Input current measured across the harvester.*

![Figure 5.6](image-url)

*Figure 5.6 measured output signal and gate signal applied to the converter.*
The frequency of the harvester’s rotation could vary from 0 Hz to 120 Hz with the help of the milling machine. The harvester output was measured under optimal resistance of 4.9Ω. The MOSFET used is low drive voltage (FDV305N manufacture by Fairchild Semiconductor Corp) and diode used in the converter circuit was Schottky diode (NSR0320 from ON Semiconductor Corp). The voltage drop across the diode is 0.23V. The converter was operated in open loop configuration with a fixed Duty cycle ratio of 0.85 at switching frequency of 25 kHz. The load resistance value connected across the harvester is 200Ω. The DC converter could supply voltage of 3.3V at 54 mW of total output power. The harvester produced maximum output power of 130 mW under optimal resistance of 4.9Ω.

5.4 Battery Charging Circuit for the Rotational Harvester

Although the Dual polarity boost converter prototype circuit lacks proper impedance matching mechanism, it has showed very good improvement in the amount of power delivered to the load resistance. The dual polarity boost converter circuit successfully delivered 130 mW of power to the load resistance. By replacing the boost converter stage with self-sustaining energy converter modules, this disadvantage of external gate supply circuit can be overcome. The approach used in this prototype is to implement a battery charging circuit with Advanced Linear Device’s energy harvesting module EH 301. The approach has showed some considerable improvement in the power delivered to the load resistance.

5.4.1 Advanced Linear Devices EH 301 module

The EH 301 Series EPAD® energy harvesting module can accept electrical energy and store the energy in the capacitor bank to power conventional 3.3 and 5.0V electrical circuits. The advantage is the EH 301; it is completely self-powered and always works in active mode. The module can accept instantaneous input voltage from 0.0 V to +/- 500 V AC or DC, and input currents from 200 nA to 400 mA. This wide flexibility in the input range makes them suitable for
energy harvesting application. The device module offers flexibility of providing varying input impedance to the energy harvester. The EH 301 series module actively operates to capture, accumulate, and conserve energy from the harvester. When the energy harvester starts to input energy into the EH 301 module, it starts to collect and accumulate the charge and stores it onto an internal storage capacitor bank. As the rotation of harvester drop to low voltage threshold, the EH 301 module’s internal capacitor storage bank delivers the power to load resistance. If the voltage of harvester is constant for the time more than sample time, the EH 301 harvester rectifies it and couples the harvester output power to the load resistance. The EH 301 can cycle within 4 minute at an average input current of 10 mA and within 40 minutes at an average input current of 1.0 mA.

5.4.2 Working Principle

When the harvester output power is applied to the EH 301 module, then it start to collect the charge and stores it in the internal capacitor storage bank. The EH 301 modules voltage on the onboard storage capacitor bank is +V, which is the positive supply voltage switched to power the output power load. Initially the modules start at 0.0V, i.e. when there is no input supply voltage. As the harvester starts to inject power into the EH 301 converter circuit, the onboard capacitor voltage starts charging from 0.0 V. The module’s internal circuit monitors and detects the voltage across the capacitor bank. The charging time of the capacitor depends on the input current fed into the EH 301 converter circuit. As the voltage across the capacitor reaches the voltage level \( V_{th} \), the modules internal circuit monitor enables output \( V_p \) and the device is now turned in to ON state, and thus can supply power to a power-consuming load such as microprocessors, sensor circuit or a battery. Thus, the amount of useful energy available is function of the capacity of the storage capacitor. Meanwhile the EH 301 circuit continues to accumulate energy generated by the harvester and stores it in the intermittent capacitor storage bank. If the condition arises where the harvester’s supply is sufficiently large for long duration of time, the EH 301 maintains itself in
ON state until the time such that harvester output is lower than the load power. As the external energy input exceeds the power loading, \(+V\), which is the voltage across the capacitor, continues to increase until the internal clamp circuits limits it to the maximum clamp voltage.

During the normal operation, as the power is drawn from an EH 301, the \(+V\) voltage decreases. When the voltage \(+V\) drop to the voltage \(V_L\), the output switch is turned off and the circuit stops supplying power to the load. The EH 301 boosts a built in hysteresis circuits within the module, which enable \(V_P\) to remain in the OFF state, even when the external energy sources starts to inject fresh new charge in to the circuit. The hysteresis circuits allow the flexibility of maintaining the converter circuit in stable operation. The operation of the EH 301 circuit is shown in Fig. 5.7 and the Fig. 5.8 show the interface connection of the EH 301.

![Figure 5.7 EH 301 waveforms reproduced from [62]](image)

*The charging cycles waveform of EHD 301 charging circuit.*

Input energy charging times \(t_1\) and \(t_2\) are limited by input energy available minus energy loss by an EH300/EH301 Series module. The energy output time period \(t_3\) is determined by the rate of energy used by the power load as a function of energy stored. Low input energy hold time \(t_4\) is typically many orders of magnitude greater than the sum of \(t_1\), \(t_2\) and \(t_3\). The energy harvester is
connected to EH 301 module through EH J1C input connector cable and the output of the EH 301 was connected to Lithium Ion battery through EHJ2C connector cable. The specification of the battery is depicted in the table 5.3.

<table>
<thead>
<tr>
<th>Battery PGEB021235</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>2 mm</td>
</tr>
<tr>
<td>Dimensions</td>
<td>2 x 12 x 35 mm</td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>3.7 V</td>
</tr>
<tr>
<td>Theoretical Current Capacity</td>
<td>40 mAh</td>
</tr>
</tbody>
</table>

The experimental result are shown in Fig. 5.10 and 5.11

![Figure 5.10 Measured Output Voltage, Current and Total Power across the converter circuit.](image)

The Converter circuit delivered total DC output power of 0.55 W under the no load conditions measured by performing open circuit voltage test and short circuit current test, and the converter circuit provide power of 181 mW to a Lithium ion battery connected across the circuit. The maximum power achieved can be increased by raising the clamp voltage above 7V. In Fig 5.10 (a), demonstrates that internal clamp circuit does not allow the voltage across the output to increase, which can be desirable in some cases, and also vice versa.
Thus, the device successfully demonstrated that it can deliver maximum power of 500 mW (which happens under the case of proper impedance match, since the harvester power is 2.0 W) under no load conditions, and successfully delivered 180 mW of power to a Lithium Ion Battery.

5.5 Conclusion

In this chapter, two prototype circuits have developed. The first prototype consists of a novel dual polarity boost converter circuit. The dual polarity boost converter circuit used a novel approach of utilizing the leakage inductance of the harvester coil as the boost inductor in the converter. This approach also significantly reduces the power losses in the circuit. The use of high permeability magnetic cores enables the greater induced voltage. The dual polarity boost converter when combined with harvester dramatically reduced the rectification voltage drops when compared with the conventional diode bridge rectifier. The usage of leakage inductance as a boost inductor dramatically reduces the converter size and thus increases the power density. The performance of the novel dual polarity boost converter can be further optimized with application of high Q inductors, and adjustment of leakage inductance, and by using low voltage drop and zero voltage drive gate MOSFETS.
The second prototype was developed with the aim of widening the frequency range of the harvester and providing a good impedance match. The second prototype could effectively provide an impedance match and delivered the maximum DC power of 500 mW at 100 Hz under no load conditions. The circuit also delivered a DC power of 181 mW at the frequency of 110 Hz to a battery connected as a load.
CONCLUSION

6.1 Summary of Main Results

The work reported in this thesis was undertaken to investigate a complete rotational motion energy harvesting system, which incorporates a working prototype of the harvester and power circuit that enables a proper impedance match and delivers maximum output power. Presently the energy harvesting system for rotational motion scavenges energy from vibrations of the rotating machinery. Thus, this served the motivation to develop an energy harvester scavenging the energy directly from the rotational motion. The harvester’s novel designed was accomplished partly due to the use of novel magnetic materials, and the two new prototype circuits developed for the harvester.

The harvester achieved a maximum power density of 50 mW/cm$^3$ that showed significant improvement over the existing the rotational generators and harvesters. The prototype rotational motion energy harvesters were realized by modified version of a typical axial flux machine. The device incorporated the axial flux arrangement of the magnets, which provided several benefits over the conventional energy harvester. The two stator and one rotor topology, nullified the extremely strong axial loading caused by high performance NdFeB magnets. The axial flux array topology also reduces the axial length of the harvester very significantly. The use of the axial flux topology enables to change the axial air gap, which is very advantageous because the air gap can be used to optimize the leakage inductance of the coil and to reduce the problem of excessive temperature, which can damage the permanent magnets. Thus rotational energy harvester topology allows significant improvement such as overcoming of the problem of overheating, optimization of the air gap for optimal leakage inductance. The harvester could deliver a 2.5 W of power at the 110 Hz frequencies.
The two different prototype power electronics circuits were developed to interface the output of the rotational energy harvester to load. The Dual polarity boost converter was developed with motive of removing the boost inductors, and replacing them with leakage inductance of the inductor coils in the harvester. The device showed a significant improvement over the conventional diode bridge rectifier. The novelty of the dual polarity boost converter also allows for further optimization of the entire system as in whole. The dual polarity boost converter generated maximum of 130 mW of the DC power. The second prototype circuit is developed with motive of increasing output power and to demonstrate the working of the entire system to be able to charge a battery. The prototype circuit could deliver a 500 mW of DC power under proper impedance matched conditions, and 180 mW of DC power to a battery at 110 Hz.

6.2 Suggestion for Future Work

A number of potential improvements can be established on the current implementation of the work done in this thesis. The future research work can be directed in improvements on the current version of rotational energy harvesting system can be summarized as follows:

1) Size reduction of the energy harvesting system
2) Building a new low frequency high Q inductors for better performance
3) The widening the frequency bandwidth of the rotational energy harvester when coupled with power electronics circuits.
4) Increasing the harvester power output by application of materials with improved magnetic properties.

6.3 Publications Related to this Work

Journals

Conference


Patents

1) **Green and Compact Hybrid Driving and Energy Harvesting Systems: Hybrid Bicycles, Hybrid Skateboards and Hybrid Roller Blades**, U.S. Provisional Application No. 61/706,272

2) **Dual Polarity Boost Converter for Inductive Magnetic Energy Harvester**, U.S. Prov. Application No. 61/698,802
APPENDIXES

A.1 Properties of Permanent magnets used in the Prototype generator

The magnets used in the prototype rotational motion energy harvester used grade 42 Neodymium-Iron-Boron magnets manufactured by K&J Magnetics Corporation. The summary of the properties of the Magnets is discussed below

A.1.1 Product Specifications

<table>
<thead>
<tr>
<th>Type</th>
<th>Disc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>0.3125 dia × 1Thick (in)</td>
</tr>
<tr>
<td>Tolerance</td>
<td>All dimensions ± 0.004inch</td>
</tr>
<tr>
<td>Material</td>
<td>NdFeB, Grade 42</td>
</tr>
<tr>
<td>Plating</td>
<td>NiCuNi</td>
</tr>
<tr>
<td>Max Op Temp</td>
<td>176°F (80°C)</td>
</tr>
<tr>
<td>$B_r_{\text{max}}$</td>
<td>13,200 Gauss</td>
</tr>
<tr>
<td>$B_H_{\text{max}}$</td>
<td>42 MGOe</td>
</tr>
<tr>
<td>Pull Force, Case 1</td>
<td>6.61 lbs</td>
</tr>
<tr>
<td>Magnetization Direction</td>
<td>Axial (Poles on the Flat Ends)</td>
</tr>
</tbody>
</table>

A.1.2 Physical and Mechanical Properties

The physical and mechanical properties of the magnets are summarized in the Table A.1 [62].

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7.4-7.5 g/cm³</td>
</tr>
<tr>
<td>Compression Strength</td>
<td>110 kg/mm²</td>
</tr>
<tr>
<td>Bending Strength</td>
<td>25 kg/mm²</td>
</tr>
<tr>
<td>Vickers Hardness (Hv)</td>
<td>560-600</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>7.5kg/mm²</td>
</tr>
<tr>
<td>Young's Modulus</td>
<td>1.7 x 10⁴ kg/mm²</td>
</tr>
<tr>
<td>Recoil Permeability</td>
<td>1.05 jurec</td>
</tr>
<tr>
<td>Electrical Resistance (R)</td>
<td>160 μ-ohm·cm</td>
</tr>
<tr>
<td>Heat Capacity</td>
<td>350-500 J/(kg·°C)</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient (0 to 100°C) parallel to magnetization direction</td>
<td>$5.2 \times 10^{-6} /°C$</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient (0 to 100°C) perpendicular to magnetization direction</td>
<td>$-0.8 \times 10^{-6} /°C$</td>
</tr>
</tbody>
</table>
The Table A.2 tells about the conversion formulae used for converting unit in CGS to SI systems.

<table>
<thead>
<tr>
<th>cgs System to SI system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Oe = 79.62 At/m</td>
</tr>
<tr>
<td>10,000 G = 1 T</td>
</tr>
<tr>
<td>1 Gb = 0.79577 At</td>
</tr>
<tr>
<td>1 Maxwell = 1 Line = 10⁻⁸ Wb</td>
</tr>
<tr>
<td>1 G = 0.155 lines/in²</td>
</tr>
</tbody>
</table>

Reproduced from [62]

The BH-curves for the values of NdFeB N 42 are shown in the Fig. A.1

Figure A.1 Material Characteristic for the material NdFeB N42, reproduced from [62]
B.1 TECHNICAL SPECIFICATION OF EH 301EPAD® MODULE

The EPAD EH 301 energy harvesting modules is manufactured by the Advanced Linear Devices Corporation. The technical and mechanical specification of the device is discussed below [61].

B1.1 Mechanical Specifications

Outline Dimensions:
1) W × L × H: 0.55in. × 2.00 in. × 0.70 in.
2) 4 Mounting holes: 0.085 in. diameter
3) Weight: 0.5 ounce (14 grams) nominal

Figure B.1, shows the dimensions of EH 301 EPAD circuit:

![Figure B.1 Physical dimensions of the EH 301.](image)

B.1.2 Absolute Maximum and Minimum Ratings

1) Max. instantaneous input voltage: +/- 500V
2) Max. instantaneous input current: 400mA
3) Max. input/output power: 500 mW
4) Operating temperature range: 0°C to +70°C
5) Min. input: 0.0V@1nA
6) Internal voltage clamp: 7.0V@10mA

7) Max. output current: 1A

B.1.3 Operating Electrical Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Low Level</td>
<td>(V_L)</td>
<td>3.1</td>
<td></td>
<td></td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Output High Level</td>
<td>(V_H)</td>
<td>5.2</td>
<td></td>
<td></td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Charging Input</td>
<td>(V_{in})</td>
<td>6.0/300</td>
<td></td>
<td></td>
<td>V@nA</td>
<td></td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>(P_D)</td>
<td>55</td>
<td></td>
<td></td>
<td>µW</td>
<td>1 cycle</td>
</tr>
<tr>
<td>Useful Energy Output</td>
<td>( t \times I )</td>
<td>885/150</td>
<td></td>
<td></td>
<td>mJ</td>
<td>1 cycle</td>
</tr>
<tr>
<td>(V_P) Output Resistance</td>
<td>(R_{V_P})</td>
<td>0.1</td>
<td></td>
<td></td>
<td>Ω</td>
<td>(V_P = 5.0V)</td>
</tr>
<tr>
<td>(V_R) Output Sink Current</td>
<td>(I_{sink})</td>
<td>5</td>
<td></td>
<td></td>
<td>mA</td>
<td>(V_P = 5.0V, V_R = 5.0V)</td>
</tr>
<tr>
<td>(V_R) Output Source Current</td>
<td>(I_{source})</td>
<td>-2</td>
<td></td>
<td></td>
<td>mA</td>
<td>(V_P = 5.0V, V_R = 0.0V)</td>
</tr>
<tr>
<td>Output Load</td>
<td>(R_{load})</td>
<td>5</td>
<td></td>
<td></td>
<td>Ω</td>
<td>(I_{OUT} = 1A)</td>
</tr>
<tr>
<td>Output Current</td>
<td>(I_{OUT})</td>
<td>1 A</td>
<td></td>
<td></td>
<td></td>
<td>(R_{load} = 5.0 \Omega)</td>
</tr>
</tbody>
</table>

\(T_A = 25\degree C, V_{in} = 6.0V\) unless other specified, reproduced from [61]

Typical Connections for EH 301

![Typical Connections for EH 301](image)

*Figure B.2 Typical System Applications of EH 301 EPAD\textsuperscript{®} energy harvesting module*
BIBLIOGRAPHY

1. Photograph of a windmill in Germany; http://en.wikipedia.org/wiki/Windmill


