AUTOMATIC FLIPPING MAGNET TYPE ELECTROMAGNETIC ENERGY HARVESTER

A THESIS

submitted by

RAJA PAUL
(EE14M079)

for the award of the degree

of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY MADRAS

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CERTIFICATE

This is to certify that the thesis titled **'AUTOMATIC FLIPPING MAGNET TYPE ELECTROMAGNETIC ENERGY HARVESTER'**, submitted by **Raja Paul (EE14M079)**, to the **Indian Institute of Technology Madras**, Chennai in partial fulfilment of the requirements for the award of the Degree of **Master of Technology** (Control and Instrumentation) in Electrical Engineering, is a bonafide record of work done by him, under my supervision and guidance. The contents of this project thesis, in full or in parts, have not been submitted to any other University/Institute for the award of any Diploma or Degree.

Dr. Boby George
Project Guide
Associate Professor
Dept. of Electrical Engineering,
IIT-Madras, 600 036

Place: Chennai
Date:

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Raja Paul

ABSTRACT

✓ KEYWORDS: Energy Harvesting, Electromagnetic Induction, Sensors, Energy Conservation

A new flipping magnet type Electromagnetic Energy Harvester (EEH) suitable for scavenging energy from low frequency vibrations is presented. The proposed EEH has a Spherical Permanent Magnet (SPM), which is free to move inside a spherical bobbin that carries coils. Two Cylindrical Permanent Magnets (CPM) are employed to flip the SPM fast, even if the frequency of vibration source is low. This induces sufficient voltage in the coil to convert to dc and use. No such scheme has been reported so far and the existing EEHs give very low induced voltage for low frequency vibrations < 5 Hz. Two versions of the new EEH prototypes, were built and tested. The peak-to-peak open circuit voltage of version-1 was 3.5 V and the power density was 445 $\mu W/cm^3$ for a matched load of 52.5 Ω at 3.5 Hz vibration. The power density of the version-2 harvester was 538.6 $\mu W/cm^3$. The prototype developed generated up to 2.44 mW for an emulated railway track vibration in the range of 4 Hz, which is a considerable improvement compared to the existing EEHs considering its simplicity in design. The second phase of the work included power conditioning of the output of the EEH and developing a practical working model. The output of the EEH was rectified and power conditioning was done using power management IC Bq25570, which was used as boost converter. The output from boost converter was used to charge a super capacitor and a rechargeable Li-ion battery. The energy delivered per cycle (Each up-down movement of EEH) was 70μJ. A practical working model was built in-house which gave similar results as the prototype EEHs. One of the applications of the proposed EEH is to harvest energy from railway tracks, for powering trackside monitoring sensors.

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ABBREVIATIONS

CPM	Cylindrical Permanent Magnets
EEH	Electromagnetic Energy Harvester
ELVIS	Educational Laboratory Virtual Instrumentation Suite
MEMS	Micro-electromechanical system
SC	Supercapacitor
SPM	Spherical Permanent Magnet
VI	Virtual Instrument
WSN	Wireless Sensor Nodes

NOTATIONS

V	Voltage
I	Current
R	Resistance
C	Capacitance
L	Inductance
Z	Impedance
f	Frequency
µ	Micro
m	milli
k	kilo
M	Mega
Hz	Hertz
Ω	Ohm
ω	Angular frequency
J	Joule

CHAPTER 1

INTRODUCTION

1.1 Background

Advancements in sensing techniques and sensor technologies have made reliable and less expensive sensors available, but their large scale and high impact applications such as condition monitoring of railway network are not yet fully exploited due to the limited availability of power required for such sensors and associated wireless network unit. These are usually powered by rechargeable batteries that store energy from energy harvesters whose source can be sun-light, wind, heat, radio wave, vibration, etc as in Fig.1.1. [1]

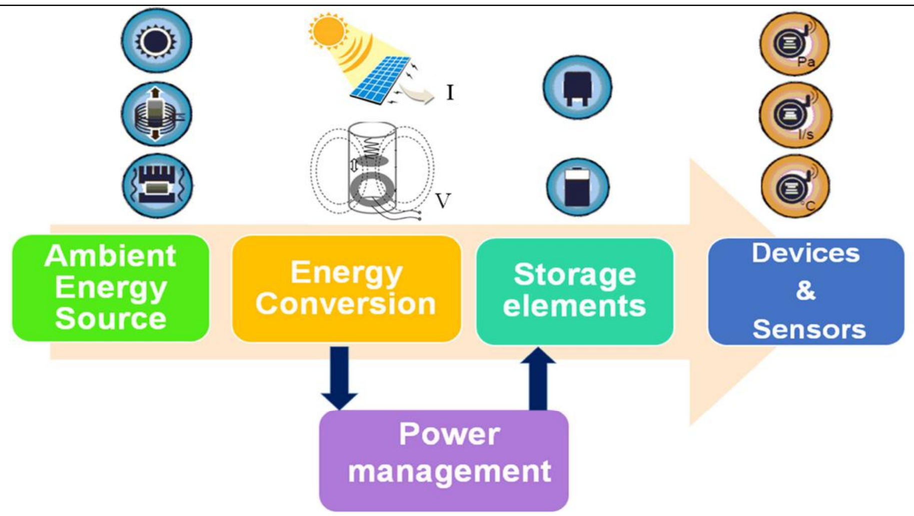

Fig.1.1 *Components of an intelligent remote sensor system.* (Source: IDTechEx)

In the case of a railway sensing network, one of the main sources of energy that can be used is from the vertical movement of the rail when the train goes. Harvesting this energy is a challenge as the movement of rail is limited to about 1-2 cm and the frequency is usually less than 5 Hz.

Under such low frequency vibrations, the Electromagnetic Energy Harvesters (EEH) fail to get sufficient voltage induced in their coils, for ac-to-dc conversion and storage in a battery. A piezoelectric harvester has been developed and integrated into a rail, but the energy harvested was small and the integration was complex [2]. Another approach of converting the linear vertical motion of rail into a rotational motion and then giving it to an EEH has been presented in [3]. Efficiency and life span of this system will be poor owing to the frictional losses in the linear-to-rotational converter. Recently, an EEH that captures energy from human motions, e.g., waving of hands, using a spherical magnet which moves in an arbitrary manner inside a spherical coil has been reported in [4]. Output voltage from such a unit will be very small when the movement is only in one direction (up/down) and swing is limited to about 1 or 2 cm with a frequency of 1 to 4 Hz.

A new EEH based on a novel automatic flipping arrangement of a Spherical Permanent Magnet (SPM) is developed. The SPM flips every time there is an up/down cyclic movement in the vibration source, e.g., cyclic bending of rail owing to the weight of the train. This flipping arrangement helps to induce sufficient voltage in the surrounding coil even if the frequency of vibration source is low, say 1-4 Hz. The constructional details and operation of the harvester, details of two versions of the prototype units developed and the test results are presented in the rest of the letter.

1.2 Definition of the problem

In today's highly competitive landscape, railway industry players need to strike a balance between reducing maintenance and operational costs, without compromising on safety, while simultaneously meeting commercial objectives such as punctuality and network velocity. Railway operations are highly reliant on the health of assets as well as real time information on events occurring during operations. However, current manual methods for monitoring rail assets are expensive, and these practices adopt a find-and-fix rather than predict-and prevent approach.

Adopting Remote Condition Monitoring technologies using smart sensors/wireless sensor networks (WSN) is imperative in order to cover all aspects of rail asset management and safety systems especially in difficult and remote terrains with harsh climatic conditions. Remote monitoring of asset condition data integrated with other relevant information such as events, GPS data, and planned schedules provides enormous value to the railways in terms of boosting reliability, safety and other operational parameters such as on-time performance, and fuel efficiency among others. The challenges faced by railway organizations vary based on where they are in their RCM adoption journey. While advancements in sensor technology has reduced the cost and size of remote sensors, a major area of concern is the short life of batteries that power sensors and devices, requiring research to focus on energy optimization of sensing instruments, and energy harvesting, with special emphasis on rechargeable methods.

The power supply of the sensor nodes evokes some serious challenges because the sensors need to be wireless. The power is usually provided by primary or secondary batteries but their energy is inherently limited. Energy harvesting from energy sources like light, wind, heat, radio wave, vibration etc. readily available around our environment promises to make ubiquitous sensing possible by charging batteries or supplying wireless sensor nodes directly with power, so that the nodes become maintenance free.

The vertical deflection of the track under the weight of a passing train can be used for harvesting energy. If suitable energy harvesting systems can be developed, this harvested energy can be used to power railway trackside sensors. Compared to other mechanical machinery-based vibration sources, track vibrations are particularly challenging for energy harvesting because of the low-frequency (1–4 Hz), small amplitude of track oscillations, aperiodic, generally unpredictable and time varying vibration signatures.

1.3 Objective and Scope of the Project

The overall objective of the work is to develop an energy harvester to harvest energy from available sources to power remotely located sensors. The proposed application mentioned above, requires an efficient harvester which can convert energy from vibrational sources, even if the frequency of vibrations is less than 5 Hz. This requires development of a new mechanism as none of the existing techniques work well at such low frequencies. An automatic flipping type magnet approach is proposed in this work. The flipping causes a rapid rate of change in the magnetic flux linkage with it's (a spherical magnet) flux and the coils surrounding it. The resulting induced voltage is less dependent on the speed/frequency of vibrations of the movement of vibrational source. Another objective of the work is to condition the generated voltage into a suitable dc supply and charge a battery. In this work, the prototype of the proposed overall system mentioned above is expected to be built and tested, and compared with existing harvesters for similar application.

1.4 Organisation of Thesis

The Chapter-1 gives an introduction to the need for energy harvesting. It brings out the problems in harvesting energy from low frequency vibrational sources especially railway track vibrations. The overall objective is to find a suitable energy harvester for such low frequency vibrational sources.

The Chapter-2 discusses the ambient energy sources and energy harvesting methods thereby giving out an inference that electromagnetic energy conversion is suited for achieving our goal.

Design and development of Electromagnetic Energy Harvester (Version-1 prototype) is discussed in Chapter-3. The chapter also discusses the experimental set-up and test results.

Chapter-4 explains the design and testing of Version-2 prototype driven from the test results of version-1 prototype. The effect of vibrational frequency on the induced voltage is also studied.

Chapter-5 discusses the power condition circuit for proposed EEH and Virtual Instrument developed for the circuit in LabVIEW environment. Details of the circuit developed in the lab along with the experimental results are also discussed.

Chapter-6 discusses the practical working model developed in the lab which can be easily installed under a railway track for scavenging energy from track vibrations.

In Chapter-7, conclusions have been drawn on the present work and scope of the future work has been presented.

CHAPTER 2

AMBIENT ENERGY SOURCES AND ENERGY HARVESTING

2.1 Need for Energy Harvesting

There has been a continuous reduction in size and power consumption of electronic devices which enables the extended use of wireless sensors in industrial and automotive applications [5] as seen in Fig.2.1. Self-powered sensors are also of great importance in the industry due to the limitations of the available power and inaccessibility related maintenance costs. They play a significant role mainly in many process industries where sites are very large or spread out (e.g. railway network). Cost saving is also a biggest motivator for using wireless links in industry. The cost savings from not having to install cables is substantial.

However, the power supply of the sensor nodes is a major challenge for extensive implementation of WSN's. The power to the WSNs is usually provided by primary or

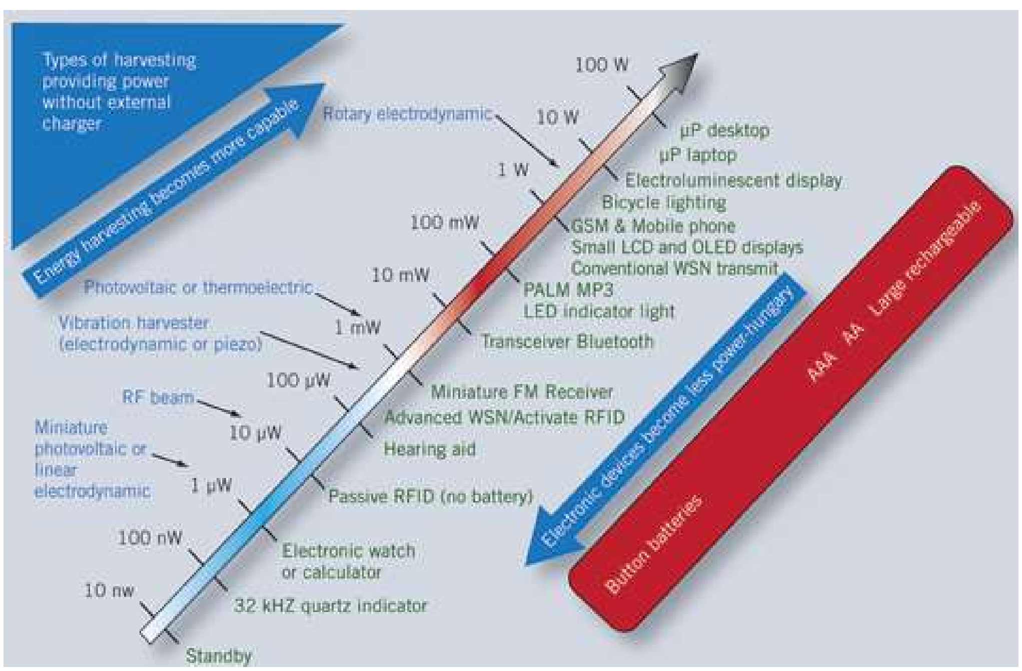

Fig. 2.1. *Shrinking IC chip line geometries and low power consumption levels come at a time when energy harvesting devices are becoming more effective and practical. (Source: IDTechEx)*

secondary batteries but their energy is inherently limited. Thus the battery must be replaced or recharged sooner or later. Particularly in inaccessible areas or systems with many sensor nodes it is not a viable option because maintenance becomes too costly. Energy harvesting from energy sources like light, wind, heat, radio wave, vibration etc. readily available around our environment promises to make ubiquitous sensing possible by charging batteries or supplying wireless sensor nodes directly with power, so that the nodes become maintenance free.

In a recent study, Yildiz, Zhu, Pecen, and Guo (2007) [6] have brought out a comparison of estimated power and performance of various ambient energy sources. They are tabulated below (Table.2.1). The values are derived from a combination of published studies, and information commonly available in textbooks. The source of information for each technique is given in the third column of the table. The table brings out a broad range of possible methods to scavenge and store energy from a variety of ambient energy sources. Light is a significant source of energy, but it is greatly reliant on the application and the experience to which the device is exposed. Thermal energy, in contrast, is limited as temperature variation across a chip are usually low. Vibration energy is a moderate source, but it is dependent on the specific application, as cited by Torres and Rincon-Mora (2005) [7]. Extracting energy from environmental vibration has drawn much attraction over the last few decades due to its abundance in nature and unlimited lifetime.

Comparison of Power Density of Energy Harvesting Methods			
Energy Source	**Power Density & Performance**		**Source of Information**
Acoustic Noise	0.003 0.96	μW/cm3 @ 75Db μW/cm3 @ 100Db	(Rabaey, Ammer, Da Silva Jr, Patel, & Roundy, 2000)
Temperature Variation	10	μW/cm3	(Roundy, Steingart, Fréchette,Wright, Rabaey, 2004)
Ambient RF	1	μW/cm2	(Yeatman, 2004)
Ambient Light	100 100	mW/cm2 (direct sun) _W/cm2 (illuminated office)	Not Cited
Thermoelectric	60	_W/cm2	(Stevens, 1999)
Vibration (micro generator)	4 800	_W/cm3 (human motion - Hz) _W/cm3 (machines – kHz)	(Mitcheson, Green, Yeatman, & Holmes, 2004)
Vibrations (Piezoelectric)	200	μW/cm3	(Roundy, Wright, & Pister, 2002)
Airflow	1	μW/cm2	(Holmes, 2004)
Push Buttons	50	_J/N	(Paradiso & Feldmeier, 2001)
Shoe Inserts	330	μW/cm2	(Shenck & Paradiso, 2001)
Hand Generators	30	W/kg	(Starner & Paradiso, 2004)
Heel Strike	7	W/cm2	(Yaglioglu, 2002) (Shenck & Paradiso, 2001)

Table.2.1 *Comparison of power density for energy harvesting methods*. [5]

2.2 Ambient Energy Sources

Ambient energy harvesting is the process where energy is obtained and converted from the environment and stored for use in electronics applications. Solar power, ocean waves, piezoelectricity, thermoelectricity, and physical motions (active/passive human power) are some of the ambient energy sources available. No single power source is ample for all applications, and that the selection of energy sources must be carefully planned according to the application characteristics.

Fig.2.2 shows a block diagram of general ambient energy-harvesting systems. The first row shows the energy-harvesting sources. Actual application and tools

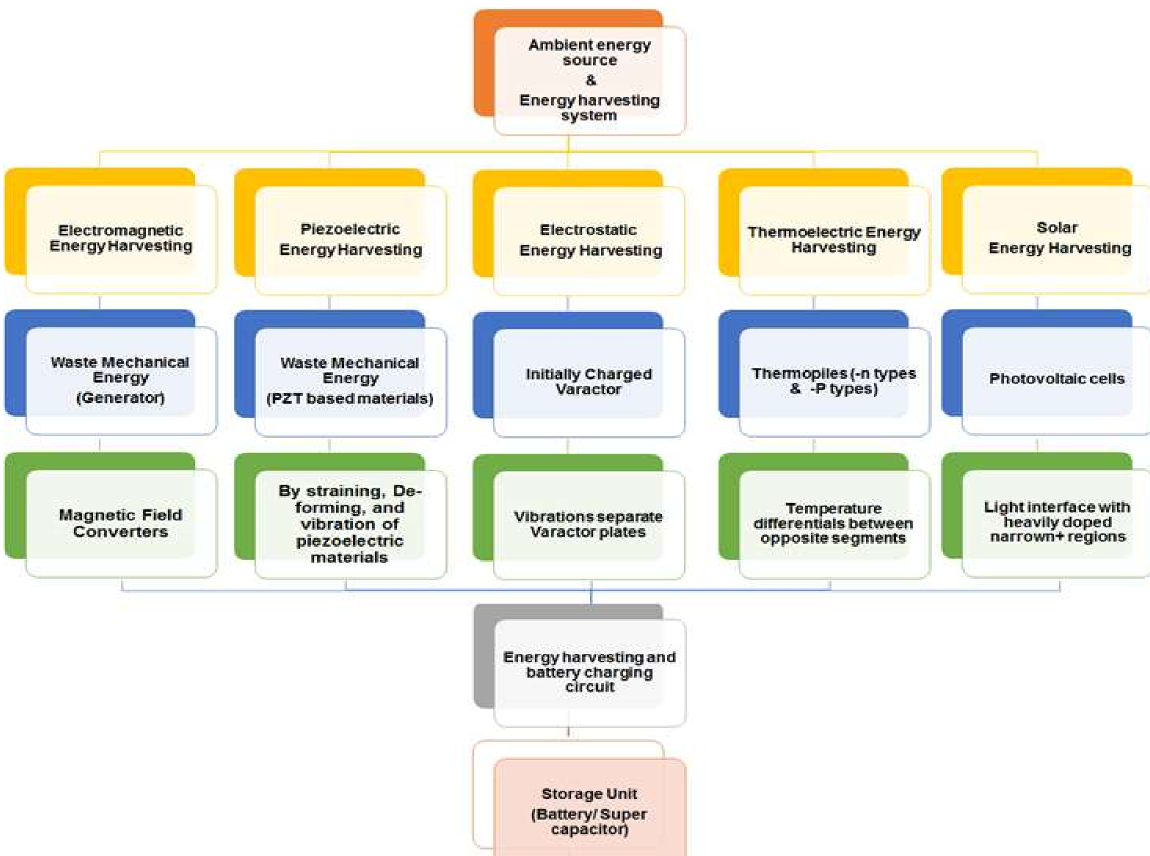

Fig.2.2. *Ambient energy sources* [5]

employed to harvest the energy from the source are illustrated in the second row. The third row shows the energy-harvesting techniques from each source.

2.3 Thermal (Thermoelectric) Energy Harvesting

Thermal gradients in the environment are directly converted to electrical energy through the Seebeck (thermoelectric) effect, as reported by Disalvo (1999) and Rowe (1999) [8]. Temperature changes between opposite segments of a conducting material result in heat flow and subsequently charge flows since mobile, high-energy carriers diffuse from high to low concentration regions. Thermopiles consisting of n- and p-type materials electrically joined at the high-temperature junction are therefore constructed, allowing heat flow to carry the dominant charge carriers of each material to the low temperature end, establishing in the process a voltage difference across the base electrodes as shown in Fig.2.3. The generated voltage and power is relative to the temperature differential and the Seebeck coefficient of the thermoelectric materials. Applications of this energy-harvesting design are varied, including automotive performance monitoring, homeland and military security surveillance, biomedicine, and agricultural management. It is also recognised that the thermoelectric energy harvester is suitable for many other stand-alone, low-power applications, depending on the nature of the application. A thermal-expansion-actuated piezoelectric generator has also been suggested as a method to convert power from ambient temperature gradients to electricity by Thomas, Clark and Clark (2005) [9].

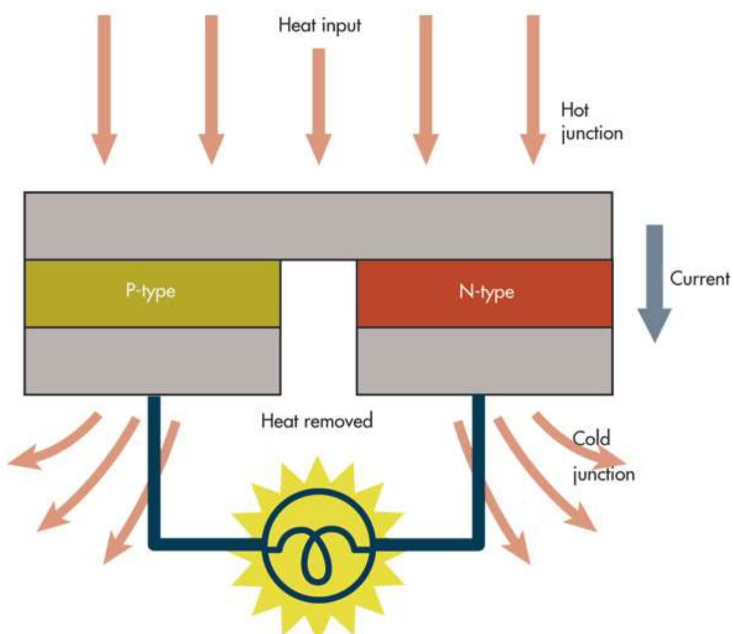

Fig.2.3. *Thermal Energy Harvesting (Source: electronicdesign.com)*

2.4 Pyro-electricity Energy Harvesting

The "pyro-electric effect" converts changes in temperature into electrical voltage or current (Lang, 2005) [10]. Pyro-electricity is the capability of certain materials to generate an electrical potential when they are either heated or cooled. Pyro-electric energy harvesting applications require inputs with time changes which results in small power outputs in energy-scavenging applications. One of the main advantages that pyro-electric energy harvesting has over thermoelectric energy harvesting is that pyro-electric materials or elements are stable up to 1200 °C or more. Stability allows energy harvesting even from high temperature sources with increasing efficiency.

2.5 Light Energy (Solar Energy) Harvesting

Light energy is converted into electrical energy by a photovoltaic cell (Kasap, 2001 Raffaelle, Underwood, Scheiman, Cowen, Jenkins, Hepp, Harris, & Wilt, 2000) [11], [12]. Each cell is made of a reverse biased pn+ junction. On absorption of light energy electron-hole pairs are generated. The electric field is built across the junction which immediately separates each pair, collecting electrons and holes in the n+ and p regions, respectively, creating an open circuit voltage. When the load is connected, electrons travel through the load and recombine with holes at the p-side, causing a photocurrent proportional to the light intensity and independent of the cell voltage. Photovoltaic energy conversion is a familiar technology that offers higher power output levels, when compared with other energy-scavenging mechanisms but its power output is highly dependent on environmental factors i.e., varying light intensity.

2.6 Acoustic Noise:

Acoustic noise is the outcome of the pressure waves produced by a vibration source. Very few research has been carried out in the field of acoustic noise harvesting from environment. For example, a research team at the University of Florida examined acoustic energy conversion. They reported analysis of strain energy conversion using a flyback converter circuit (Horowitz et al. 2002) [13]. The output of a vibrating PZT piezo ceramic beam is connected to an AC to DC flyback converter, which is estimated to provide greater than 80 percent conversion efficiency at an input power of 1 mW and 75% efficiency at an input power of 200 μW (Kasyap, Lim, et al. 2002) [14]. But the amount of power available from acoustic noise is insufficient apart from very rare environments with extremely high noise levels.

2.7 Mechanical Vibrations

Vibration energy harvesting devices can be either electromechanical or piezoelectric. Electromechanical harvesting devices, however, are more commonly researched and used. Roundy, Wright, and Rabaey (2004) [15] reported that energy withdrawal from vibrations could be based on the movement of a spring-mounted mass relative to its support frame. These energy conversion schemes are explained under the three listed subjects because the nature of the conversion types differs even if the energy source is vibration.

Electromagnetic: This technique uses a magnetic field to convert mechanical energy to electrical energy (Amirtharajah & Chandrakasan, 1998) [16]. A coil is fixed to the oscillating body and is made to pass through a magnetic field, which is established by a stationary magnet, to produce electric energy. The coil travels through a varying amount of magnetic flux, inducing a voltage according to Faraday's law. The induced voltage is inherently small and therefore must be

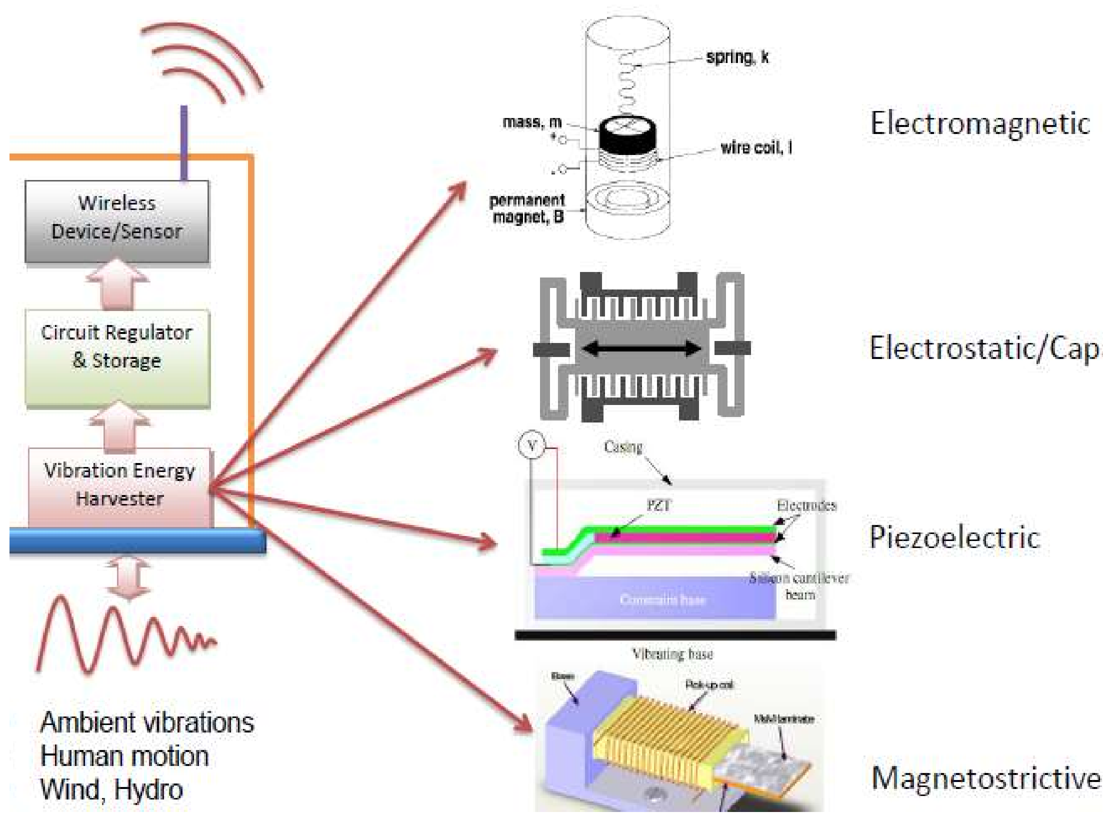

Fig.2.4. *Vibrational Energy Harvester (Source: IDTechEx)*

increased to become a viable source of energy. Also in this case the magnet can be attached to the oscillating body and coil can be around it. This method is preferred in many applications as it easier to construct and install.

Piezoelectric: In this method mechanical energy is transformed into electrical energy by straining a piezoelectric material (Sodano, Inman, & Park, 2004) [17]. Strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field. The vibrating system is normally a cantilever beam arrangement with a mass at the unattached end of the cantilever. The introduction of mass at the unattached end provides higher strain for a given input force (Roundy & Wright, 2004) [18]. The voltage produced varies with time and strain. Piezoelectric energy conversion produces relatively higher voltage and power density levels than electromagnetic system but has to be connected properly to the oscillating body. Electric cigarette lighter is one application of piezoelectric energy. In this system, pushing the button causes a spring-loaded hammer to hit a piezoelectric crystal, and the voltage that is produced injects the gas slowly as the current jumps across a small spark gap. With the same idea, portable speakers, gas lighters, gas stoves, and a variety of gas burners have built-in piezoelectric based ignition systems.

Electrostatic (Capacitive): This method relies on the variable capacitance of vibration-dependent varactors (Meninger, Mur-Miranda, Amirtharajah, Chandrakasan, & Lang, 2001) [19]. A major advantage of this method is its IC-compatible nature. This system produces higher and more practical output voltage

	Electrostatic	**Electromagnetic**	**Piezoelectric**
Complexity of process flow	LOW	VERY HIGH	HIGH
Energy density	4 mJ/cm^3	24.8 mJ/cm^3	35.4 mJ/cm^3
Current size	Integrated	Macro	Macro
Problem	Very high voltage and need of adding charge source	Very low output voltages	Low output voltages

Table.2.2. *Comparison of vibration energy harvesting techniques*. [18]

levels than the electromagnetic method, with moderate power density. Marzencki (2005) [20] conducted a study to test the feasibility of the different ambient vibration energy sources by, and the results are summarized in Table 2.2 according to their complexity, energy density, size, and encountered problems.

2.8 Inference

After studying the various energy harvesting methods, electromagnetic method of energy conversion from ambient vibrations is found to be ideal for powering railway trackside sensors as it would be easier to install and has moderate energy density. The vertical deflection of the track under the weight of a passing train can be used for harvesting energy but the major concern with these vibrations is low frequency (1-4Hz), aperiodic and small amplitude. A suitable electromagnetic based energy harvesting systems designed for such vibrations is presented in the following sections which can scavenge energy from track vibrations to power remote sensors on railway track.

CHAPTER 3

DESIGN AND DEVELOPMENT OF THE VERSION-1 EEH

3.1 Automatic Flipping Magnet Type EEH

Fig. 3.1(a) shows a simplified 3D diagram of the EEH. The SPM is surrounded by two sets of coils marked as horizontal and vertical windings. These windings are in quadrature as illustrated in Fig. 3.1(a). There are two Cylindrical Permanent Magnets (CPM); one at the top and another at the bottom of the vertical winding, aligned in the direction of vibration from the source. The CPMs are arranged such that the top and bottom regions of the vertical winding face the south of these magnets. This is illustrated in Fig. 3.1.

Let us consider that the bobbin of the winding is mechanically coupled to the vibration source. It can freely move with the source, while the CPMs are fixed to a frame, which is stationary with respect to the vibration. A reverse arrangement is also possible, with a movable CPM and a fixed bobbin. Let us assume that the vibration source moved the bobbin upwards and it is now close to the top CPM. A simplified cross-sectional view

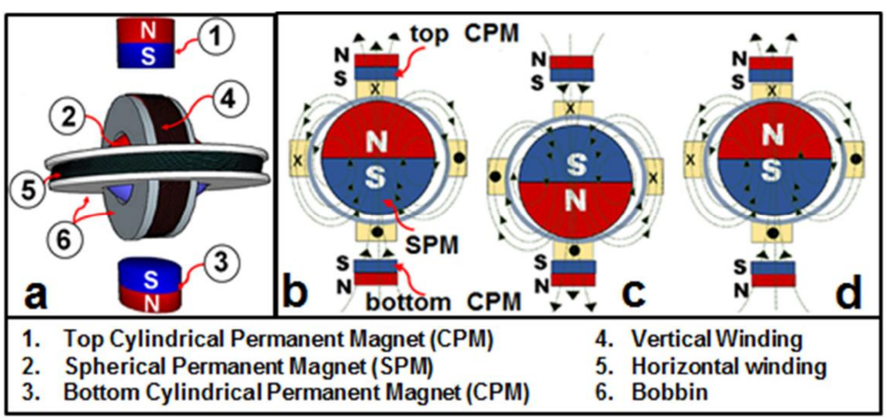

Fig. 3.1. *Electromagnetic Energy Harvester (EEH)*
a Simplified three dimensional schematic of the proposed EEH
b-d Cross-sectional view that illustrates the operating cycle and the principle of automatic flipping of SPM

of the EEH is given in Fig. 3.1(b). Let us name it as state-1. In this condition, the north of the SPM will be facing the south of top CPM, due to the magnetic force of attraction.

When the vibration source move the bobbin down, the CPM will leave the top CPM and enter into the magnetic field of the bottom CPM. As the top face of bottom CPM is south, now the SPM will get repelled. Since it is a free to rotate body, it will turn by say some small angle. Once it rotates by some angle, the north face of SPM will get attracted towards the south of the bottom CPM and will quickly align as in Fig. 3.1 (c). This is the state-2 of the system. Now, when the vibration source pulls the bobbin up, the reverse of this occurs and the SPM will flip back to the initial position as in Fig. 3.1 (d), which is the state-1. Thus, the magnetic arrangement of the new EEH is such that whenever there is an up/down movement in the vibration source the SPM flips. The flipping of the SPM occurs whenever the SPM reaches a specific position in its vertical travel path, making the flipping independent of the speed at which the source moves. Whenever SPM flips, there will be a rate of change of flux linkage for the vertical and horizontal windings and hence voltages will be induced in them, irrespective of the speed of the movement of the vibration source, which is a major advantage for EEHs that are coupled to low frequency sources.

3.2 Prototype EEH (Version-1)

A prototype of the proposed harvester was developed. The windings were made on a spherical bobbin, with an inner diameter of 16 mm, housing a 15 mm diameter NdFeB SPM. The spherical enclosure is fabricated using two V-shaped pulleys made of Teflon. One of the V-shaped pulley was cut appropriately and glued over the horizontal V-pulley thus giving it an almost spherical shape as shown in Fig. 3.2.

The outer surface of the V-shaped pulleys are wound with 300 turns 42 gauge copper wire in both horizontal and vertical directions. Typical coil resistance varied

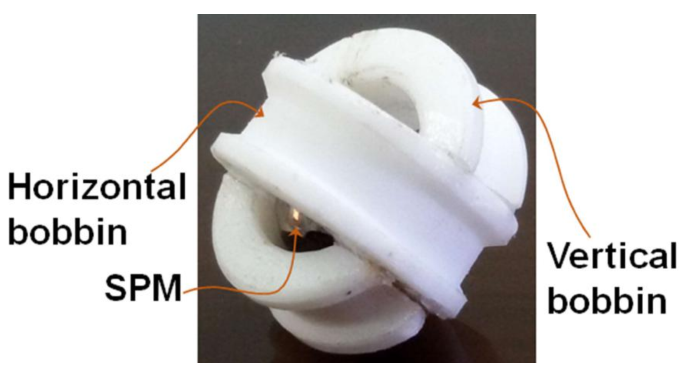

Fig. 3.2. *Spherical bobbin*

between 50-60 Ω. The volume of the EEH is 3.59 cm^3. The size of the CPMs used are 6mm × 6 mm.

The spherical magnet is placed in close proximity to the upper cylindrical magnet and as a result they remain attached. This is the initial/top position of the setup. At this position the North Pole of the spherical magnet is in the upward direction. Now as we force the spherical assembly to move down towards the lower cylindrical magnet the spherical magnet flips as same poles come close to each other resulting in a high rate of change of flux.

The magnetic field lines of the spherical magnet cut the horizontal winding perpendicular to it which induces emf in the coil. In a similar fashion emf is induced in the vertical winding due to the flipping motion of the spherical magnet. After the spherical magnet flips it gets attached to the bottom cylindrical magnet as it is now in close proximity to bottom cylindrical magnet. This is the bottom position of the spherical magnet. Now, the North Pole of the spherical magnet will be in downward direction. Now when we force the spherical cavity to move upwards, the spherical magnet gets separated from lower cylindrical magnet and starts moving upwards. Once the spherical magnet is under the influence of upper cylindrical magnet, it flips due to similar poles coming close to each other. Again the flipping action induces emf in both the coils.

3.3 Experimental setup

The experimental setup is shown in Fig. 3.3. The arrangement mimics the vertical displacement of a railway track. It has been developed such that the bobbin of the EEH can undergo an up and down movement, equivalent to that of a railway track, when the servo-motor in the set-up operates. The bobbin is attached to the end of the cantilever as in Fig. 3.3 and the normal position of the bobbin is set as state-1, i.e., close to the top CPM. Whenever the servo-motor is rotated by 180^o, using a simple motor driver circuit based on ATMEGA-328 micro-controller (micro-controller program is appended as Appendix 'A') the cantilever moves in the downward direction. In this process, when the bobbin enters into the magnetic field of bottom CPM and the SPM flips (state-2) as explained earlier.

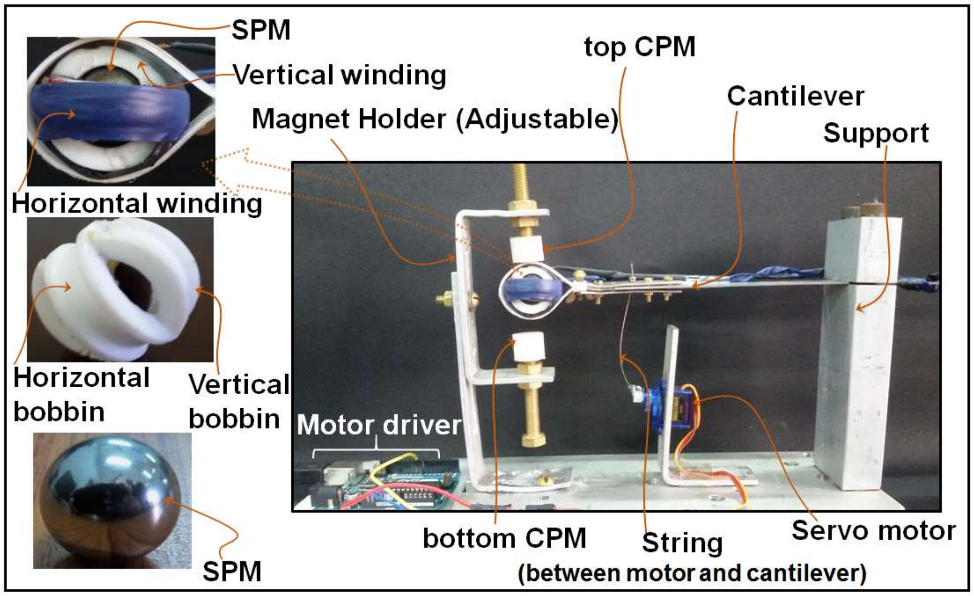

Fig. 3.3. *Photograph of the experimental setup. The bobbin with windings and the NdFeB SPM are shown in inset.*

When the motor rotates back, the cantilever will go back to its original position bringing the system back to the state-1. This process can be continued at a set/variable rate to emulate the vibration source and to record and study the inducted voltages for a range of vibration frequencies.

The cylindrical magnets are kept in a Teflon case and a nut-bolt arrangement is made to adjust the spacing between the magnets and the spherical cavity. The test results and discussions are presented in the next section.

3.4 Preliminary Test Results and Discussion

An experiment was conducted by operating the motor as described above and the voltages V_H and V_V induced in the horizontal and vertical windings respectively, were recorded for a vibration at 2.5 Hz. The waveforms were recorded using NI ELVIS II. The control voltage V_S given to the servo-motor is also shown in Fig. 3.4. When the motor operates, the SPM flips each time it comes under the influence of either of the CPMs. As can be seen, when the SPM flips at the top position, 1.7 V is observed in V_V, while V_H has about −1.8 V. When the SPM flips in the bottom position, peak of V_H

observed was 1.7 V and the corresponding V_V was 0.8 V. These were recorded on a no-load condition. From the above test, it is clear that every time when the SPM flips a few volts is induced as expected irrespective of the speed of the movement of the vibration source. This is a major advantage for EEHs that are coupled to low frequency vibration sources. The stimulus (V_S) given to the servo motor form the driver is also shown. It is seen that the induced voltages in the horizontal and the vertical windings at top position of SPM are out of phase and hence are not additive.

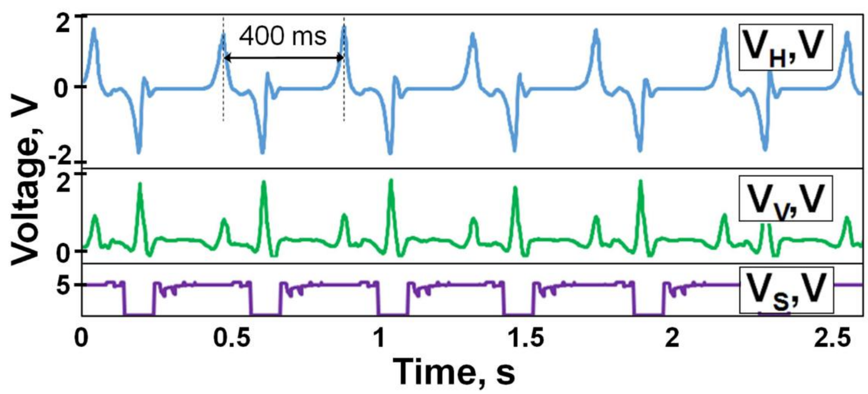

Fig. 3.4. *Induced voltages recorded from the version-1 of the prototype*

The peak induced voltage varies as a function of the distance between the spherical assembly and the cylindrical magnets. The recorded waveforms of the induced voltages are placed as Appendix 'B'. Fig. 3.5 shows the peak induced voltage (V_{TOP}) at top position of the spherical magnet. The spherical cavity is kept close to the upper cylindrical magnet and readings of induced voltages were taken by varying the gap between the spherical cavity and lower cylindrical magnet. It is seen that when the lower cylindrical magnet is placed very close to the spherical assembly say 5mm, the spherical magnet does not get enough chance to flip but as the distance increases the induced voltage increases. When the gap increases beyond 15mm the voltage starts to reduce because the flip of the spherical magnet ball tends to happen at slower speed. The maximumm induced voltage is when the gap between the vertical winding and bottom CPM is 13mm .

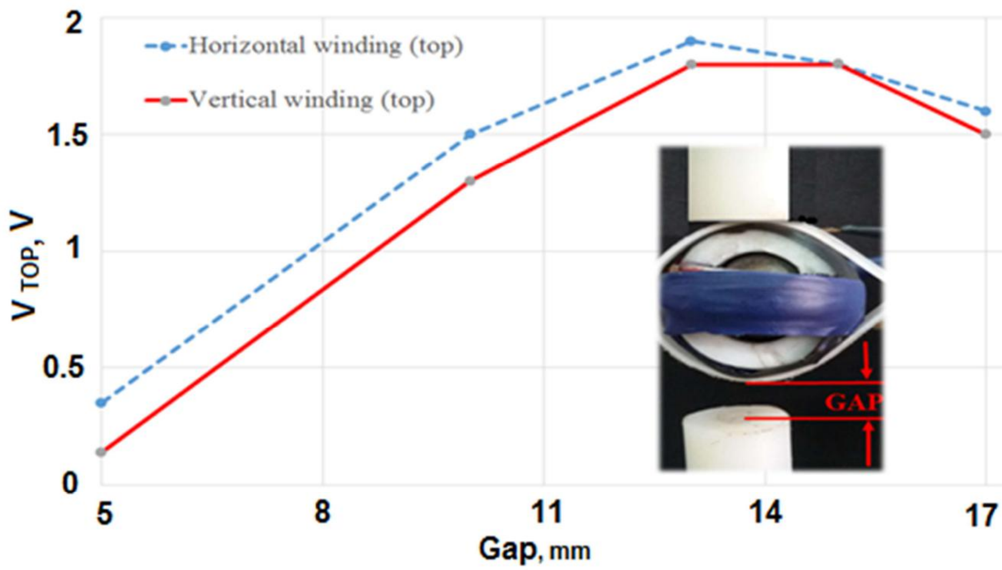

Fig. 3.5. *Measured no-load peak voltage (top position) vs. gap between the vertical winding and lower cylindrical magnet*

3.5 Conclusion

From the studies it is noted that the voltages V_H and V_V are not additive, in addition, the magnitude of voltages induced in the vertical winding is found to be sensitive to constructional misalignments. Thus, a revised (version-2) prototype winding is designed and developed, which consists of three horizontal windings. The version-2 prototype is discussed in the next chapter.

CHAPTER 4

DESIGN AND TESTING OF THE VERSION-2 EEH

4.1 Version-2 Prototype EEH

The second design is driven from the above results where we can see that at bottom position the voltage induced are out-of-phase and causes a cancellation of the voltages when added in series. Thus, a revised (version-2) prototype is designed and developed, which consists of three horizontal windings.

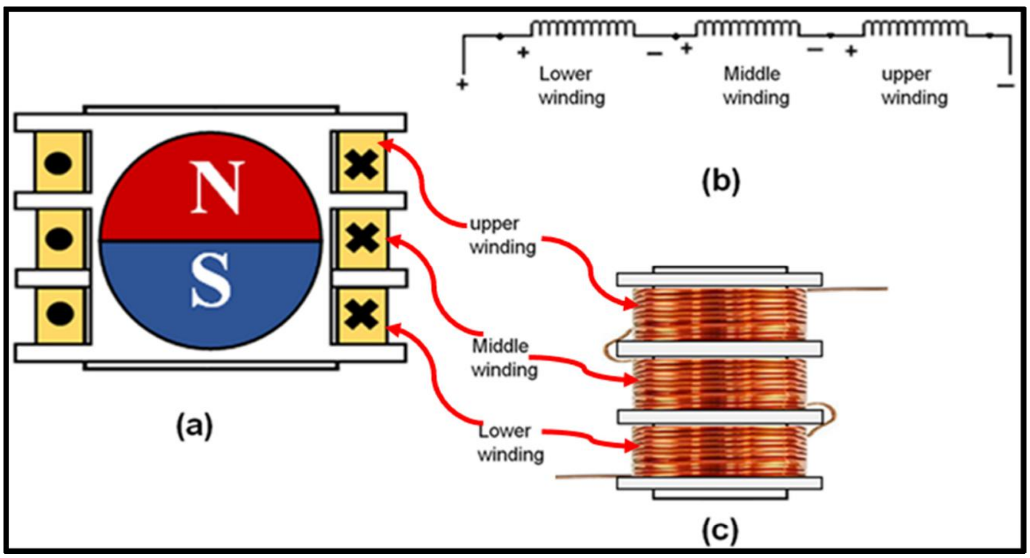

Fig. 4.1. *Version-2 prototype. The three horizontal windings (Lower, Middle, Upper) are shown.*

Fig. 4.1 shows SPM enclosed in a cylindrical bobbin structure. It has three windings (lower, middle, upper) and all three are in the horizontal plane. The volume of the version-2 prototype is 4.53 cm^3 . Typical coil resistance was 130 Ω. The polarity of the induced voltages with every flip is indicated in Fig.4.1 (b) suggesting that the induced voltages in the three coils are additive. They can be combined in series as shown in Fig. 4.1(b) & 4.1(c) to get higher power.

4.2 Version-2 Prototype EEH testing and results

The version-2 EEH was attached to the cantilever arrangement and track like vibration were simulated using the servo motor driven by ATMEGA-328 micro-controller as in the previous case. Fig. 4.2 shows the voltage waveforms induced in the horizontal windings; upper (V_U), middle (V_M), lower (V_L) of the version-2 of the prototype. As can be seen, the voltages induced at every instant during the flip have same polarity, and hence they can be connected in series, which is not viable in the version-1 prototype. The peak of the series combination was found to be more than 4 V, and the peak-to-peak voltage was 8.25 V.

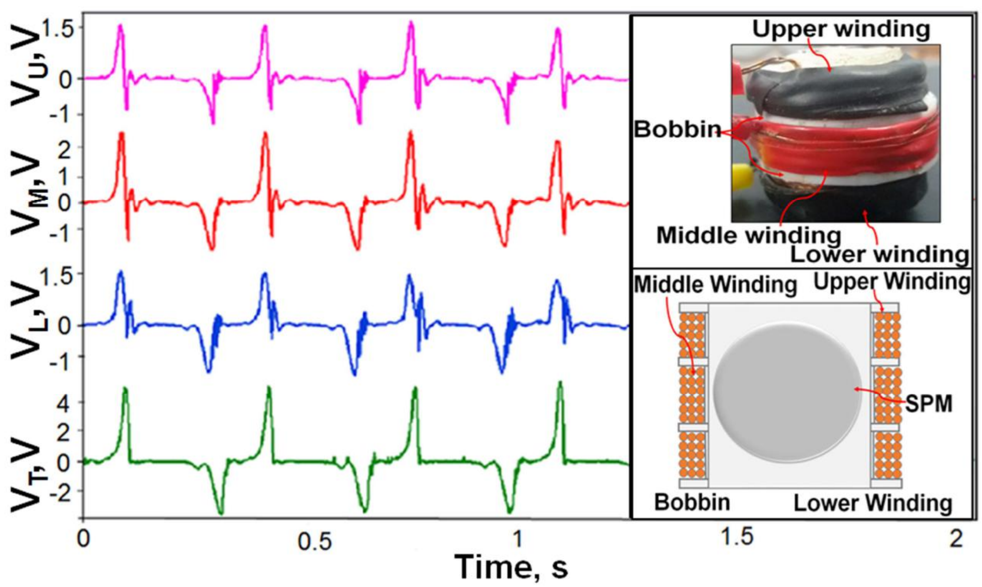

Fig. 4.2. *Voltage waveform recorded from the version-2 of the prototype EEH. A photograph of part of the prototype and the associated diagram are shown in inset. The CPMs are not shown.*

4.3 Power Output of the Energy Harvesters

The energy harvesters were tested for the power that they can deliver. The circuit consists of a rectifier, storage capacitor C_s and load resistor R, as shown in Fig.4.3. The AC signal from the EEH is rectified and the energy is stored in the capacitor C_s. It is chosen sufficiently large as to maintain a nearly constant DC voltage. In other words, the storage circuit has a comparatively high RC time relative to the cycle time of the EEH. Here *Cs* is acting as a buffer, smoothing the voltage ripple after the rectifier. The output

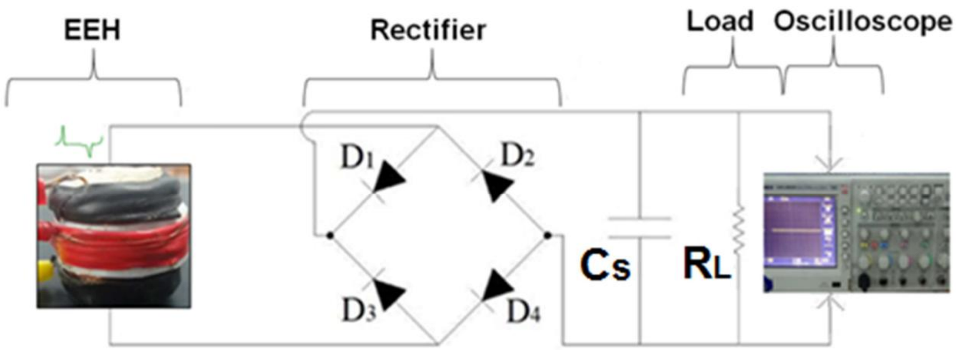

Fig. 4.3. *Circuit for testing power output of proposed EEHs*

of the harvester is rectified and various resistors are connected across the rectified output as shown in Fig. 4.3. An average output power (P_{avg}) of 1.66 mW was obtained at matched load of 52.5 Ω at ~3.5Hz for the version-1 prototype and while 2.44 mW at a matched load of 130 Ω (windings in series) was noted for the version-2 prototype.

In order to study the effect of the vibration frequency, the peak-to-peak voltages, V_{P-P}, of the versions 1 and 2 prototypes were recorded for a frequency range of 0.25 Hz to 3.5 Hz. Fig. 4.4 shows the V_{P-P} recorded from the windings at different frequencies for

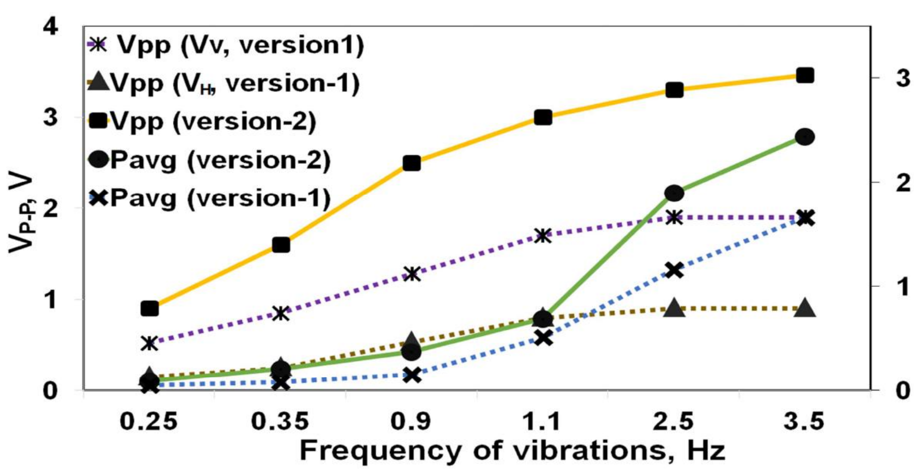

Fig. 4.4. *Measured peak-peak voltage, V_{P-P}, and average power P_{avg} for matched load at different frequencies.*

a matched impedance. For this, the servo motor (using the driver board) was made to operate such that it introduces vibrations to the bobbin in the range of 0.25 Hz to 3.5 Hz. The vertical movement of the bobbin was 1 cm. The volume and power density of the version-1 EEH were 3.59 cm^3 and 445 $\mu W/cm^3$, respectively. These parameters for the version-2 were 4.53 cm^3 and 538.6 $\mu W/cm^3$, in order.

4.4 Conclusion

The proposed EEH can be used to harvest energy from the railway track, to power the track monitoring sensors. A simple and suitable mechanical arrangement can be made to install the EEH below the rail between two sleepers. A power management circuit is required for efficiently converting the generated energy from the harvesterand using it for charging a rechargeable storage element (Rechargeable Li-ion battery or a supercapacitor). IC-BQ25570 from Texas Instruments was chosen for power management and as boost converter. The details are covered in the following chapter.

CHAPTER 5

POWER CONDITIONING UNIT

5.1 Power Conditioning

The output of the harvester is AC with the amplitude varying with excitation and load, hence for a usable DC supply rectification and voltage regulation are required. The power conditioning also determines the mechanical operating conditions by setting the equivalent load impedance seen by the harvester. Rectification can be implemented using a full bridge of Schottky diodes, or for lower losses a synchronous scheme can be adopted. A key component of any micro-scale energy harvesting subsystem, and our main focus, is the power converter that boosts the output voltage of the energy transducer to a suitable level as shown in Fig. 5.1 that enables energy storage in a rechargeable battery or an ultra-capacitor.

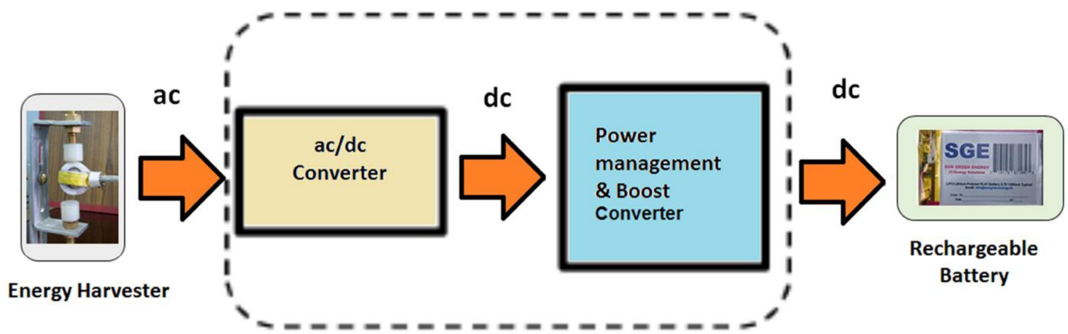

Fig. 5.1. *Energy harvester with boost converter.*

5.1.1 AC/DC Converter

The output of the energy harvester is rectified using a bridge rectifier. The bridge rectifier is one of the most widely used rectifier circuits. It offers a high level of performance when compared to other rectifier circuits. SR1100 Schottky diode [20] is used for building the bridge rectifier. A diagram of the basic bridge rectifier circuit is shown below. In view of the high level of use of the bridge rectifier circuit, bridge rectifiers are available as blocks containing all the diodes contained in a single "component" for use within the target circuit assembly. The use of these bridge rectifiers simplifies their use and the assembly of the final equipment as well as reducing the overall component count. The same was implemented by replacing the Schottky diodes by W10 [21].

5.1.2 Boost Converter

The output of the rectifier is fed to a boost converter and power management IC Bq25570 from Texas Instruments. The Bq25570 [22] device is a highly integrated energy harvesting Nano-Power management solution that is well suited for meeting the special needs of ultra-low-power applications. The product is specifically designed to efficiently acquire and manage the microwatts (μW) to milliwatts (mW) of power generated from a variety of DC sources like photovoltaic (solar) or thermal electric generators targeted toward products and systems, such as wireless sensor networks (WSN) which have stringent power and operational demands. The main boost charger is powered from the boost output, VSTOR. Once the VSTOR voltage is above VSTOR_CHGEN (1.8 V typical), for example, after a partially discharged battery is attached to VBAT, the boost charger can effectively extract power from low voltage output harvesters. The bq25570 also implements a programmable maximum power point tracking sampling network to optimize the transfer of power into the device.

5.1.3 Energy storage

In this design a super capacitor or a rechargeable lithium-ion (Li-ion) battery is used as the energy storage element.

Supercapacitor: Supercapacitors (SCs), also known as ultra-capacitors and electric double-layer capacitors, are finding use in a variety of power management applications. Supercapacitors are advantageous because they can be charged and discharged significantly more times than traditional lead-acid batteries, and can also absorb energy more rapidly without degrading their expected lifetime. These capabilities also make SCs attractive for industrial backup power supply systems, quick-recharge cordless power tools and remote sensors where the frequent replacement of batteries isn’t practical.

Li-ion battery: A Li-ion battery is chosen not only because of its small size, light weight, and good energy density, but also because it has no memory effect and slow self-discharge rate. However, Li-ion batteries should be handled with caution, especially in high temperatures, because they can easily ignite or explode. A commercial Li-ion rechargeable battery with nominal voltage of 3.7 V and maximum capacity of 100 mA h is used. The battery has a smaller size and a longer life time (up to 500 cycles charge/discharge) than conventional rechargeable cells. It has a built-in self-protection circuit to avoid over-charge or over-discharge.

5.1.4 Virtual Instrument for Acquiring Data

The software package used to build the virtual instrument for the project is LabVIEW-2012. LabVIEW stands for Laboratory Virtual Instrumentation Engineering Workbench. It is a system designing platform and development environment for a visual programming language from National Instruments. Virtual instrumentation is defined as the combination of measurement and control hardware and application software with industry standard technology to create user defined instrumentation system. LabVIEW programs are called Virtual Instrumentation (VI) where the operation resembles physical instruments and their functions. VI has the following two components:-

- Front panel - serves as user interface and control
- Block diagram - contains the graphical blocks and icons to define the functionality of the VI

LabVIEW has a set of blocks to perform function of an oscilloscope, function generator, bode analyser, impedance analyser, variable power supply etc., inbuilt in it for simulating the input signals and observe the output responses.

Block diagram and front panel of the VI developed for reading the data and storing it in a file is shown in Fig. 5.2 (a) & 5.2 (b) respectively. Then signal waveforms at different stages are displayed. 1st graph displays the VSTOR waveform. VBAT has been shown in 2nd graph. Output from rectifier stage (V_{RO}) is displayed in 3rd graph. EEH output from version-2 EEH (V_T) is displayed in 4th graph. The same signals are read from a file as shown in 5.3 (a) and 5.3 (b).

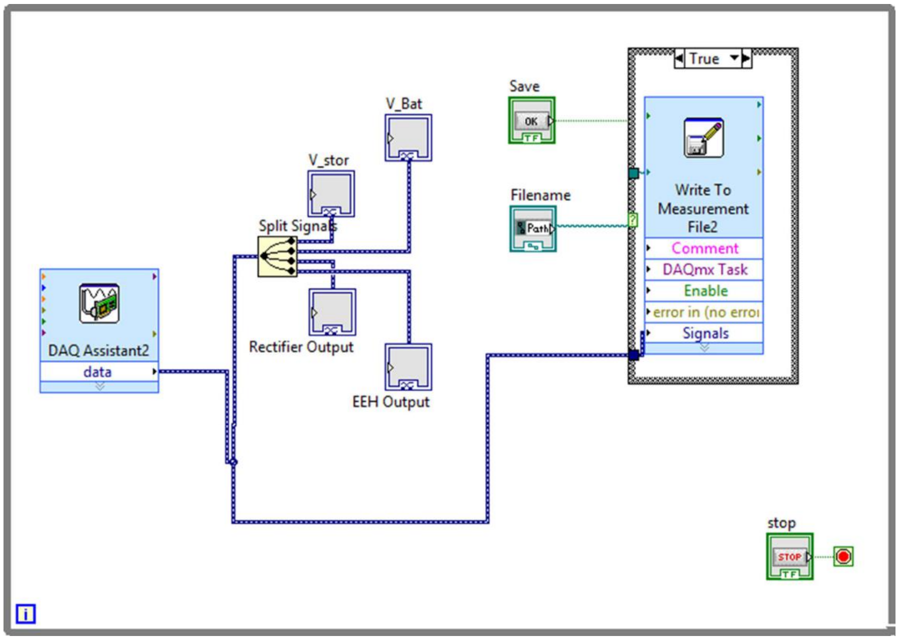

Fig. 5.2(a). *Block diagram of VI for writing the measured values into a file*

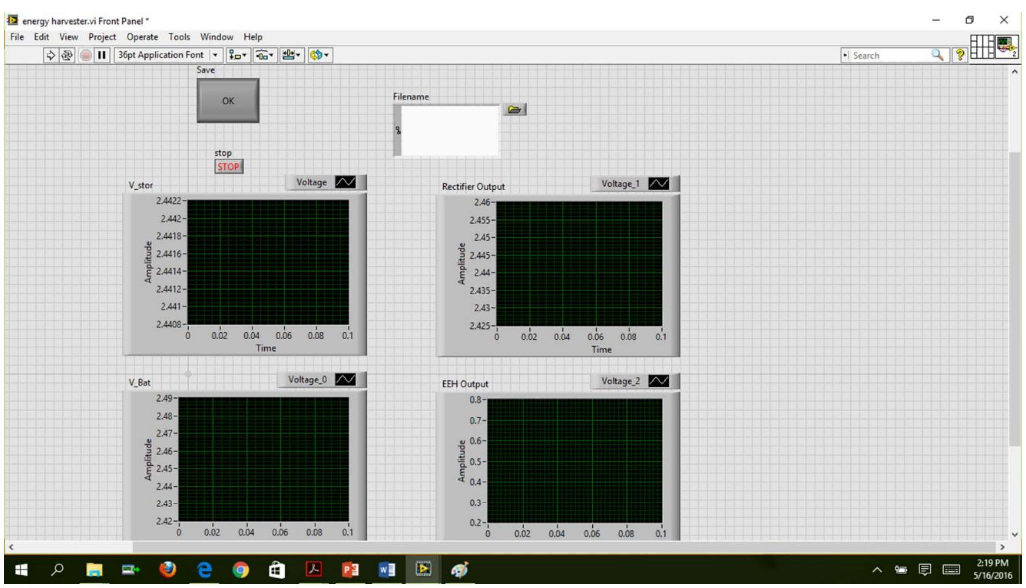

Fig. 5.2(b). *Front panel of VI for writing the measured values into a file*

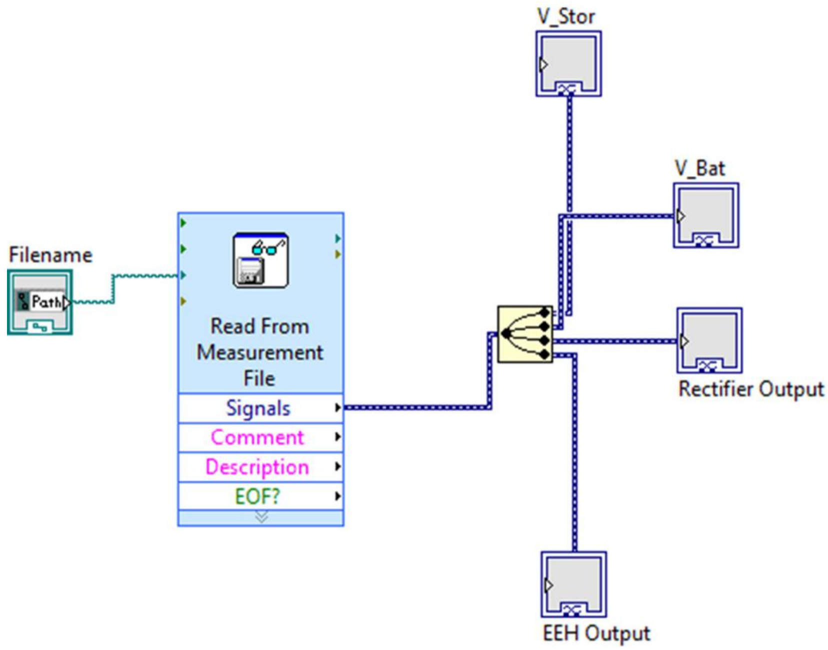

Fig. 5.3(a). *Block diagram of VI for reading the measured values from a file*

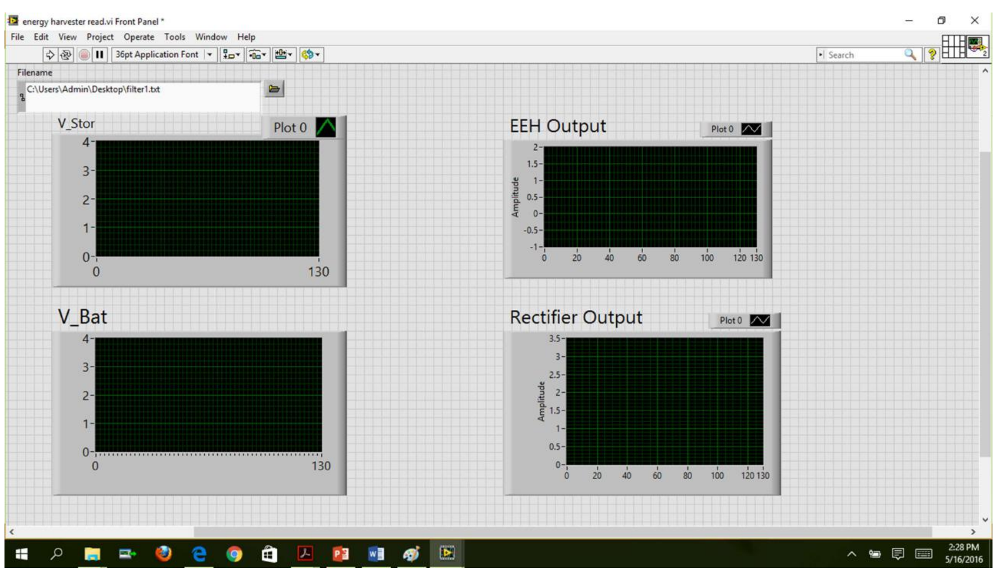

Fig. 5.3(b). *Front Panel of VI for reading the measured values from a file*

5.1.5 Complete Circuit

The complete circuit is shown in Fig.5.4. The EEH is the version-2 prototype. The power conditioning circuit is implemented using a Evaluation Module (EVM) of Bq25570 (Detailed description is placed as Appendix 'C') from Texas Instruments. The output from the rectifier stage is given to VIN of Bq25570 EVM and the storage element

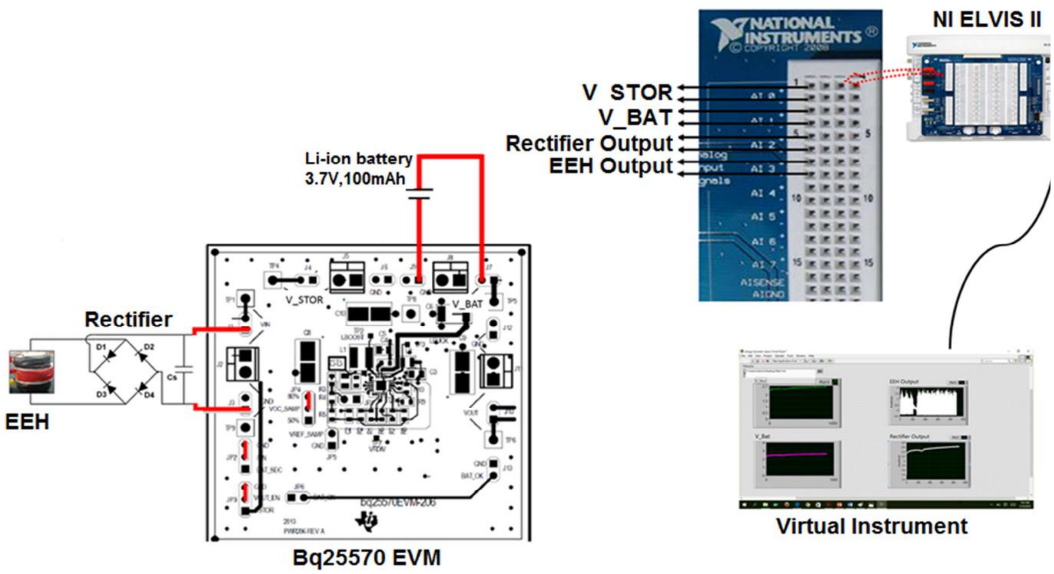

Fig. 5.4. *Test set-up for charging rechargeable Li-ion battery*

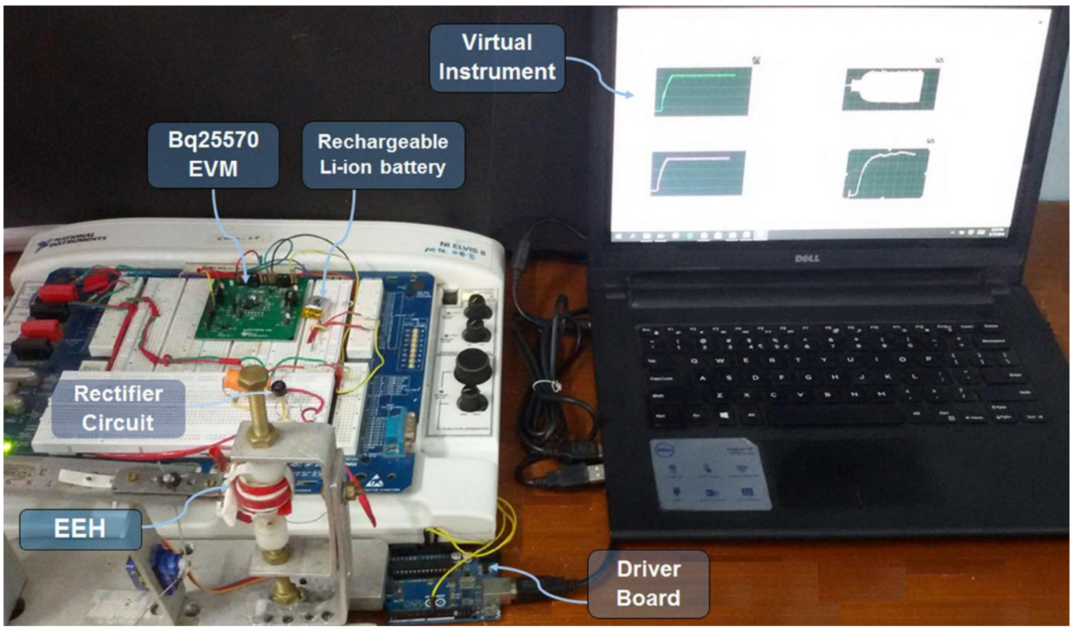

Fig.5.5. *Photograph of the experimental set-up. The Li-ion battery is charged via Bq25570 EVM.*

is connected to VBAT. The parameters are recorded using NI Elvis-II. A photograph of the entire set-up is shown in Fig.5.5.

5.1.6 Delivered energy

The energy reclamation of the harvester is checked by charging a super capacitor and a rechargeable Li-ion battery. A 47 mF supercapacitor is charged using the version-2 prototype EEH. The VSTOR, VBAT, Rectifier output (V_{RO}) and EEH output (V_T) are shown in Fig. 5.6.

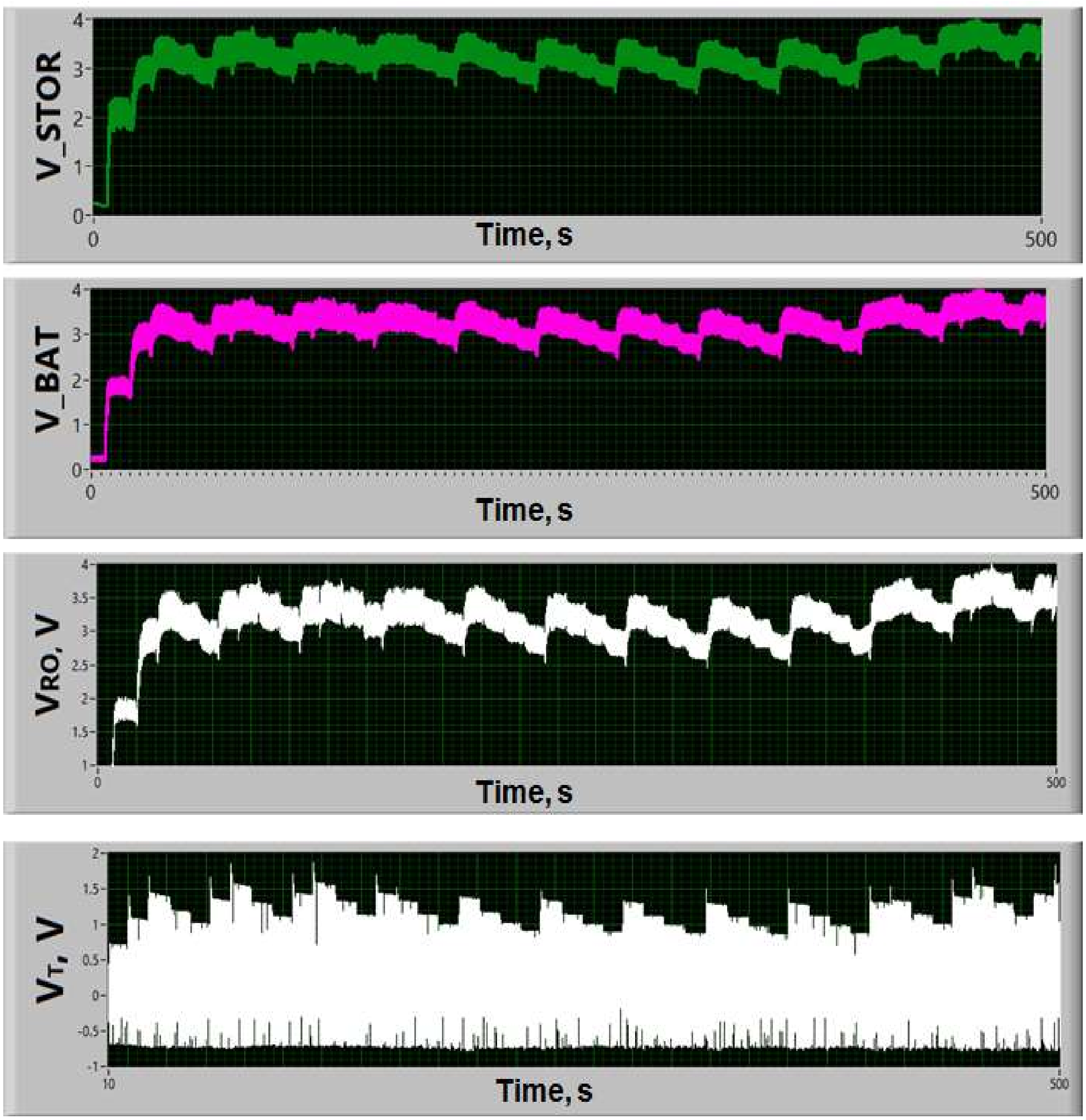

Fig.5.6. *Charging a 47mF supercapacitor*

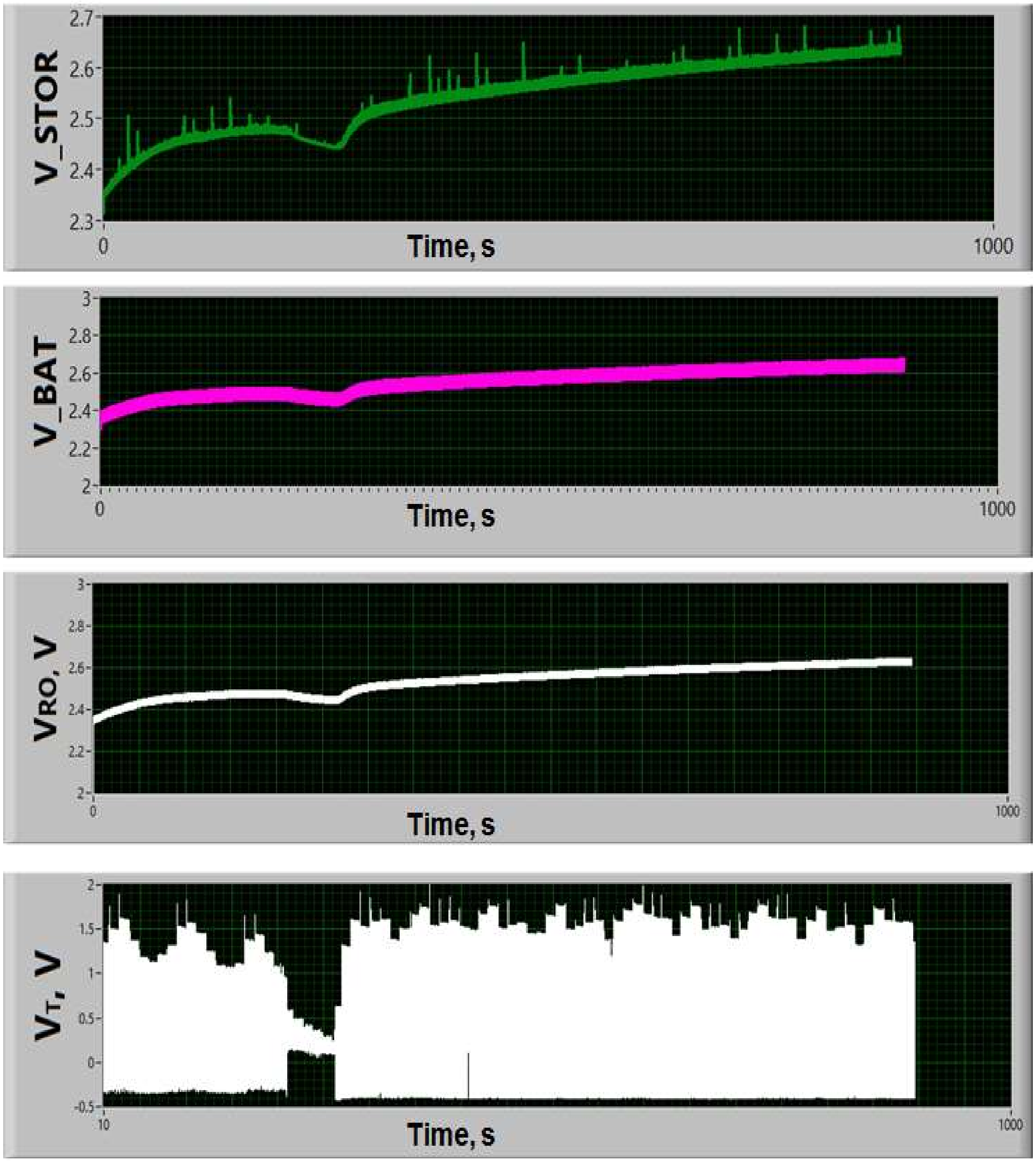

Fig.5.7. *Charging a rechargeable 3.7 V, 100 mAh Li-ion battery. The slight drop in voltage is attributed to a sudden fault in the string pulling the cantilever and hence EEH output was not available during that instant.*

It is observed that the supercapacitor charges to 1 V in 100 seconds meaning that the energy delivered is 23.5 mJ. This implies 70 µJ of energy is delivered per cycle (i.e., EEH making one up-down movement). A 3.7 V rechargeable Li-ion battery is also charged and the recorded waveforms are shown in Fig. 5.7.

5.1.7 Conclusion

The recorded parameters show that the harvester is suited for powering remote sensors especially in applications where we can have vibrations as that of a railway track. The prototype EEH delivers considerable energy at low frequency. A simple and suitable mechanical arrangement can be made to install the EEH below the rail between two sleepers. In the next chapter, design and working of a practical working model is discussed.

CHAPTER 6

A PRACTICAL DESIGN

In the previous chapter, it was brought out that the new flipping type EEH is superior to its counterparts considering its simplicity in construction and performance at low frequency vibrations. The proposed EEH can be used to scavenge energy from the railway track, when the train goes, and power the track monitoring sensors.

6.1 Design of EEH for Remote Sensors on Railway Track:

In this section the design of the practical Electromagnetic Energy Harvester (EEH) for powering railway trackside sensors is discussed. The arrangement and the working is illustrated in Fig. 6.1, 6.2 and 6.3. The Cylindrical Permanent Magnets (CPM) are mechanically coupled to the vibration source using an adjustable magnet holder. The whole arrangement is placed such that when the train wheel moves over the track, due to the vertical movement of the rail, the adjustable magnet holder moves down as shown in Fig. 6.2(a) &6.2(b) and when it moves up it retains back its original position as shown in Fig.6.1(a) & 6.1(b). The spring is intended for the up movement of the adjustable

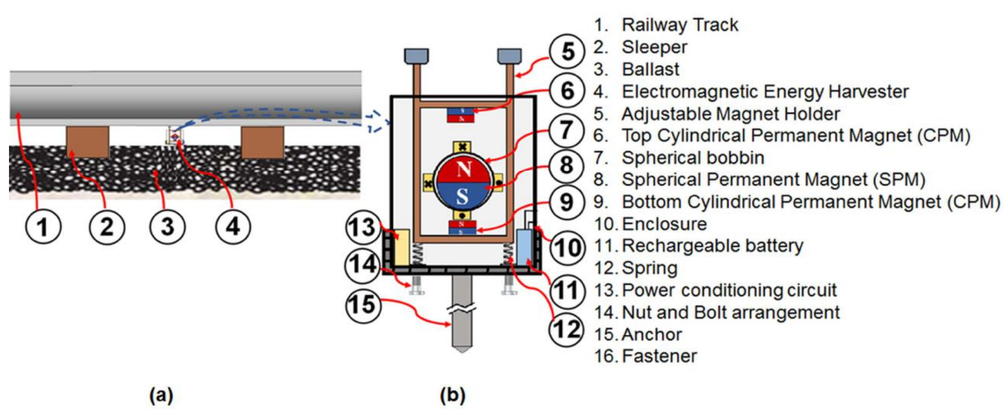

Fig. 6.1. *EEH under the no load condition of the track (Spherical bobbin structure).*

magnetic holder as the train wheel leave the track position. The vertical position of the spring and thereby of the magnet holder (in relation to the enclosure) is adjusted by a nut and bolt mechanism. The top most section of the adjustable magnet holder can be a rubber shoe or a magnet so that the EEH remains attached to the track. Hence the CPMs can freely move with the rail, while the Spherical Permanent Magnet (SPM) inside the spherical bobbin remains fixed to the frame, which is stationary with respect to the vibration.

As mentioned above, when the train moves over the track, the track deflects vertically due to the load exerted by the train bogies. Fig. 6.1(a) shows the state when the load is not on the EEH. In this state, the springs are relaxed and holds the magnet holder in its position as shown in Fig. 6.1(b). Also, the bottom CPM (north) remains close to the SPM (south). When the wheel is over the track, the load is exerted on the EEH as shown in Fig. 6.2 (a). The magnet holder is pushed down and the springs get compressed. Now, as the magnet holder is pushed down, the top CPM approaches the SPM and the bottom CPM moves away. As the north face of the top CPM approaches the north face of the SPM, the SPM gets repelled. Since it is a free to rotate body, it will turn by say some

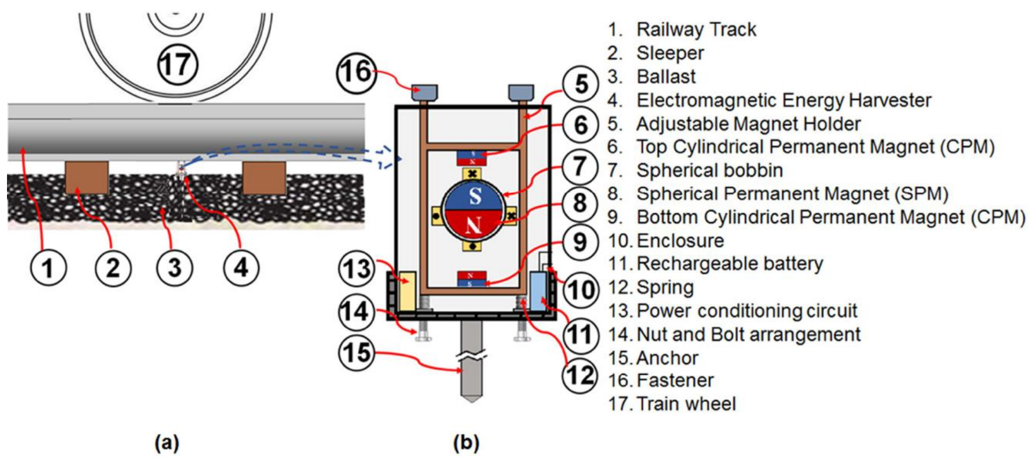

Fig.6.2. EEH *when the load is exerted on the track (Spherical bobbin structure).*

small angle. Once it rotates by some angle, the south face of SPM will get attracted towards the north of the top CPM and will quickly align as in Fig. 6.2 (b). Once the wheel moves away from the position of EEH installation, the magnet holder moves back to its position, moving the bottom CPM towards the SPM and the top CPM away. Under the influence of bottom CPM the SPM again flips to the initial position as in Fig. 6.1(b).

Thus, the magnetic arrangement of the new EEH is such that whenever there is an up/down movement in the vibration source the SPM flips. The flipping of the SPM occurs whenever the SPM reaches a specific position in its vertical travel path, making the flipping independent of the speed at which the source moves. Whenever SPM flips, there will be a rate of change of flux linkage for the vertical and horizontal windings and

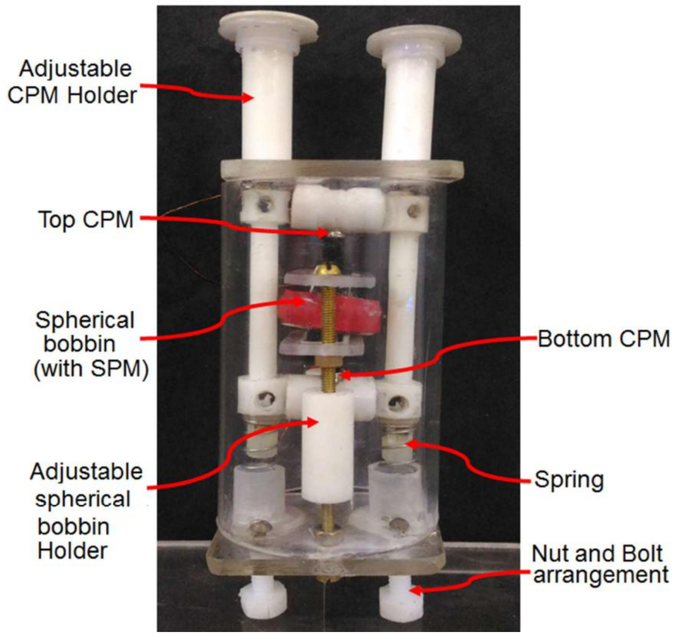

Fig.6.3. *Practical working model.*

hence voltages will be inducted in them, irrespective of the speed of the movement of the vibration source, which is a major advantage for EEHs that are coupled to low frequency sources. A photograph showing the practical working model developed and its working are placed as Fig. 6.3 and Fig.6.4 respectively.

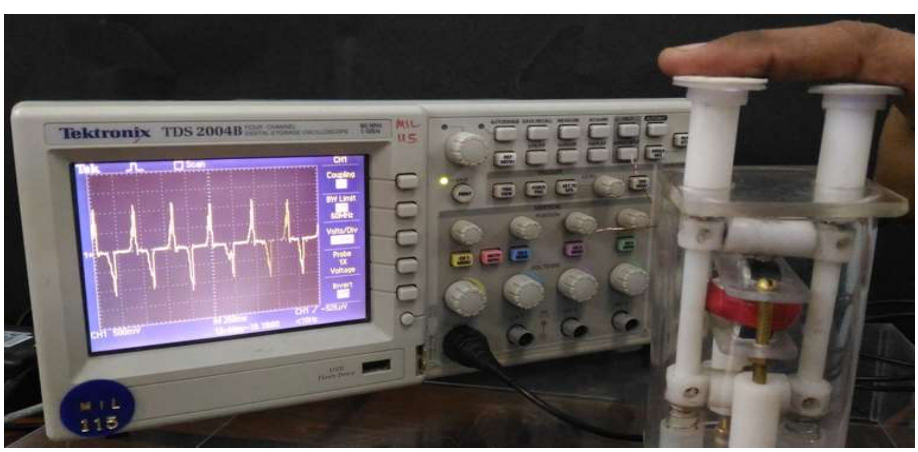

Fig.6.4. *Photograph showing the working of the EEH developed.*

CHAPTER 7

CONCLUSION

7.1 Summary of the Work

In this work, flipping magnet based vibrational energy harvester intended for scavenging energy from low frequency vibrations such as railway tracks are researched. A simple design is employed using a spherical permanent magnet NdFeB ball that is allowed to flip in a particular fashion inside a cavity wrapped with copper coil windings. Two prototypes, one spherical cage and other its optimized version in cylindrical configuration were built and tested. As the ball flips within the cavity, the time- varying magnetic flux induces a voltage in the coil according to Faraday's Law. The major advantage is that induced voltage is not dependent on the speed of the vibrational source. The spherical cage harvester can generate an open circuit voltage of 3.5 V (P-P). The power density of the harvester is 445µW/cm^{3}obtained at a matched load of 52.5Ω at 3.5Hz. The cylindrical prototype harvester has power density of 538.6µW/cm^3 .The generator can be fixed to the railway track to harvest energy from railway track low frequency (1-4Hz) vibrations and the power levels of the generator can reach up to 1.6 to 2.4mW, which is a considerable power for trackside sensors.

The EEH is capable of charging rechargeable batteries or super capacitor. A rechargeable Li-ion battery (3.7V, 100mAh) and a 47mF supercapacitor were charged using the proposed EEH. The maximum energy delivered per cycle is 70µJ. A working model with simple design is developed in the laboratory which can be placed under the railway track for scavenging energy.

The work has been submitted to IET Electronic letters which is under review and a provisional patent has been filed.

Journal under Review : Raja Paul and Boby George "Automatic Flipping Magnet Type Electromagnetic Energy Harvester" *IET Electronic Letters*.

Patent (Provisional Filed) : "Automatic Flipping Magnet Type Electromagnetic Energy Harvester" Application *no.201641014441 dated* 26/04/2016.

7.2 Future Scope

The system can be further improved by shrinking the size and increasing the output power. The spherical energy harvester design can also be improved by optimizing the structure and the coil winding. Furthermore, impedance matching techniques can be implemented to maximize the output power of the system, especially when the transducer type and the load conditions are pre-defined.

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[21] http://www.farnell.com/datasheets/315955.pdf

[22] http://www.ti.com/lit/ds/symlink/bq25570.pdf

APPENDIX-A

C-CODE PROGRAM :ATMEGA8 MICROCONTROLLER

The program is written for driving the servo motor by using ATMEGA8 microcontroller. With minor changes in the code the same program was used for driving the motor at different speeds so as to mimic the railway track like vibrations.

```
/* servo.c
  * Created: 12-07-2015 10:11:56
 *  Author: Raja
*/

#include <Servo.h>
 Servo myservo;  // create servo object to control a servo
 int pos = 0;    // variable to store the servo position
 void setup()
{
 myservo.attach(9);  // attaches the servo on pin 9 to the servo object
}
 void loop()
{
 for(pos = 0; pos <= 130; pos += 1) // goes from 0 degrees to 130 degrees
{                                   // in steps of 1 degree
 myservo.write(pos);              // tell servo to go to position in variable 'pos'
delay(2);                       // waits 2ms for the servo to reach the position
}
```

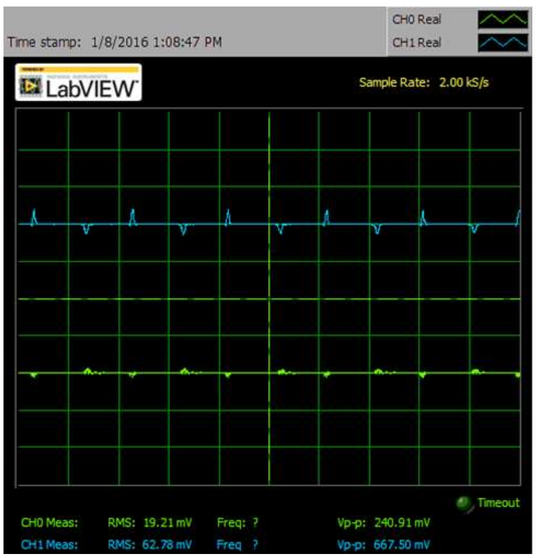
```
for(pos = 130; pos>=0; pos-=1)     // goes from 130 degrees to 0 degrees
{
 myservo.write(pos);              // tell servo to go to position in variable 'pos'
 delay(15);                       // waits 15ms for the servo to reach the position
}
}
```

APPENDIX-B

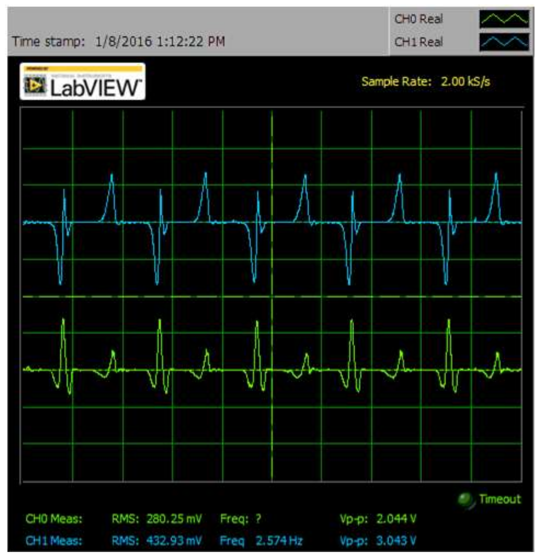
TEST RESULTS : VERSION-1 EEH PROTOTYPE

Induced peak voltage vs Gap between the cylindrical magnets

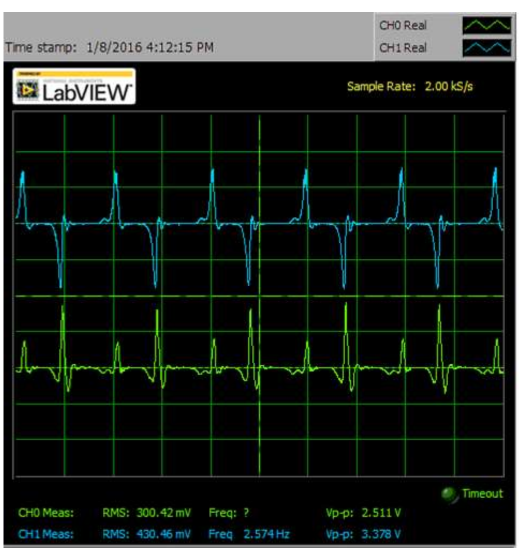
The peak induced voltage varies as a function of the distance between the spherical assembly and the cylindrical magnets. The GAP referred here is the distance between the vertical winding and bottom cylindrical magnet. The recorded waveforms of the induced voltages is given below.



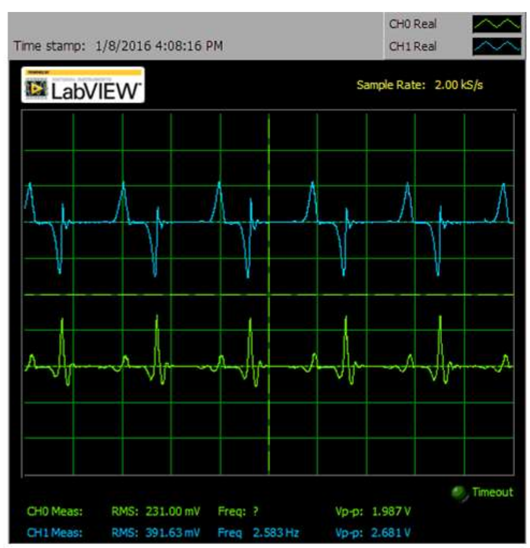
Gap=5mm



Gap=10mm



Gap=13mm



Gap=17mm

APPENDIX-C

POWER CONDITIONING MODULE

1 *EVM Bq25570 Features*

- Evaluation module for bq25570
- Ultra-low power boost charger and buck converter with battery management for energy harvester applications
- Resistor-programmable settings for over voltage providing flexible battery management
- Programmable push-pull output indicator for battery status (VBAT_OK)
- Test points for key signals available for testing purpose – easy probe hook-up.
- Jumpers available – easy to change settings

2 *General Description*

The bq25570 is an integrated energy harvesting Nano-Power management solution that is well suited for meeting the special needs of ultra-low power applications. The product is specifically designed to efficiently acquire and manage the microwatts (µW) to miliwatts (mW) of power generated from a variety of high output impedance (HiZ) DC sources like photovoltaic (solar) or thermal electric generators; or with an AC/DC rectifier, a piezoelectric generator. The bq25570 implements a highly efficient, pulse-frequency modulated (PFM) boost converter/charger targeted toward products and systems, such as wireless sensor networks (WSN) which have stringent power and operational demands. Assuming a depleted storage element has been attached, the bq25570 DC-DC boost converter/charger that requires only microwatts of power to begin operating in cold start mode. Once the boost converter output, VSTOR, reaches ~1.8 V and can now power the converter, the main boost converter can now more efficiently extract power from low voltage output harvesters such as thermoelectric generators (TEGs) or single and dual cell solar panels. For example, assuming the HiZ input source can provide at least 5 μW typical and the load on VSTOR (including the storage element leakage current) is less than 1 μA of leakage current, the boost converter can be started with VIN_DC as low as 330 mV typical, and once VSTOR reaches 1.8 V, can continue to harvest energy down to VIN_DC ≃ 120 mV. The integrated PFM buck converter is also powered from VSTOR and, assuming enough input power is available, provides up to 100 mA from the VOUT pin. The VOUT voltage is externally programmed to slightly less than the VSTOR voltage.

HiZ DC sources have a maximum output power point (MPP) that varies with ambient conditions. For example, a solar panel's MPP varies with the amount of light on the panel and with temperature. The MPP is listed by the harvesting source manufacturer as a percentage of its open circuit (OC) voltage. Therefore, the bq25570 implements a programmable maximum power point tracking (MPPT) sampling network to optimize the transfer of power into the device. The bq25570 periodically samples the open circuit input voltage every 16 seconds by disabling the boost converter for 256 ms and stores the programmed MPP ratio of the OC voltage on the external reference capacitor (C2) at VREF_SAMP. Typically solar cells are at their MPP when loaded to ~70–80% of their OC voltage and TEGs at ~50%. While the storage element is less than the user programmed maximum voltage (VBAT_OV), the boost charger loads the harvesting source until VIN_DC reaches the MPP (voltage at VREF_SAMP). This results in the boost charger regulating the input voltage of the converter until the output reaches VBAT_OV, thus transferring the maximum amount of power currently available per ambient conditions to the output.

The battery under voltage, VBAT_UV, threshold is checked continuously to ensure that the internal battery FET, connecting VSTOR to VBAT, does not turn on until VSTOR is above the VBAT_UV threshold (2.0 V).The over voltage (VBAT_OV) setting initially is lower than the programmed value at startup (varies on conditions) and is updated after the first ~32 ms. Subsequent updates are every ~64 ms. The VBAT_OV threshold sets maximum voltage on VSTOR and the boost converter stops switching when the voltage on VSTOR reaches the VBAT_OV threshold. The open circuit input voltage (VIN_OC) is measured every ~16 seconds in order for the Maximum Power Point Tracking (MPPT) circuit to sample and hold the input regulation voltage. This periodic update continually optimizes maximum power delivery based on the harvesting conditions.

The bq25570 was designed with the flexibility to support a variety of energy storage elements. The availability of the sources from which harvesters extract their energy can often be sporadic or time-varying. Systems will typically need some type of energy storage element, such as a re-chargeable battery, super capacitor, or conventional capacitor. The storage element will make certain constant power is available when needed for the systems. In general, the storage element also allows the system to handle any peak currents that cannot directly come from the input source. It is important to remember that batteries and super capacitors can have significant leakage currents that need to be included with determining the loading on VSTOR.

To prevent damage to a customer's storage element, both maximum and minimum voltages are monitored against the internally programmed under-voltage (VBAT_UV) and user programmed over-voltage (VBAT_OV) levels. One of the applications using a solar energy harvester is given below is shown below.

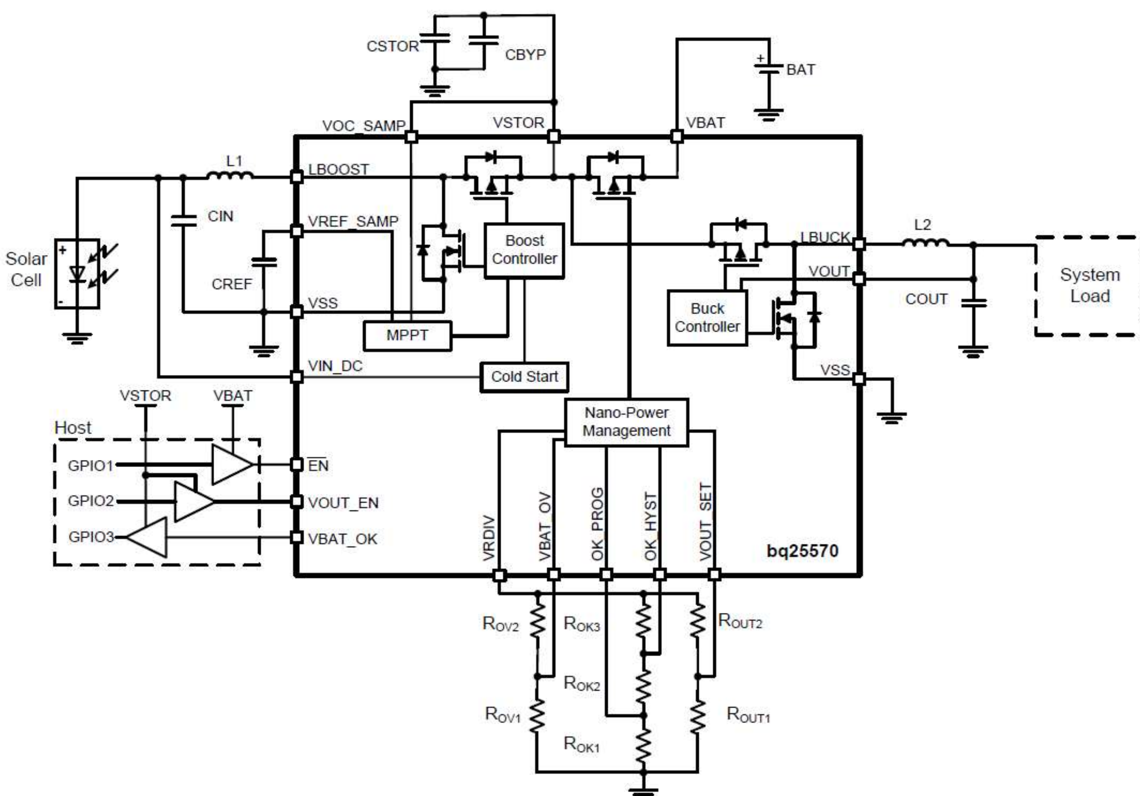


Fig.C1. *Application of Bq25570* [22]

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Patent (Provisional Filed) : "Automatic Flipping Magnet Type Electromagnetic Energy Harvester" Application *no.201641014441 dated* 26/04/2016.