DEVELOPMENT OF LOW VOLTAGE MANAGEMENT CIRCUIT FOR LOW FREQUENCY VIBRATION ENERGY HARVESTING

MOHAMAD IZUDIN BIN ALISAH

UNIVERSITI SAINS MALAYSIA

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by

MOHAMAD IZUDIN BIN ALISAH

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LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct current
DLC	Double-layer capacitor
FB	Feedback
FE	Finite element
IC	Integrated circuit
ICI	MOSFET control circuit
LDO	Low-dropout
LT	Linear Technology
MEMS	Microelectromechanical system
MOSFET	Metal-oxide-semiconductor field-effect transistors
MPPC	Maximum power point control
MPPC	Maximum power point control
NdFeB	Neodymium boron
NI	National Instrument
NimH	Nickel-metal hydride
PC	Personal computer
PCB	Printed circuit board
PFIG	Parametric Frequency-Increased Generator
PN	P-type and N-type semiconductor materials
PVDF	Polyvinylidene fluoride
PZT	Ceramic lead zirconate titanate

RF	Radio frequency
RFID	Radio-frequency identification
RP	Rapid prototyping
SECE	Synchronous electric charge extraction
SHM	Structural health monitoring
Si	Silicone
SmCo	Samarium cobalt
SSDCI	Synchronous Switching and Discharging on a storage Capacitor
SSHI	Synchronous switch harvesting on inductor
VCA	Voice coil actuator
WSN	Wireless sensor nodes

LIST OF SYMBOLS

A	Area of the coil
B	Magnetic flux density
c	Damping coefficient
C	Capacitance
C_{AUX}	Auxiliary capacitor
C_o	Output capacitor
C_P	Piezoelectric capacitance
C_r	Smoothing capacitor of rectifier circuit
C_s	Smoothing capacitor of synchronous electric charge extraction circuit
C_u	Smoothing capacitor of synchronous Switching and Discharging on a storage Capacitor trough an Inductor circuit
E	Amplitude of voltage multiplier
$\boldsymbol{E}_T$	Total energy
$\boldsymbol{i}$	Electric current
I_P	Piezoelectric current
I_r	Rectified current
k	Spring constant
L	Inductance
m	Inertia mass
N	Number of turn of the coil
P	Total power
P_{AC}	Alternative current input power

$P_{average}$	Average power
P_{DC}	Direct current output power
R_L	Load resistance
R_{MPPC}	Resistance of maximum power point control
S	Electronic switch
t	Run time
V	Voltage
V_{AUX}	Auxiliary voltage
V_c	Voltage across capacitor
V_{dd}	Positive supply voltage of field-effect transistor
$\boldsymbol{V_{emf}}$	Back electromotive force
V_{IN}	Input voltage
V_{MPPC}	Voltage of maximum power point control
V_{OUT}	Output voltage
V_P	Piezoelectric voltage
V_{PP}	Peak to peak voltage
W	Energy store
$y(t)$	Displacement of vibrating generator housing
$z(t)$	Displacement of the mass relative to the generator housing
η	Efficiency
Φ	Magnetic flux
ω_n	Natural frequency

PEMBANGUNAN LITAR PENGURUSAN VOLTAN RENDAH UNTUK PENUAI TENAGA GETARAN BERFREKUENSI RENDAH

ABSTRAK

Kajian ini membentangkan pembangunan tenaga penuai getaran berfrekuensi rendah menggunakan penjana electromagnet dan litar pengurusan voltan untuk membekalkan kuasa kepada penderia tanpa wayar. Tujuan kajian ini adalah untuk menyelesaikan masalah apabila penderia kehabisan bekalan tenaga terutamanya pada unit yang dipasang pada struktur yang sukar diakses dan diselenggara. Memandangkan voltan dan kuasa yang dihasilkan bergantung pada frekuensi masuk, maka litar pengurusan voltan yang khusus diperlukan untuk mengawal dan menyimpan tenaga elekrik. Penjana elektromagnet difabrikasi menggunakan empat penggerak gegelung suara yang dibuat daripada magnet neodimium dan gegelung tembaga. Kuasa maksimum sebanyak 0.94, 3.3, 6.4 dan 15.5 mW dijana oleh penjana elektromagnet pada frekuensi 4 Hz, 6 Hz, 8 Hz dan 10 Hz pada tahap pecutan 3.5 m/s^2. Nod penderia iaitu penganding suhu NI-WSN 3212 menggunakan sebanyak 9.5 mW ketika mod siap sedia, 42.1 mW ketika mod mengesan suhu dan 105.3 mW ketika mod menghantar data. Sumbangan utama kajian ini ialah pembinaan litar yang berupaya menukar voltan rendah serendah 0.24 V dan menjana kuasa sendiri tanpa memerlukan bekalan kuasa luar. Litar tersebut terdiri daripada pengganda voltan berambang rendah, LTC3105 penukar peningkat dan kapasitor besar sebagai penyimpan tenaga. Tenaga yang disimpan berupaya untuk membekalkan tenaga kepada penderia tanpa wayar ketika mod penghantaran data iaitu sebanyak 3300 dan 2100 kitaran bagi setiap bacaan sampel 5 saat dan 1 saat. Kesimpulannya, integrasi antara penjana elektromagnet dan litar pengurusan voltan yang dibina berjaya membekalkan tenaga untuk menghidupkan NI-WSN 3212.

DEVELOPMENT OF LOW VOLTAGE MANAGEMENT CIRCUIT FOR LOW FREQUENCY VIBRATION ENERGY HARVESTING

ABSTRACT

This research presents a development of a low frequency vibration energy harvesting based on electromagnetic harvester with voltage management circuit to power up wireless sensor nodes. This is important for cases where the sensors have no consistent energy supply especially at installations where access is difficult. Since the generated voltage and power are strongly dependent on the input frequency, it is necessary to have specific low voltage management circuit to condition and store the electrical energy. The electromagnetic harvester consists of four voice coil actuators made of neodymium magnet and copper coils. Maximum power output of 0.94, 3.3, 6.4 and 15.5 mW were generated by the harvester for frequency of 4 Hz, 6 Hz, 8 Hz and 10 Hz at acceleration level of 3.5 m/s^2. The sensor node based on NI-WSN thermocouple input consumed 9.5 mW during standby mode, 42.1 mW when temperature sensing and 105.3 mW during data transmission mode. The main contribution of this research is the circuit which can rectify low voltage as low as 0.24 V and requires no external power supply to operate. It comprises of low threshold diode voltage multiplier, LTC3105 boost converter and supercapacitor as storage energy. The stored energy was enough to power up the sensor node transmission for 3300 and 2100 cycles when connected to sensor node for every 5 s and 1 s reading samples. The integration of the electromagnetic harvester and voltage management circuit constructed has successfully powered the NI-WSN 3212.

CHAPTER 1

INTRODUCTION

1.1 Background

Development of wireless sensor networks (WSN) technology in the last decade has enabled these miniaturized embedded modules to be integrated in various applications for example habitat tracking, structural surveying, response in medical emergency and building energy management (Merlino and Abramo 2009). With the use of WSNs, the installation and maintenance of the wires are avoided and reduced in costs. These have made it suitable sensors for remote areas where access is difficult. There is also benefit of reduced risk to the exposure to the hazardous electro chemicals with less leakage and aging effects, flexibility re-location of such electronic devices (Mitcheson et al., 2008b).

The biggest issue faced by the sensor nodes and other electronic devices is energy supply. As the sensor device is drained of energy, it can no longer complete its function until the energy source is renewed. Various researches on the sensor nodes considered the usage of a finite energy source which consists of rechargeable batteries in order to power the sensors. Minimizing the usage of energy by prolong the network lifetime also considered by several researches. However, batteries will facing leakages of current that will drain the energy despite they are left unused (Guan and Liao 2007). Furthermore, replacing the drained batteries can be expensive and also impracticable if the sensor node comprises of multiple numbers or if the nodes are placed at remote location. Furthermore, some disposable batteries are harmful and dangerous to the surrounding environment (Kang et al., 2013).

To overcome this problem, it has inspired the investigation for an alternative source of energy to power WSNs for example applications that require sensors to be assembled for a long operation time especially in area that are challenging to access. Also, when the sensors are embedded in the structures where replacement of the battery is impossible. A practicable method is by replacing the conventional batteries with the energy harvester from ambient.

Energy harvesting or energy scavenging is a process of conversion of ambient energy from surrounding into useful electrical energy. These may come in the form of thermal (Venkatasubramanian et al., 2007), radio-frequency (RF) (Burch et al., 2006), solar (Sangani, 2007), and vibration (Le et al., 2006; Mitcheson et al., 2008a; Kulah and Najafi 2004). This energy can be a usable source of energy to power up WSNs. Figure 1.1 shows a comparison of the stored energy of battery and an energy harvesting device. In this figure, the batteries will finally deplete however for the energy harvesting device it can generate energy over a much longer period. In short, energy harvesting device can be potentially used for powering WSN.

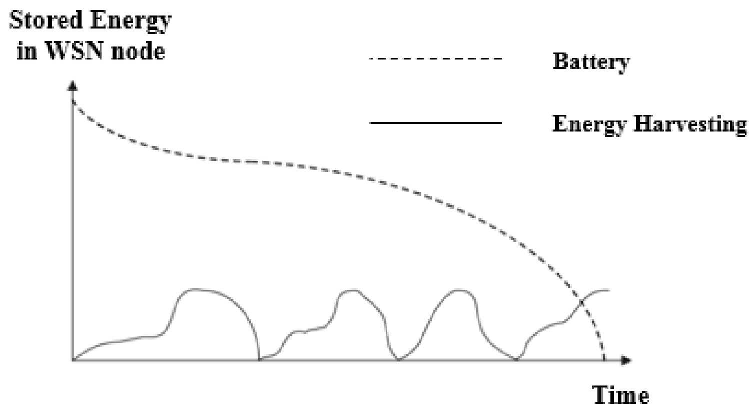

Figure 1.1: Comparison of the stored energy in a wireless sensor node system powered by a battery or powered by energy harvesting (Eu et al., 2011)

This research is focusing on vibration energy harvesting of ambient structure. Harvesting energy from the bridges vibration is the most feasible harvester method of extracting the wasted energy where this energy can be scavenges from the vibration of the structure as the vehicles passing through it. For vibration, WSNs and energy harvesters have been implemented on trial basis on bridges as presented by Zribi and Almutairi (2006) and Whelan et al. (2007). For bridges, it is still a challenge due to the location, communication and also the very low frequency in the range of 4 - 10 Hz. In order to solve this problem, this project focuses on the possibility of harvesting the energy at low frequency in the range of 4 - 10 Hz.

Electromagnetic (Zorlu et al., 2013), piezoelectric (Ferrari et al., 2008) and electrostatic (Mitcheson et al., 2008a) are type of mechanism that can transform mechanical vibration into useful electrical energy. Electromagnetic harvesters are robust, inexpensive and do not require smart material. Hence, they are a suitable vibration energy source for the sensors.

Another challenge of vibration energy harvesting is that the power output from the electromagnetic harvester is not necessarily in the form of specific voltage and power characteristics as required by the load. Thus, low voltage circuitry is required to realize the real application.

In addition, as the output from the electromagnetic behave as alternative current (AC) and the maximum electromotive force and generated electrical power from a vibrating mass is strongly dependent on the vibration frequency (Mizuno and Chetwynd 2003), it is necessary to develop specific energy harvesting circuit to condition and store the electrical energy to adapt to the intermittent energy from the bridge vibration.

1.2 Problem statement

Utilizing low frequency energy harvesting on the structural vibration to power up WSNs in condition monitoring presents a big challenge due to the voltage and power characteristics of such harvester is strongly dependant on input frequency (Mizuno and Chetwynd 2003). As the input frequency of bridges is low (below than 10 Hz), the generated power would be low and it is insufficient to power up the WSN. Therefore, it is necessary to have special low powered circuit to condition and store the electrical energy to power up the WSN.

1.3 Motivation

The application of the low frequency vibration energy harvesting for powering low power consumption electronic devices are needed because most of frequency found at ambient vibration are in low range.

1.4 Objectives

The objective of this research is

a) to develop low power circuit to condition and store the electrical energy obtained from a vibration energy harvester at frequency range 4 Hz to 10 Hz.
b) to determine the power consumption of the wireless sensor nodes and design the voltage management circuit.
c) to fabricate and implement the circuit to capture the electrical energy from harvester to power up wireless sensor node.

1.5 Scope of the project

To power a wireless sensor node from vibrational energy, the whole system including an electromagnetic harvester, a voltage management circuit, and storage element is needed as shown in Figure 1.2.

Figure 1.2: Block diagram describing a vibration energy harvesting system.

Key definitions in the project scope are:

AC Converter – Rectifying circuit, which is the voltage multiplier that rectifies the electromagnetic AC voltage into direct current (DC) voltage while charging the supercapacitor.

Boost converter – LTC3105 that step up the generated low voltage to the voltage requirement by WSN.

Low voltage – Electromagnetic harvester output voltages of below 1.5 V

Low frequency – Mechanical vibration of below 10 Hz

Power – The generated power levels is in miliwatts range

1.6 Thesis outline

The thesis introduces the concepts of vibrational energy harvesting based electromagnetic harvester, self-powered sensor node using vibration energy harvesting and interface electronic. Different vibrational harvesting conversion and energy harvesting circuitry topologies will be analysed and compared and a topology is chosen to be implemented and tested. The thesis rounds off by discussing the results and stating the further work needed. Abbreviations are listed in the nomenclature placed immediately after the table of contents.

1. **Introduction** introduces the reader to energy harvesting and what the harvested energy is being used for.
2. **Literature review** covers the mechanical and electrical aspects of vibration harvesting energy with electromagnetic harvesters. The common circuit topologies for harvesting energy based vibration are discussed. The topologies are compared and one is chosen to be analysed further and implemented as a prototype.
3. **Methodology** analyses the detail design of electromagnetic harvester prototype and chosen circuit topology via simulations and implementation.
4. **Results** present the harvesting results from the test of the implemented prototype.
5. **Conclusion** rounds off the thesis and discusses the challenges of vibrational energy harvesting in the low frequency range.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Ambient energy sources feasible for harvesting are typically thermoelectric power converter (Strasser et al., 2004; Stordeur and Stark 1997; Venkatasubramanian et al., 2007), RF converter (Burch et al., 2006; Valberg et al., 2006), solar energy converter (Sangani 2007); and mechanical vibration converter (Glynne-Jones et al., 2004; Gherca and Olaru 2011).

Thermoelectric harvester is available commonly from thermocouples based on a temperature different or heat flowing between different materials however less of successful work for capturing enough power until recent days (Chao 2011). The waste radiation energy from the environment can be used in the conversion of RF waves into electrical energy for powering electronic circuit in RF module (Piñuela et al., 2013). However, scavenged energy is finite but sufficient for decoding RF signals.

Solar energy harvesting becomes the most grown-up technology and commercially however they are not suited for portable devices due to the absence of continuous lighting (Chao 2011). Thus, the vibration energy conversion becomes the best choice for portable low power consumption devices such as wireless sensor nodes because of its high efficiency, ubiquitous availability and scalability to small sizes (Poulin et al., 2004). Based on the above, the main focus of this research is on the development of vibration energy harvesting transducers and associated power conditioning circuit for powering WSN.

2.2 Vibration energy harvesting

Vibration energy is present all around us mainly in bridges, roads, rail tracks and vehicle engine. Transformation of vibration energy into electrical energy can be based on electrostatic (Mitcheson et al., 2008a; Mitcheson et al., 2003), piezoelectric effect (Anton and Sodano 2007; Roundy and Wright 2004) and electromagnetic (Glynne-Jones et al., 2004). The detail of each transducer mechanism is presented below.

2.2.1 Electrostatic harvester

The concept of electrostatic harvester is a variable capacitor (two conductors) which is move relative to one another separated by dielectric materials. The harvester can be configured as in-plane overlapping, in-plane gap closing and out-of-plane closing as illustrated in Figure 2.1.

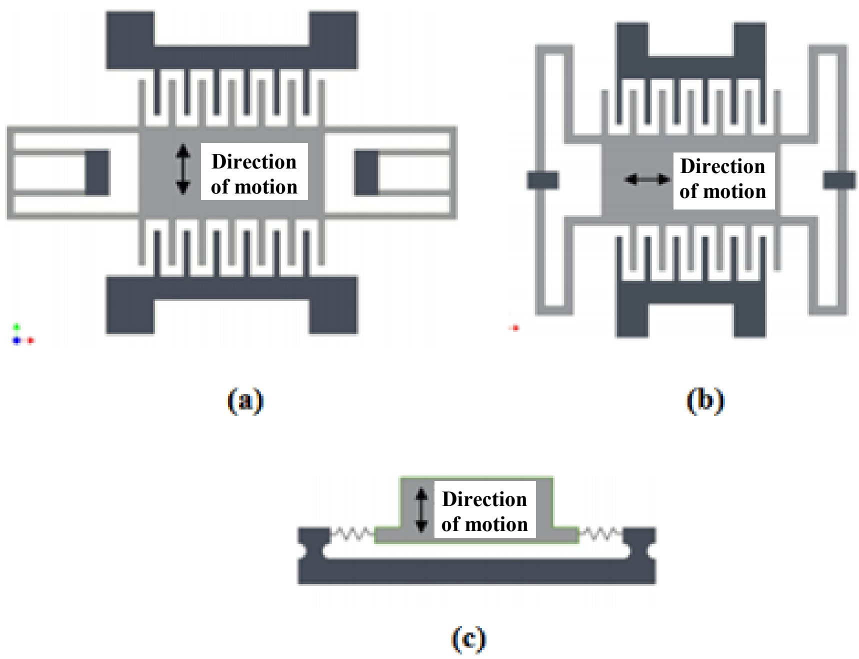

Figure 2.1: Electrostatic harvesters configuration (Beeby et al., 2006) (a) In-plane overlapping (b) In-plane gap closing (c) Out-of-plane gap closing

The transducer in-plane overlapping has the smallest parasitic damping ratio but has the least capacitance. The out-of-plane gap closing transducer has the greatest capacitance but have the largest mechanical damping while the in-plane gap closing transducer has a large capacitance but requires mechanical stops to avoid the capacitor plates from in contact to each other.

Effort on harvesting vibration energy by the electrostatic mechanism has being researched for example microelectromechanical system (MEMS) in-plane gap closing electrostatic generators for generator area of 80 mm^2 was designed and developed by Chiu et al. (2007), output power of 0.2 μW was obtained for optimal load of 8 MΩ. Next, Naruse et al. (2009) developed electrostatic generator to harvest energy from human motion where the excitation frequency is 2 Hz at 0.4 g amplitude vibration. As shown in Figure 2.2, this generator is fabricated with the use of detached spring, mass to manage the vibration, two glass substrates, two silicone (Si) substrates and micro balls for supporting the moving parts between the substrates. The report shows 40 μW power output was produced respectively.

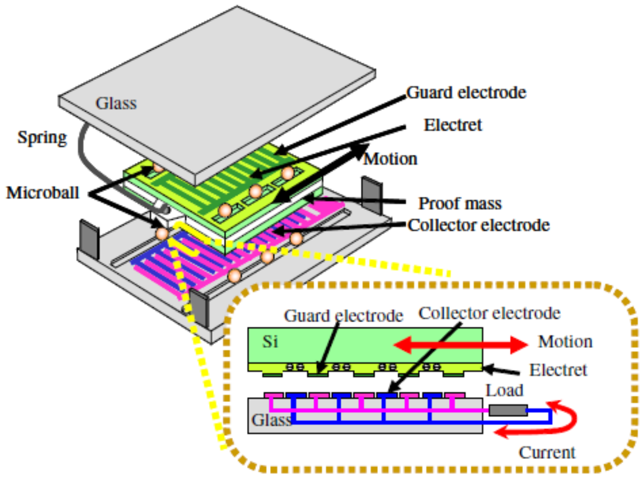

Figure 2.2: Electrostatic power generator for human motion (Naruse et al., 2009)

MEMS electrostatic generator has been developed by Suzuki et al. (2010) to implement the control of gap-spacing approach for preventing stiction actuator, sensor and generators. The prototype produced 1.0 μW of total power at acceleration of 2 g and frequency of 63 Hz. Basset et al. (2009) also presented MEMS electrostatic harvester without using an electret layer for harvesting vibration energy and generated 61 nW at vibration level of 0.25 g and frequency excitation of 250 Hz. Several works on harvesting vibration energy based electrostatic transducer has been studied and developed however this devices are dependent on external voltage supply.

2.2.2 Piezoelectric effect

Piezoelectric transducer generate electric charge when a mechanical load is enforced and can be used to convert energy in form of force or pressure into electrical energy (Anton and Sodano 2007; Roundy and Wright 2004). As shown in Figure 2.3, these mechanisms deform when the electric field is applied and the voltage produced is corresponding to the strain applied. This phenomenon is called the converse effect. Polyvinylidene fluoride (PVDF) and the ceramic lead zirconate titanate (PZT) are the commonly used of piezoelectric materials because of its high conversion efficiency (Chalasani and Conrad 2008).

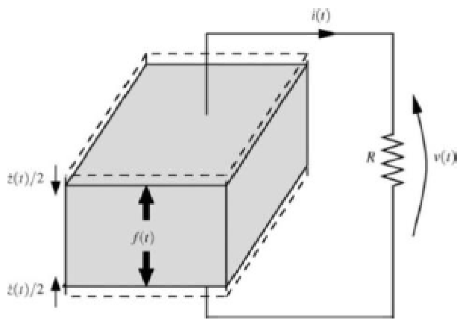

Figure 2.3: Schematic of direct effect within piezoelectric materials (Mitcheson et al., 2008b)

In 1998, a sneaker insole made of laminated PVDF was developed by Kymissis et al. (1998) with an elongated hexagon shape. Average power of 1.3 mW was obtained when 250 kΩ of resistive load was connected. Next, the PZT bimorph was developed by Shenck and Paradiso (2001) which is fixed at the heel of Navy boot to scavenge the energy of heel strike. The device comprised of two thunder piezoelectric harvester named TH6R with dimension of 5 cm x 5 cm x 5μm. At 0.9 Hz, it generates 8.4 mW of average power with resistive load of 500 kΩ.

Beeby et al. (1999) and Glynne-Jones et al. (2001) presented tapered thick film PZT generator. With load resistance of 333 kΩ at frequency of 80.1 Hz, 3 μW of maximum power was generated. Another novel application of piezoelectric generator was by Khaligh et al. (2008) who investigated hybrid energy scavenging for human powered mobile electronic. The research showed that 43 mW of powers output can be generated from the hybrid mechanism.

A circular and square PVDF plates were used by Sohn et al. (2005) for scavenging energy from changes in blood pressure while another work done by Ramsay and Clark (2001) using square PZT-5A membrane to capture energy from the variation of blood pressure. Roundy et al. (2003b) and Roundy et al. (2005) presented bimorph piezoelectric cantilever beam as shown in Figure 2.4 where a PZT-5A layer was attached to the prototype generator with a proof mass made by nickel and tungsten alloys. The maximum power output was 80 μW with 250 kΩ resistive load and acceleration level of 2.5 m/s^2 at frequency of 120 Hz.

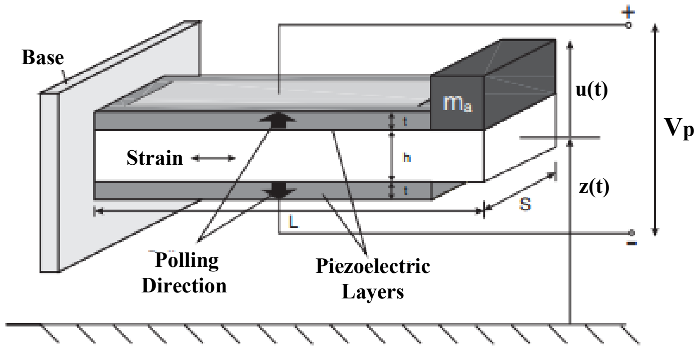

Figure 2.4: Diagram of the piezoelectric bimorph beam generator (Shu and Lien 2006)

2.2.3 Electromagnetic transducer

Electromagnetic transducer is based on Faraday's law of electromagnetic induction which stated that at the closed circuit the electrical current will be induced if the magnetic flux over the surface surrounded by the changes of conductor, which can be achieved with the use of a permanent magnet and a coil (Priya and Inman 2009). As shown in Figure 2.5, the voltage and current will induced from the variation of magnetic flux when there is relative motion between magnet and the coil. The mechanical movement of the permanent magnet is caused by structural vibrations. The power obtained reaches its maximum value when the resonance frequency is attained.

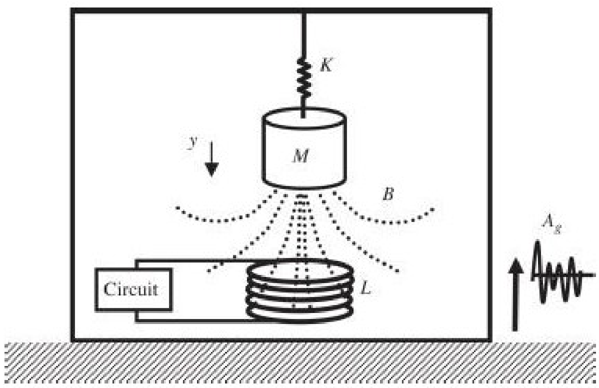

Figure 2.5: Schematic of basic electromagnetic system (Elvin and Elvin 2011)

Mechanical self-winding watches is the first example of successful vibration energy harvester device invented by Perrelet in 1770 (Mitcheson et al., 2008b). Hayakawa further this technology to generate electromagnet to power up watches in 1989 (Hayakawa 1991). This describes the ideas behind the Seiko Kinetic watch, which is now a commercial product. An exploded view of Seiko Kinetic watch is shown in Figure 2.6.

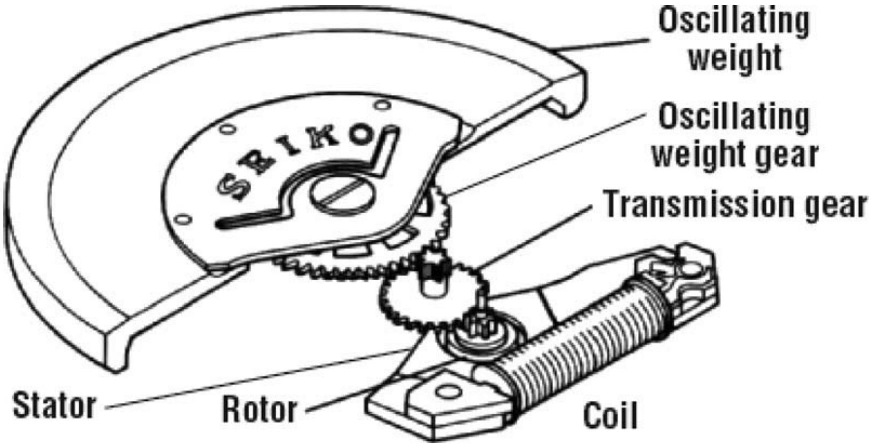

Figure 2.6: Exploded view of Seiko Kinetic watch (Mitcheson et al., 2008b)

Several researchers have examined the usage of electromagnetic transduction method for vibration energy harvesting for example Williams and Yates (1995) developed electromagnetic harvester with dimensions of 5 mm x 5 mm x 1mm as shown in Figure 2.7 comprises of a flexible circular membrane, a samarium cobalt (SmCo) magnet and a planar gold (Au) coil. However, the experimental result showed that this generator could only generate 0.3 μW of output power at a high excitation frequency of 4.4 kHz due to the nonlinear effects of spring stiffening.

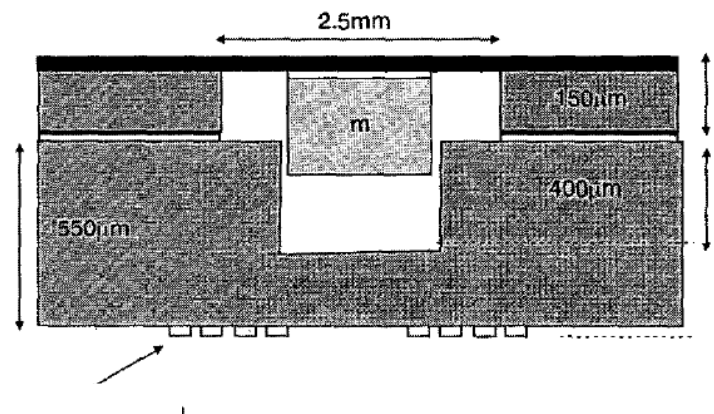

Figure 2.7: Schematic of the electromagnetic harvester designed by Williams et al. (2001)

In 1998, Amirtharajah and Chandrakasan (1998) developed electromagnetic harvester to harvest energy from human motion. The electromagnetic harvester of 23.5 cm^3 comprises of PM components, shelf spring and wire is capable of producing 400 µW of power at frequency of 2 Hz and amplitude of 2 cm. A Japanese researchers Sasaki et al. (2005) presented a 500 cm^3 generator prototype which utilizes a variable air gap magnetic yoke with 95 mW of output power achieved at 6 Hz. Niu and Chapman (2006) and Niu et al. (2008) developed a backpack generator powered by human during walking in order to harvest the energy. The prototype harvester was fabricated based on ceramic magnets with power achievement in the range of 90 – 360 µW generated at different walking patterns.

A team from University of Barcelona, Serre et al. (2007) presented electromagnetic harvester which almost similar as reported by Williams and Yates (1995) and Williams et al. (2001). At frequency of 360 Hz, the prototype produced output power of 0.2 µW at very low vibration which is 6.8 µm.

For instance, four-magnetic pole electromagnetic harvesters have been developed by Glynne-Jones et al. (2004) as the energy source for sensor nodes for condition monitoring as shown in Figure 2.8. Due to the presence of the four magnets, the speed variation of the flux is doubled and producing of 2.5 mW of power output.

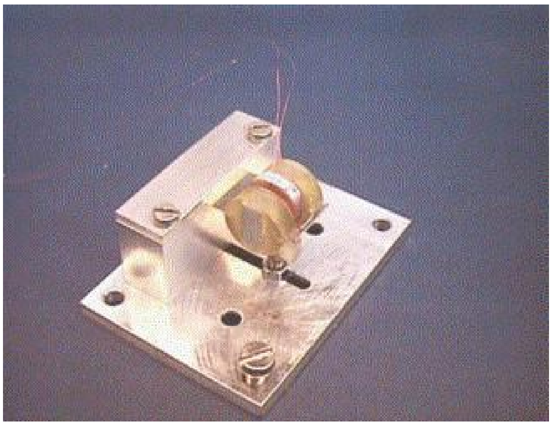

Figure 2.8: Electromagnetic harvester based on four magnets in movement and coil fixed (Glynne-Jones et al., 2004)

Another European project called VIBES by Torah et al. (2006), produces millimeter-scale cantilever beam device also using the four-pole configuration as shown in Figure 2.9. In this figure, the generator comprises of four neodymium boron magnet (NdFeB), copper coil and associated keepers attach to the beam. The device volume is 150 mm^3 and the measured output was 17.8 W at 89 mV, for a frequency of 60 Hz and input acceleration 0.6 m/s^2.

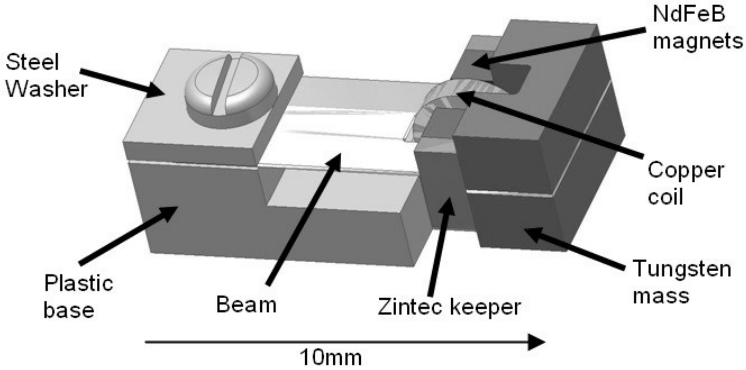

Figure 2.9: Cantilever electromagnetic harvester from Torah et al. (2006)

Another field test using an electromagnetic harvester was presented by Sazonov et al. (2009) by designing the natural frequency of the electromagnetic harvester equal to one of the natural frequencies of the bridge producing 12.5 mW of maximum power from bridge vibrations induced by passing traffic in the resonance mode at the frequency excitation of 3.1 Hz.

2.2.4 Hybrid harvester

Combination electromagnetic and piezoelectric harvester produces a hybrid generator. Wischke et al. (2009) presented a double-side suspended hybrid generator with two magnets fixed at the middle of a PZT beam, to obtain more power from the magnets vertical movement, and conductors. At resonance frequency of 753 Hz and acceleration level of 10 m/s^2, the PZT and electromagnetic harvesters produced 300 μW and 120 μW respectively. Challa et al. (2009) reported a hybrid harvester consists of PZT and electromagnetic parts. The electrical damping induced by the harvesting mechanism was matched to the mechanical damping in order to maximize the efficiency. At resonance frequency of 21.6 Hz, a maximum power of 332 μW was obtained.

Hybrid generator consists of a multi-layer piezoelectric cantilever, permanent magnets and substrate of two-layer coil was presented by Yang et al. (2010). The hybrid system produced voltage and maximum output power of 0.84 V and 176 μW respectively under frequency at 310 Hz and acceleration of 2.5 g. A low frequency hybrid harvester with ring magnets comprising of piezoelectric and electromagnetic harvester was reported by Salim et al. (2016). The researcher used finite element (FE) simulation to obtain the magnetic field, design the coil and locate its position relative to the magnets. At frequency range of 34 – 40 Hz, the maximum power and efficiency of 710 μW 30.1 % was generated respectively.

2.2.5 Comparison

The power density for the three different vibrational harvesters is shown in Figure 2.10. From the figure, only a few of them are in the frequency range below than 10 Hz which is a sparsely explored frequency, where mostly found in ambient vibration and electromagnetic harvester is the commonly used at very low frequency. Considering the simplicity of the structure, these harvesters do not require smart materials or source of voltage and high energy density. Electromagnetic transducer is selected as generator for this project and the principles is described in detail in Section 2.3.

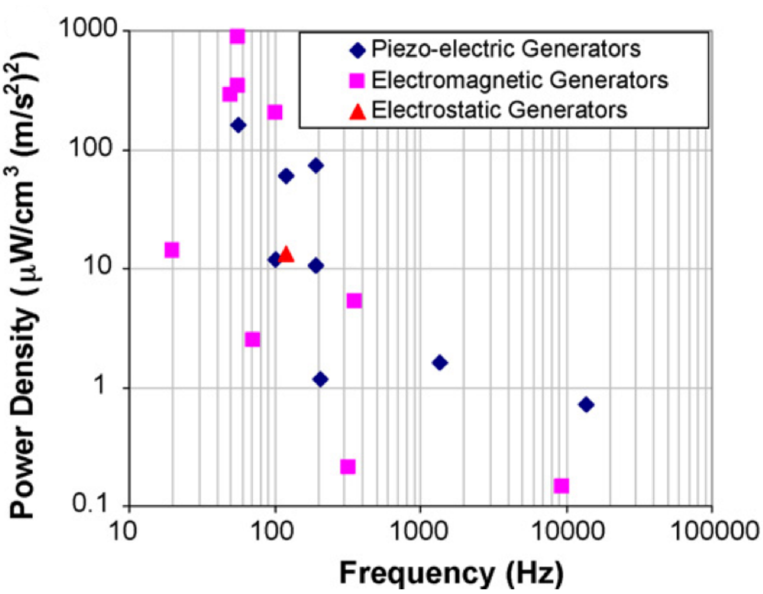

Figure 2.10: Power density for the 3 different vibrational harvesters vs. frequency (Mathúna et al., 2008)

2.3 Principles of electromagnetic harvester

A basic schematic of vibration energy based electromagnetic harvester can be illustrated as shown in Figure 2.11. As illustrated in this figure, the harvester consists of a magnet hanging on a spring where *m* is inertia mass, *k* is the spring constant, *c* is the damping coefficient, *y* is the displacement of vibrating generator housing and *z* is the displacement of the mass relative to the generator housing.

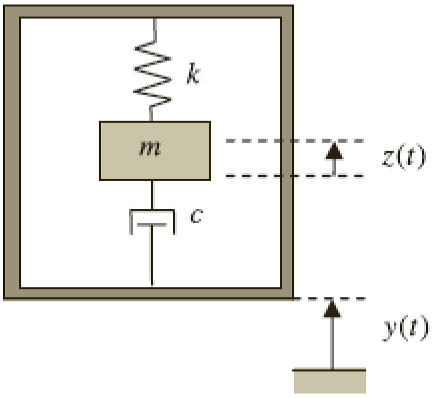

Figure 2.11: Schematic diagram of an electromagnetic harvester proposed by Williams and Yates (1995).

When the magnet oscillates due to an external force, the coil cuts the flux line of the magnet, thus producing the back electromotive force, V_{emf} as shown in equation 2.1.

$$\boldsymbol{V_{emf} = -N\frac{d\Phi}{dt}} \tag{2.1}$$

Where *N* is the number of turns of wire and *Φ* is the magnetic flux linkage through each turn. The magnetic flux, *Φ* is in Weber (Wb) as shown in equation 2.2.

$$\Phi = \int_{A} \boldsymbol{BdA} \tag{2.2}$$

Where *B* is the magnetic field strength and *A* is the area of the coil.

Considering the Lenz's Law, the induced V_{emf} will be in a direction such that the induced current magnetic field opposes the original magnetic flux change in magnetic field (Sadiku 2007). By substituting equation 2.2 into equation 2.1, the equation 2.3 is obtained as below,

$$\boldsymbol{V_{emf} = -N\frac{d\Phi}{dt} = -N\frac{d}{dt}\left(\int_A BdA\right)} \tag{2.3}$$

Based on equation 2.3, it shows that a time-varying condition between electric and magnetic fields are correlated and dA is according to right hand rule as well as Kevin-Stokes's theorem (Sadiku 2007).

The equivalent circuit for electromagnetic harvester in term of electrical is shown in Figure 2.12. The electromagnetic harvester can be seen as a voltage source, *V* connected in series with resistance, *R* and inductance, *L*. The proportional coefficient between the produced voltage and the velocity of the mass depends on the magnetic flux and on the geometry of the electromagnetic harvester.

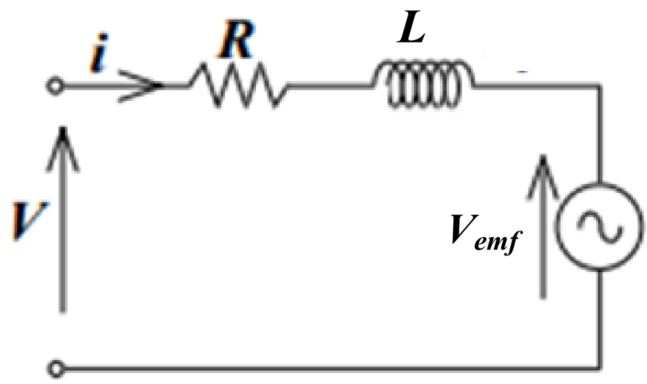

Figure 2.12: Equivalent circuit of electromagnetic harvester (Cheng et al., 2007)

By taking account of the effect of electromechanical coupling and Kirchhoff's voltage law, the equation of total voltage, V can be written as

$$\boldsymbol{V = iR + iL + V_{emf}} \tag{2.4}$$

If the load resistance, R_L is being used, the equation is

$$\boldsymbol{V = iR} + iL + i\boldsymbol{R_L} + \boldsymbol{V_{emf}} \tag{2.5}$$

$$\boldsymbol{V = (R + R_L)i + \dot{\imath}L} + \boldsymbol{V_{emf}} \tag{2.6}$$

Since there is load in the circuit, the power, P_L can be estimated by equation 2.7

$$\boldsymbol{P_L = i^2 R_L = \frac{V^2}{R_L}} \tag{2.7}$$

The total energy, E_T that can be assumed from level resistor is

$$\boldsymbol{E_T = \int_{t=0}^{t} P_L \, d(t)} \tag{2.8}$$

The average power,$P_{average}$ is the energy divided by the run time, t such in equation below

$$\boldsymbol{P_{average} = \frac{E_T}{t}} \tag{2.9}$$

2.4 Self-powered sensor using vibration energy harvesting

The concept of energy harvesting in relation to wireless sensor network entails the idea of scavenging energy from mechanical, vibrational, rotational, solar or thermal means rather than relying on mains power or rechargeable batteries for powering the WSNs. Energy harvesting is increasingly gaining notice in the WSN research because of the potential solution to prolong the operation lifetime.

In 2005, a temperature and humidity wireless sensor powered by piezoelectric sensor was reported by Arms et al. (2005) as shown in Figure 2.13. As shown in this figure, piezoelectric cantilever beam was utilized in order to harvest the vibration energy at 1 m/s^2 of vibration level. The integrated system is able to produce 2000 μW, sufficient for the RF transmitter that consuming 300 μA at 3 VDC (900μW).

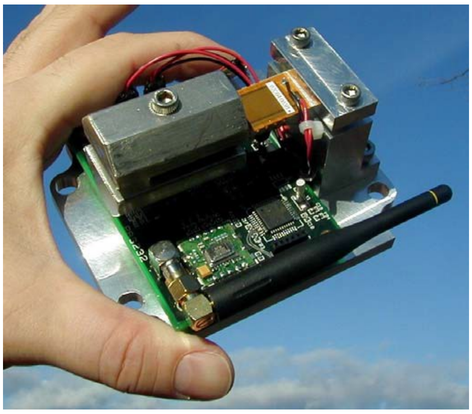

Figure 2.13: A wireless temperature and humidity wireless sensor (Arms et al., 2005)

Roundy et al. (2003a) presented a beacon transmitter that is completely self-powered as shown in Figure 2.14. A customized RF integrated circuit and energy scavenging devices are integrated together to create an efficient beacon at 1.9 GHz. The required energy comes from solar energy and vibrations.

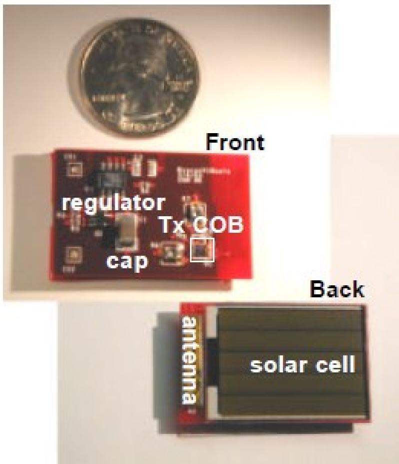

Figure 2.14: The integrated transmitter beacon (Roundy et al., 2003a)

Arms et al. (2009) developed an energy harvesting wireless sensor in order to track the load history of rotating helicopter components thereby improving safety, reducing the cost of flight testing, and enhancing condition based maintenance as shown in Figure 2.15. In this figure, piezoelectric materials bonded to the pitch link, which is a control rod responsible for controlling the rotors' angle of attack and sustains high dynamic loads, harvested sufficient strain energy to successfully operate an integrated wireless sensor node during flight. This work demonstrated that an energy harvesting wireless sensor for rotating helicopter components could be operated indefinitely, using only the strain energy of operation for power.

Figure 2.15**:** Microstrain's energy harvesting, wireless loads tracking pitch link installed on Bell M412 (Arms et al., 2009)

Dumas et al. (2011) also presented a smart wireless network of piezoelectric patches for destruction tracking in airplane and helicopter structures. The project showed that such a system was feasible in a vibrating aircraft environment, but further work should be made to have a decisive and long lasting system. A fully autonomous WSN system which is capable of detecting dangerous working conditions for vehicle operating with a connected trailer, and improve the pre-crash safety system was developed by Dondi et al. (2012) together with a vibration energy harvester to eliminate the need of battery replacement with capability of 845μW and 86% of maximum efficiency.

Wischke et al. (2011) demonstrated wireless sensor nodes powered by the harvester mounted on the railway sleeper in a tunnel. In average 260 μWs have been scavenged per train and a new ultra-low power circuitry was designed to avoid a deadlock of the sensor node. Kim et al. (2009) has developed a wireless sensor node powered by harvested energy for universal miniature self-powered wireless as illustrated in Figure 2.16. This sensor module harvests the energy from a solar cell panel and a vibrating PVDF cantilever beam. A power management circuit was designed and implemented to fulfil the function of radio-frequency identification (RFID). In addition to the two different types of harvesters, there are a microcontroller board, antenna and a power management circuit on a printed circuit board (PCB) as shown in this figure. The circuit in the form of switched capacitors is designed to be activated by a wakeup pulse and deactivated after RFID signal transmission. At distance of 20 m, the RFID signal communication was tested for every 5 minute and successfully operated for 8 hours without connected with external power supply.

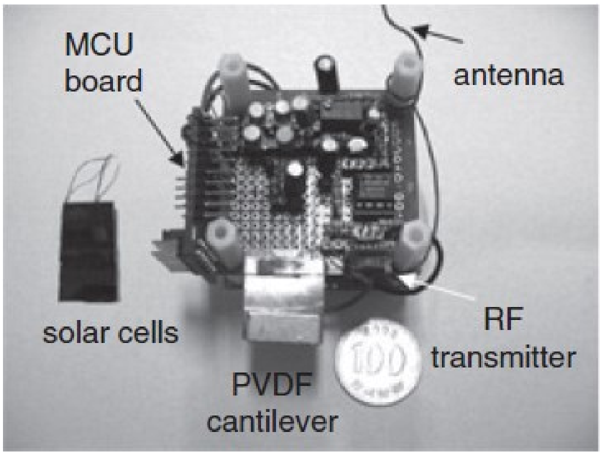

Figure 2.16: The miniature self-powered sensor unit (Kim et al., 2009)

A recent study has examined the feasibility of using the low frequency vibrations of concrete and cable-stayed bridges to power Structural Health Monitoring (SHM) sensors. Sazonov et al. (2009) reported self-powered sensors for monitoring of highway bridges at excitation frequency of 3.1 Hz utilizing electromagnetic harvester and generates 12.5mW of peak power. Field tests show the feasibility of the proposed approach for applications of SHM.

2.5 Electronic interface for vibration energy harvesters

The voltage delivered by the electromagnetic harvester based vibration is not DC but AC signal. Thus, an electronic interface is needed to ensure the voltage compatibility between the terminal electric load and the electromagnetic element. An electric energy storage element, such as a capacitor or an electrochemical battery, may be included to compensate a temporary level reduction of the environmental vibrations or to overcome a peak of the power consumed by the electronic load. The general requirements for interfacing to an electromagnetic transducer on a vibration generator are rectification, voltage step-up capability, and storage energy.