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

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by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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.

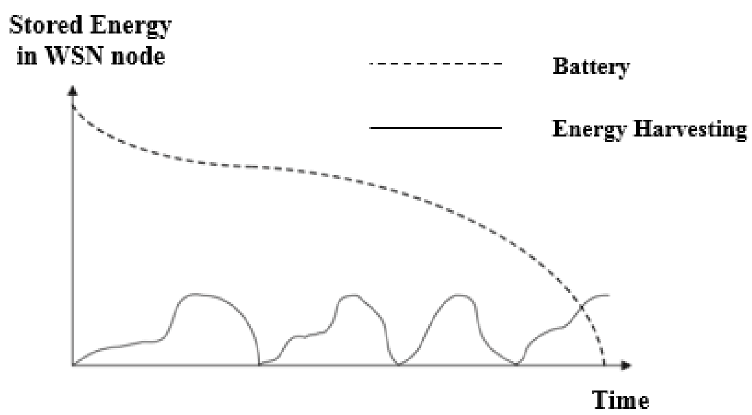

Figure 1.1: Comparison of the stored energy in a wireless sensor node system powered by a battery or powered by energy harvesting (Eu et al., 2011)

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