Faculty of Electronic and Computer Engineering

CHARACTERIZATION ON HYBRID CIRCUIT FOR PIEZOELECTRIC AND ELECTROMAGNETIC ENERGY HARVESTING FROM AMBIENT VIBRATION SOURCES

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DECLARATION

I declare that this thesis entitled “Characterization On Hybrid Circuit For Piezoelectric And Electromagnetic Energy Harvesting From Ambient Vibration Sources” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :.....

Name : Noraini Binti Mat Ali

Date :

APPROVAL

I hereby declare that I have read this thesis and my opinion this thesis is sufficient in term of scope and quality for the award of Master of Science of Electronic Engineering.

Signature :.....

Supervisor Name : PM Dr.Kok Swee Leong

Date :

DEDICATION

To my beloved mother and father

ABSTRACT

In this research, a series of experimental analyses for the performance of a hybrid energy harvester is carried out in order to produce an optimum electrical output power. The hybrid energy harvester in this research is an integration of piezoelectric and electromagnetic mechanisms. This research is divided into three main stages. In first stage, characterizations of energy harvesters were studied and hybrid energy harvesting topologies using series and parallel connection are proposed. Characterization was based on resonant frequency, acceleration level and output power. It was found that, series topology of piezoelectric and electromagnetic energy harvester at 25 Hz and 0.5 ***g*** level is the best topology compared to parallel topology. In the second stage, diode bridge rectifier and active rectifier were designed and simulations were performed to verify with experimental results. Evaluation was based on rectified electrical output from the energy harvester using two topologies. First topology is piezoelectric and electromagnetic energy harvesters connected in hybrid unit was rectified by sharing the same rectifier circuit and second topology is both of energy harvesters were rectified individually. It was found that piezoelectric and electromagnetic rectified individually using active diode performed a higher output power. The last stage is the integration of hybrid energy harvesting system with active rectifier circuit. Piezoelectric and electromagnetic energy harvester was rectified individually using active diode before both energy harvesters were connected in series topology and fed into capacitor. From the experiment result, it was found that hybrid energy harvesting showed significant improvement in overall performance by producing an optimum electrical output power 100 μW derived at resonant frequency of 25Hz with 0.5 ***g***-level from ambient vibration source.

ABSTRAK

*Dalam kajian ini, satu siri ujikaji dijalankan untuk menganalisis prestasi penuaian tenaga hibrid dengan tujuan menghasilkan kuasa keluaran electrik yang optimum. Penuaian tenaga hibrid dalam kajian ini adalah gabungan mekanisme piezoelektrik dan elektromagnetik. Kajian ini terbahagi kepada tiga peringkat utama. Pada peringkat pertama, ciri-ciri tenaga penuai telah dikaji dan topologi penuaian tenaga hybrid menggunakan sambungan selari dan sesiri adalah dicadangkan. Pencirian adalah berdasarkan frekuensi tertingi, tahap pecutan dan kuasa keluaran. Didapati bahawa, topologi sambungan sesiri tenaga penuai piezoelektrik dan elektromagnetik pada frekeunsi 25 Hz dan tahap 0.5**g** adalah topologi yang terbaik dibandingkan dengan topologi sambungan selari. Pada peringkat kedua, penerus diod jambatan dan penerus aktif telah direka dan simulasi telah dijalankan untuk disahkan dengan keputusan ekperimen. Penilaian adalah berdasarkan kepada keluaran elektrik penerus daripada tenaga penuai menggunakan dua topologi. Topologi pertama adalah disambungkan menjadi unit hibrid dan dibetul menggunakan penerus yang sama dan topologi kedua adalah kedua-dua penuai dibetulkan secara individu. Didapati bahawa penuai piezoelektrik dan elektromagnetik yang diperbetulkan secara individu menggunakan penerus aktif menghasilkan keluaran kuasa yang lebih. Peringkat terakhir ialah gabungan sistem tenaga tuaian hibrid dengan penerus aktif. Tenaga penuai piezoelektrik dan elektromagnetik diperbetulkan secara individu menggunakan penerus aktif sebelum kedua-dua tenaga penuai disambungkan secara sesiri dan dialirkan kepada kapasitor. Daripada hasil kajian didapati bahawa penuaian tenaga hibrid menunjukkan peningkatan memberangsangkan didalam keseluruhan pretasi dengan menghasilkan kuasa keluaran elektrik yang optimum dengan 100 μW pada frekuensi tertinggi 25 Hz dan tahap 0.5**g** daripada sumber getaran ambien.*

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AC	-	Alternating Current
ADS	-	Advance Design System
AWG	-	American Wire Gauge
DC	-	Direct Current
DSP	-	Digital Signal Processing
EM	-	Electromagentic
EMF	-	Electromotive force
FFT	-	Fast Fourier Transform
GND	-	Ground
IC	-	Integrated Circuit
IDT	-	Interdigitated
LCD	-	Liqiud Cyrstal Display
LED	-	Light Emmiting Diode
MOS	-	Metal Oxide Semiconductor
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
MEMS	-	Microelectromechanical systems
NdFeB	-	Neodymium Magnets
NMOS	-	N-channel Metal Oxide Semiconductor
PCB	-	Printed Circuit Board
PLC	-	Programmable Logic Controller
PMOS	-	P-channel Metal Oxide Semiconductor
PZT	-	Lead Zirconate Titanate
RDS	-	Drain to Source Resistance
RMS	-	Root Mean Square
USB	-	Universal Serial Bus
WSN	-	Wireless Sensor Nodes

LIST OF PUBLICATIONS

The research papers produced and published during the course of this research are as follows:

1. Ali, N. M., Leong, K. S. and Mustapha, A. A. 2015. Experimental Investigation on Piezoelectric and Electromagnetic Hybrid Micro-Power Generator. *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 10, pp. 6366-6370.

2. A. A. Mustapha, K. Leong, and N. M. Ali. 2016. Piezoelectric Energy Harvesting Rectifying Circuits Comparison. *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 10, pp. 6361–6365.

3. Ali, N. M., Mustapha, A. A., and Swee Leong, K. 2013. Investigation of Hybrid Energy Harvesting Circuits Using Piezoelectric and Electromagnetic Mechanisms. *IEEE Student Conference on Research and Developement*, pp. 564–568.

4. Mustapha, A. A., Ali, N. M., & Leong, K. S. 2013. Experimental Comparison of Piezoelectric Rectifying Circuits for Energy Harvesting. *IEEE Student Conference on Research and Development*, pp.556-559.

5. Ab Rahman, M. F., Kok, S. L., Ali, N. M., Hamzah, R. A., and Aziz, K. A. a. 2013.Hybrid vibration energy harvester based on piezoelectric and electromagnetic transduction mechanism. *CEAT 2013 - 2013 IEEE Conference on Clean Energy and Technology*, pp. 243–247.

6. Ali, N. M., Mustapha, A. A., and Leong, K. S. 2013. DC-DC Circuit Analysis for Harvesting Energy Using Piezoelectric and Electromagnetic Micro-Generators. *2nd International Conference on Advanced in Electronic Devices and Circuits* , pp. 978–981. Institute of Research Engineers and Doctors.

7. Mustapha, A. A., Ali, N. M., and Leong, K. S. 2013. Piezoelectric Microgenerator Rectifying Circuit Simulation using LTspice. *2nd International Conference on Advanced in Electronic Devices and Circuits,* pp. 978–981.Institute of Research Engineers and Doctors.

8. Ali, N. M., Mustapha, A. A., and Leong, K. S. 2014. DC-DC Circuit Analysis for Harvesting Energy Using Piezoelectric and Electromagnetic Micro-Generators. *International Journal of Advancements in Electronics and Electrical Engineering (IJAEEE)*, *3*(1), pp.7–10.

9. Mustapha, A. A., Ali, N. M., and Leong, K. S. 2014. Piezoelectric Microgenerator Rectifying Circuit Simulation using LTspice. *International Journal of Advancements in Electronics and Electrical Engineering (IJAEEE)*, *4*(1), pp. 24–27.

CHAPTER 1

INTRODUCTION

This chapter briefly presents introduction and background of this research including research background, research motivation, problem statement, objectives and scope of research. Contributions and thesis structure are presented in last part of this chapter.

1.1 Research Background

In this modern electronic era, demands of electrical energy are crucial for the residential and business sector, agriculture sector, manufacturing sector and transportation sector. Many researchers predict that low power electronic devices will grow rapidly in most of the sectors (Amirtharajah *et al*., 2000; Hitachi, 2003). The growing trend of low power electronics technology in Integrated Circuit(IC) design has reduced the total power requirement of the electronic devices. In general, average electrical power source for miniature electronic device require a DC voltage of 3.3V (Rekha, 2012). Battery is the most common source and used to powering the miniature electronic devices. However battery presents several drawbacks, such as limited life-span and imposing chemical waste hazard after being used. Therefore energy harvesting technique, which derives electrical energy from ambient energy, is desirable to replace the battery.

Ambient energy might be a in the form of light, temperature gradient, vibration and radio frequency. Different transducers are being used, such as photovoltaic, electromagnetic wind turbin, thermoelectric, to convert each of the sources into electrical

energies. The electrical energy produced from energy harvesting process is then stored in electrical storage system and later deliver to many different applications, which can potentially be developed as a reliable sustainable energy generation technology.

Although there are many ambient energy sources, this project focus on vibration energy due to its availability which widely presents everywhere around us. Piezoelectric, electromagnetic, electrostatic and magnetostriction have been used to transform the kinetic energy from vibration source into electrical energy (Conrad, 2008; Matak & Šolek, 2013). However, when generator operates individually the produced output power is limited, therefore to enhance the output power from vibration energy, hybrid energy harvester system is a potential candidate for powering up the miniature electronic devices.

This project will concentrate on two transduction mechanisms which are piezoelectric and electromagnetic micro-generators. These micro-generators are then integrated to form a hybrid energy harvesting system.

The fundamental of this hybrid energy harvesting system consists of two mechanism transducers, ac-dc converter and an external resistive load. The piezoelectric and electromagnetic micro-generators are used to convert the vibration source, which is in the form of mechanical energy, into electrical energy in the form of alternating current, AC. The AC electrical energy is then converted into DC form through rectifier circuit. The DC voltage is then stored in storage system before feed into the external resistive load.

1.2 Motivation

Recently, there has been a dramatic increase in production of small electrical component and integration of electronic functions of sensing, signal processing, transmitting and receiving in a miniature enclosure (Khaligh *et al*., 2010; Zhang & Zhang, 2012). Large amount of the miniature electronic devices are battery operated and therefore the life span of such system relies on battery life. Powering the electronic device using a battery becomes a problem due to the finite lifespan and requires constantly battery replacement work. It is also due to the fact that the batteries have high maintenance cost for long term deployment. Consequently the use of battery or any external source is not practical nowadays. Due to this matter, the development of energy harvesting system appears as a key to ensure effectiveness in powering the electronic devices.Therefore the motivation of this project is to develop an energy harvesting system which can supply sustainable electrical energy to power up the miniature electronic devices.

1.3 Problem Statement

In this project, electrical energy can be extracted through transduction mechanisms such as piezoelectric and electromagnetic. Due to the demand of low power electronic devices, a properly rectified and regulated voltage and current sources is important to ensure the electronic devices work accordingly. However, micro-generators produce a limited electrical power when operate individually which may not be enough to meet the minimum requirement of powering small electronic devices.

Piezoelectric is more popular than other mechanisms in deriving electrical energy from ambient vibration (Beker et al., 2011).This is due to the fact that piezoelectric has higher power output density and also capable of generating relatively high voltage, up to a

few Volt depends on vibration level, and able to overcome the voltage drop across a diode. The output electrical current, however, is in the range of micro Ampere which is not desirable for powering high current demand application such as data transmission. On the other hand, electromagnetic transduction mechanism generating higher output current but lower output voltage compare to piezoelectric. Therefore a hybrid piezoelectric-electromagnetic micro-generator can complement each other in generating maximum output power.

Another issue is the rectifying circuit, where conventionally rectifier diode-base is the most popular approach to rectify the output voltage extract from piezoelectric and electromagnetic. However, the conventional diode-based rectifier is prompted to power loss during rectification. Furthermore, with diode voltage drop of 0.2V or higher, it is not efficient for micro-generator which generate lower output voltage. Therefore, this research addresses the problem faced by the conventional energy harvesting technique and proposing a solution in the form of hybrid system to improve the energy harvesting application.

1.4 Objectives

To address the issues as stated above, this thesis is embarked on the main objective which is to produce an optimum output power more than 100 μW of hybrid energy harvesting system derived at resonant frequency of 25Hz with 0.5 ***g***-level from ambient vibration source.

In order to support the main objective, two sub-objectives are describe in details and implemented, which are:

i. To characterize and analyze individually piezoelectric and electromagnetic based micro-generators and compare the overall performance of the hybrid energy harvesting system.

ii. To design, analyze and compare a series of passive rectifier circuits as well as active rectifiers for their performance in AC to DC conversion.

1.5 Scope of Research

This project is limited to a few particular scopes includes the design of electromagnetic coil. In term of size of electromagnetic micro-generator, the coil designed in a number of turn less than 2000 turn using a 34 AWG wire. By considering the diameter of the wire, other AWG wires were not used in designing the electromagnetic coil to avoid the increasing on size. While the piezoelectric beam bender being used in the experiment is obtain from Piezo Systems, Inc., with the size of 0.051cm x 3.18cm x 6.35cm.

The proposed system is tested and measured in laboratory and not in real environment. The experiment is limited to a vibration level of 0.5 ***g*** with an operating frequency between 10Hz to 80Hz to mimic the real ambient vibration sources because most of the ambient sources are below than 0.5 ***g***-level. Then, the application part for the proposed system is not included in this research. All the circuit is simulated using the LTspice IV simulator and are then verified experimentally at the end of the project.