UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electronic and Computer Engineering

LOW POWER AND HIGH EFFICIENCY RECTIFYING CIRCUIT FOR PIEZOELECTRIC ENERGY HARVESTING APPLICATIONS

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Master of Science in Electronic Engineering

2016

LOW POWER AND HIGH EFFICIENCY RECTIFYING CIRCUIT FOR PIEZOELECTRIC ENERGY HARVESTING APPLICATIONS

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A thesis submitted
in fulfillment of requirements for the degree of Master of Science
in Electronic Engineering

Faculty of Electronic and Computer Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2016

DECLARATION

I declare that this thesis entitled "Low Power and High Efficiency Rectifying Circuit for Piezoelectric Energy Harvesting Applications" 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 : AIN ATIGA MUSTAPHA

Date : 13/11/2016

APPROVAL

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

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DEDICATION

To my beloved father and late mother

ABSTRACT

Piezoelectric cantilever generated a voltage particularly dependent on the magnitude of vibration source and the resonant frequency. The magnitude of the electrical output from the energy harvester is dependent on the size of the device as well as the acceleration level of the vibration source. The type of piezoelectric used for this research is PSI-5A4E which is unimorph standard quick- mount extension sensor. The characteristics of PSI-5A4E such as resonance frequency value, electrical equivalent circuit, the desired acceleration level, optimum power and optimum output voltage when connected to open circuit were investigated. The experiment has been set up to investigate the value of resonance frequency. After a series of experiment, the resulted value of resonance frequency is 61 Hz. To describe the electrical equivalent circuit for the piezoelectric generator, the PSI-5A4E is seen as a Norton equivalent of a voltage source, V_P, with internal impedance, Z_P. This can be used to describe the power transfer from piezoelectric generator to a load. PSI-5A4E material has a capacitance of C_P=260nF. At resonance frequency, 61Hz, the complex conjugate load inductor is calculated to be L= 26.18H. There are two values of ***g***-level were used for the analysis: 0.1***g*** and 3***g***. To determine the optimum output power, subjected to the 61Hz resonance frequency and 0.1***g*** and 3***g*** level values, the experiment was conducted by varying the external load resistance from 10Ω to 1MΩ. As a result, at 100kΩ load resistance, the optimum output is 0.38uW and 1.217uW for 0.1***g*** and 3***g***-level respectively. Piezoelectric produced AC electrical energy which needs to be rectified first into DC before powering electronic devices. Concerning this goal, the simulation and experiment of various types of passive and active rectifiers have been carried out and been compared among each other. Full wave bridge rectifier (FWBR) is the conventional due to its simplicity and ready available. However, this option would not be compatible when operating at low voltage level because the voltage generated from the piezoelectric energy harvester could be less than that being required to operate the diodes. For this reason, low voltage operated rectifying circuit is vital for piezoelectric energy harvesting application. Various types of rectifiers are being used in the experiment whereby the characteristics of each rectifier is being studied and compared in order to identify the most suitable with high efficient rectifier to be integrated with piezoelectric energy harvester. For passive rectifier, the arrangements of the rectifier is in a form of full bridge and are tested with different type of diodes namely as standard diodes, zener diodes, Schottky diodes and MOSFETs. For active rectifier, the synchronous rectification method has been investigated. The output voltage and efficiency for all rectifiers has been compared. From the experimental results, active MOSFET op-amp rectifier has shown an efficiency of 96% and 98% for acceleration level of 0.1***g*** and 3***g*** respectively which is reported as the highest efficiency among all the other types of rectifier.

ABSTRAK

*Voltan yang dihasilkan piezoelectric bergantung kepada magnitud sumber getaran dan frekuensi salunan. Magnitud output elektrik dari penuai tenaga adalah bergantung kepada saiz peranti dan juga tahap pecutan sumber getaran. Jenis piezoelektrik digunakan untuk kajian ini adalah PSI-5A4E iaitu standard penderia jenis pemanjangan piawai yang mudah dipasang. Ciri-ciri PSI-5A4E seperti nilai resonans frekuensi, litar setara elektrik, tahap pecutan yang dikehendaki, kuasa optimum dan voltan output optimum apabila telah disiasat. Eksperimen telah dijalankan untuk menyiasat nilai frekuensi resonans. Selepas beberapa siri eksperimen, nilai frekuensi resonans adalah 61 Hz. Untuk menerangkan litar setara elektrik untuk generator piezoelektrik, yang PSI-5A4E dilihat sebagai setara Norton daripada sumber voltan, V_P, dengan impedans dalaman, Z_P. Nilai ini boleh digunakan untuk menggambarkan pemindahan kuasa daripada penjana piezoelektrik untuk beban. bahan PSI-5A4E mempunyai kapasiti $C_P = 260nF$. Pada frekuensi resonans, 61Hz, kompleks pengaruh beban konjugat dikira sebagai $L = 26.18H$. Terdapat dua nilai **g** telah digunakan untuk analisis ini: 0.1**g** dan 3**g**. Untuk menentukan kuasa output optimum, yang tertakluk kepada frekuensi resonans 61Hz dan nilai pecutan 0.1**g** dan 3**g**, eksperimen telah dijalankan oleh pelbagai rintangan beban luaran daripada 10Ω untuk 1MΩ. Hasilnya, pada rintangan beban 100kΩ, output optimum adalah 0.38uW dan 1.217uW untuk 0.1**g** dan 3**g**. Piezoelektrik menghasilkan tenaga elektrik AC yang perlu ditukarkan kepada DC sebelum dijanakan kepada peranti elektronik. Sesuai dengan matlamat ini, simulasi dan eksperimen pelbagai jenis penerus pasif dan aktif telah dijalankan dan telah dibandingkan antara satu sama lain. Konvensional Gelombang penuh jambatan penerus (GPJP) adalah pilihan lazim kerana mudah dibina dan senang didapati. Walau bagaimanapun, pilihan ini tidak sesuai untuk penuai tenaga piezoelektrik yang beroperasi pada tahap voltan rendah kerana voltan yang dihasilkan biasanya kurang daripada yang diperlukan untuk mengendalikan diod. Atas sebab ini, voltan rendah yang dikendalikan untuk membetulkan litar adalah penting untuk penuaian tenaga piezoelektrik. Pelbagai jenis penerus yang digunakan dalam eksperimen di mana ciri-ciri setiap penerus sedang dikaji dan dibandingkan untuk mengenal pasti yang paling sesuai dengan penerus efisien yang tinggi untuk disepadukan dengan penuai tenaga piezoelektrik. Untuk penerus pasif, perkiraan penerus adalah dalam bentuk jambatan penuh dan diuji dengan pelbagai jenis diod iaitu diod standard, diod zener, diod Schottky dan MOSFET. Untuk penerus aktif, kaedah pembetulan segerak telah disiasat. Daripada keputusan eksperimen, MOSFET aktif op-amp penerus telah menunjukkan kecekapan pada 96% dan 98% untuk tahap pecutan 0.1g dan 3g masing-masing yang dilaporkan sebagai kecekapan yang tertinggi di kalangan semua lain-lain jenis penerus.*

ACKNOWLEDGEMENTS

Foremost, I want to offer this endeavour to Allah Almighty for the wisdom He bestowed upon me, the strength, peace of my mind and good health in order to finish this research.I would like to express the deepest appreciation to my supervisor, Dr. Kok Swee Leong for his full support, expert guidance, understanding and encouragement throughout my study and research. Without his incredible patient and timely wisdom and counsel, my thesis work would have been a frustrating and overwhelming pursuit. I would also like to thank to teammate, Noraini Mat Ali for helping me survive all the stress throughout the years and not letting me give up. To all my postgraduate lab friends, especially my housemates, even though you are not directly involved in this research, I thank you all for the moral support, encouragements, bonding, happy times that I will forever treasure. It was fun having all these years spent doing crazy things with all of you. To my beloved and supportive husband who remains willing to engage with struggle and ensuing discomfort and for your practical, emotional and financial support for me. Thank you so much for the encouragement which helped me in completion of this thesis and always be my side when times I needed him most. To my late mother who always give me wonderful support and be my best friend forever. I love you. My father and my dearest family, thanks you for untiring love, motivational and financial support throughout these years.

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LIST OF ABBREVIATIONS

AC	-	Alternating Current
ASRC	-	Active Switching Rectifying Circuit
DC	-	Direct Current
EMF	-	Electromagnetic force
FWBR	-	Full Wave Bridge Rectifier
PZT	-	Lead Zirconate Titanate
SDOF	-	Single Degree-of-Freedom
TEG	-	Thermoelectric Generator
VM	-	Voltage Multiplier

LIST OF PUBLICATIONS

1. A. A. Mustapha, N. M. Ali, K. S. Leong, 2013. "Piezoelectric Microgenerator Rectifying Circuit Simulation using LTspice", *Proceedings of the Second International Conference on Advances in Electronic Devices and Circuits (EDC)*, pp. 33-36.
2. N. M. Ali, A. A. Mustapha, K. S. Leong, 2013. "DC-DC Circuit Analysis for Harvesting Energy using Piezoelectric and Electromagnetic Micro-Generators", *Proceedings of the Second International Conference on Advances in Electronic Devices and Circuits (EDC)*, pp. 29-32.
3. A. A. Mustapha, N. M. Ali, K. S. Leong, 2013. "Experimental Comparison of Piezoelectric Rectifying Circuits for Energy Harvesting", *IEEE Student Conference on Research and Development (SCOReD)*, pp. 556-559.
4. N. M. Ali, A. A. Mustapha, K. S. Leong, 2013. "Investigation of Hybrid Energy Harvesting Circuits using Piezoelectric and Electromagnetic Mechanisms", in *IEEE Student Conference on Research and Development (SCOReD)*, pp. 564-568.

CHAPTER 1

INTRODUCTION

This chapter describes the introduction and motivation of this thesis and outline the problem statements, the project objectives and scope of the research. The project contributions of the research are also briefly mentioned. Lastly, the organizations of the thesis structure are briefly represented and described.

1.1 Energy Harvesting

Energy is the most important source in the world nowadays. Many advanced technology in the world dependent on energy to operate. Energy source can be classified into two categories; non-renewable and renewable. The non-renewable energy sources are the type of energy that can be collected directly from natural sources. Example of non-renewable energy sources are petroleum, natural gas, coal, uranium, and propane etc. These type of energy sources are limited and it takes millions years to be formed.

Alternatively, renewable energy source are abundance which is replenish and easy available from the ambient environment. Examples of renewable energy sources are biomass, hydropower, wind, geothermal and solar etc. *BP Statistical Review of World Energy June 2015* stated that the renewable energy was the fastest growing form of energy compared to the primary energy and natural gas which accounted for one-third of the increase in total primary energy used. It is reported that 3% from the world's energy needs comes from renewable energy (BP Statistical Review of World Energy, 2015).

The recent innovation for the technology of wireless sensor and low power electronics has intensified the research on the use of energy derived from ambient environment as their energy sources. The use of ambient energy as the main power source by converting into same scale electrical energy in the range of a few milliwatts is referring to the energy harvesting or scavenging energy. It is desirable for the use of low level renewable energy because it does not give negative impact towards health and nature at big scale such as hydroelectric dam.

Low level energy harvesting techniques can be derived from solar, temperature gradient using photovoltaic and thermoelectric respectively whereas that mechanical energy such as those generated by wind power, physical motions, vibration, and ocean waves can be accomplished by using electromagnetic, piezoelectric, and electrostatic and others (Maurat *et. al.,* 2012). Piezoelectricity is the most common used because of their simplicity and high power density (Cottone, 2011).

Today, wireless sensing systems has become popular choices rather than wired system due to its convenience in installation and maintenance. With the advancement of recent technology of Internet-of-thing (IoT), the wireless sensor network has increasingly gaining demand (Sheng *et. al.,* 2015). Wireless sensor networks (WSNs) are the collections of many sensor nodes where each node can work independently to collect data from environment such as temperature, pressure, gas, humidity etc in the specific areas (Yoshida *et al.*, 2011). There are many applications that WSNs can be ventured in such as healthcare, environmental monitoring, agriculture, and military to security systems. However, conventional wireless sensor and portable electronics used battery as their main power supply. This will limit the lifespan of WSNs which require continuously battery replacement work that involve high maintenance cost and difficult to implement especially where in some inaccessible locations replacement of the battery would be an impossible task. Due to this major problem, researchers from multidisciplinary areas work hard to find the solutions (Torah *et al.*, 2008). Harvesting energy from ambient environment is an alternative to overcome the problem when using battery and furthermore it is also suitable for supplying energy to low power electronic systems.

Energy harvesting is possible to be initiating the functionality of WSN as a truly self-powered system without human intervention and it is also capable of storing energy for future use. Ambient energy such as vibration is ubiquitous and all around us. Advances in low power electronics and wireless sensor networks has led to the used of ambient vibration energy as the power source. Energy harvesting is the process of using the ambient energy from the surrounding of the device which is converted into usable electrical power (Kim *et al,* 2011). Generally, the power from energy harvesting is too small, therefore an enabling power conditioning and storage circuit need to be deployed to supply to the low power electronic applications. There are various types of energy harvesting sources beside than vibration, which are thermal, or temperature gradient, wind, solar, impact and many more. Amongst all of these, mechanical vibration is the most interesting method because of the source is ubiquitous and widely available from any event anything that is subjected to mechanical movement. The mechanical vibration is typically converted into electrical energy using piezoelectric, electromagnetic or electrostatic mechanisms. Since vibration energy is ubiquitous, it is particularly applicable to WSNs which is practically embedded in inaccessible place.

1.2 Problem Statement

Piezoelectric itself has unique characteristics such as very high impedance and very low output electrical power (less than 1mW) and is dependent on the magnitude of vibration source (Ayala *et. al.,* 2009). In real application, the acceleration level of ambient vibration is quiet low (in the range of <1***g*** level) which may hamper the effort of harvesting useful energy. To date, there were so many researchers who have put efforts in maximizing the electrical power draw from the piezoelectric energy harvester (Torah *et al.,* 2008). The solution which came from previous research were promising, but those solutions were basically done for higher frequency level (>100 Hz), higher ***g***-level (>1***g***) and not focusing on low level electrical power generation in the range of a few micro-Watts (Andosca *et. al.,* 2012). If the solutions were implemented in real applications, it would not be compatible with the interfacing circuit as shown in Figure 1.1, particularly the rectifying circuit which usually consists of a number of diodes which require a voltage drop of 0.7 V each. Figure 1.1 basically shows the whole system of vibration energy harvesting to supply the sensor node which is consist of vibration energy, piezoelectric micro-generator, converter, capacitor/battery and sensor.

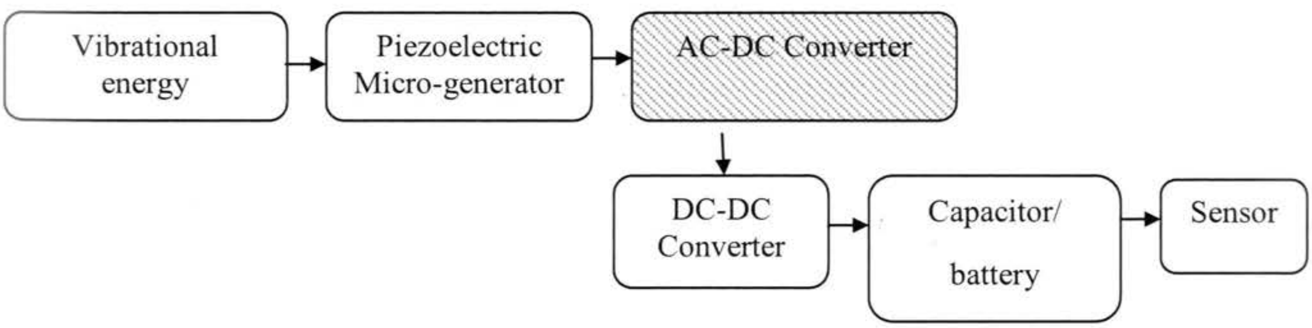

Figure 1.1: The whole system for vibration energy harvesting to supply the sensor node.

Consequently if the vibration source is too low, the voltage generation would be lower than the minimum requirement of the diode voltage drop and the system is impossible to be implemented. Therefore, this research address the problem faced by micro-generator or energy harvester which generate low electrical power at low vibration frequency with low ***g***-level or the magnitude of the vibration. For this project, the main focus is on the alternating current to direct current (AC-DC) converter as shown in Figure 1.1.

1.3 Project Objective and Descriptions

The main objective of this project is:

i. To reduce the input voltage requirements of the rectifier

ii. To extract as much energy as possible from the piezoelectric material

iii. To reduce the energy lost in the system.

The voltage requirements for the rectifier must be less than 0.7V so that, the system can extract more energy from piezoelectric material which is lead to reduce the energy lost in the system. For this purpose, an active switching rectifying circuit topology is proposed to rectify the AC output from piezoelectric energy harvester at low frequency vibrations and compare the performance with other conventional rectifying circuit with output electrical power level that is in the range of micro-Watts.

The main activities in developing a low frequency (<100 Hz) low voltage (<5V) vibration energy harvesting converters are:

a. Characterizing piezoelectric generator
    i. Determine the resonance frequency
    ii. Measure the piezoelectric acceleration
    iii. Test the piezoelectric open circuit
    iv. Determine the optimum output power and voltage
b. Choice of topology and analysis
    i. Standard full bridge rectifier- using four 1N4001 diodes in a closed group bridge configuration.
    ii. MOSFET bridge rectifier- using two N-and two P-channels constructed in bridge rectifier.
    iii. Voltage multiplier- made up of multiple stages where each stage is comprised of one diode and one capacitor.
    iv. Self-Powered Low Leakage Rectifier- placing a low resistance conduction path across the diode rectifier which is served by using MOSFETs.
c. Circuit design
    i. Switching components- using the comparator-controlled MOSFET semiconductor switches.
d. Experimental testing and verification on the complete circuit- compared the efficiency between passive rectifier and active rectifier.

1.4 Scope of the Research

The scope of the research is limited to vibration energy harvesting circuit with the inclusion of a piezoelectric micro-generator, a rectifying circuit, a matching resistive load and storage control circuit. The converter is rectifying circuit, which rectifies the piezoelectric AC voltage into DC voltage while optimizing the output power. The type of converter used for this project is passive and active switching. Piezoelectric output voltage was set to a range of low voltage (0.5V to 2V) relating with the ***g***-level. The piezoelectric vibrated at low ***g***-level values ($\leq 1g$ or 9.81 m/s^2). Mechanical vibrations are generated with electrodynamic shaker in the laboratory with less than 100 Hz, resemble to a real engine vibration source. In this case around 60 Hz suit to the off-the-shelf piezoelectric generator. The generated power level is in the microwatt range. As shown in Figure 1.1, this project is focusing on the problem faced by the rectifying circuit and optimizing the harvested electrical power. The output power for application is managed by a load matching circuit, which is another power management circuit and is beyond the scope of this project.

A deeper mechanical analysis of the mechanical structure is needed to directly link the applied mechanical vibrational energy to the generated electrical energy when analyzing the electrical output power resulting from a mechanical vibration input to a piezoelectric generator, The mechanical analysis is not within the scope of the project. Thus, the exact input mechanical vibrational energy in this project is ignoring. Instead the energy level is stated as the open circuit output voltage from the piezoelectric micro-generator and which is dependent on the input mechanical excitation of the electrodynamic shaker.