HYBRID ENERGY HARVESTER FOR RANDOM DIRECTION MOTION

BY

MOHAMAD SAFIDDIN BIN MOHD TAHIR

A thesis submitted in fulfilment of the requirement for the degree of Master of Science in Engineering

Kulliyyah of Engineering
International Islamic University Malaysia

APRIL 2022

ABSTRACT

Harvesting energy from ambient sources has sparked significant interest in its potential to drive low-powered electronic devices and reduce electronic waste. Vibration energy harvesting is particularly well suited in these micro-scale types of energy harvesting. A hybrid energy harvester that consists of piezoelectric and electromagnetic energy harvester is the approach to overcome the limitation of a single energy harvester. However, most hybrid energy harvesters suffer from random motion and unidirectional sensitivity as they can only efficiently harvest energy at constant frequency and one direction of motion. The work investigates the capability of an electromagnetic energy harvester and a piezoelectric energy harvester for a wearable device, mainly when operating at a low-frequency range between 1 Hz to 13 Hz at a random direction of human motion. The linear motion of human motion is converted into rotational motion using an eccentric mass. Each time the eccentric mass passes the beam, the magnets repel each other, resulting in the beam deflecting to its maximum possible deflection. This technique is known as the magnetic plucking technique and simultaneously changes magnetic flux around the wound copper coil to generate the largest amount of current. When the eccentric mass rotates at a constant frequency of 5 Hz, the DC voltage produced is 1.5 V, 4.9 mA, and 7.35 mW. In contrast, when manually rotated using hand, it generates 1.4 V, 4.7 mA, and 6.58 mW. However, when the full-bridge circuit replaces with a voltage doubler circuit, the voltage increases to 3.2 V and 3.8 V respectively although the current reduces to half. This research demonstrated the ability of the hybrid energy harvester to effectively harvest energy at low-frequency inputs. The findings of this work provide the possibility to cater for the energy demand for wearable electronic devices and efficiently generate energy at a low and random frequency of human motion.

DR. NOOR HAZRIN HANY BT MOHAMAD HANIF
Assistant Professor
Department of Mechatronics Engineering
Kulliyyah of Engineering
International Islamic University Malaysia

خلاصة البحث

تجميع الطاقة من المصادر المحيطة تأثر كبيرا في تشغيل الأجهزة الإلكترونية و انخفاض النفايات الإلكترونية. يعد حصاد طاقة الاهتزاز بشكل خاص في هذه الأنواع الصغيرة من حصاد الطاقة.إن حصادة الطاقة الهجينة تتكون من حصاد الطاقة الكهروإجهادية والكهرومغناطيسية هي من احدى الطريقة للتغلب على قيود حصاد الطاقة الفردي. . ومع ذلك ، معظم حاصدات الطاقة الهجينة تعاني من حركة عشوائية وحساسية أحادية الاتجاه حيث تستطيع حصاد الطاقة بكفاءة بتردد ثابت واتجاه واحد للحركة. يبحث العمل عن قدرة حصاد الطاقة الكهرومغناطيسية وجهاز حصاد الطاقة الكهرضغطية لجهاز يمكن ارتداؤه ، خاصة عند تشغيلها في نطاق تردد منخفض بين ١ هرتز إلى ١٣ هرتز في اتجاه عشوائيا في حركة الإنسان. يبحث العمل عن قدرة حصاد الطاقة الكهرومغناطيسية وجهاز حصاد الطاقة الكهرضغطية لجهاز يمكن ارتداؤه ، خاصة عند تشغيلها في نطاق تردد منخفض ما بين ١ هرتز إلى ١٣ هرتز في اتجاه عشوائيا في حركة الإنسان .يتم تحويل الحركة الخطية للحركة البشرية إلى حركة دورانية باستخدام كتلة لا مركزية. في كل مرة تمر فيها الكتلة اللامتراكزة بالشعاع ، تتنافر المغناطيسات مع بعضها البعض ، مما يؤدي إلى انحراف الحزمة إلى أقصى انحراف ممكن. تُعرف هذه التقنية بتقنية النتف المغناطيسي وتقوم في نفس الوقت بتغيير التدفق المغناطيسي حول الملف النحاسي الجرح لتوليد أكبر كمية من التيار. عندما تدور الكتلة اللامتراكزة بتردد ثابت ٥ هرتز ، يكون جهد التيار المستمر الناتج ١,٥ فولت ، ٤,٩ مللي أمبير ، و ٧,٣٥ مللي واط. في المقابل ، عند تدويرها يدويًا باستخدام اليد ، فإنها تولد ١,٤ فولت ، ٤,٧ مللي أمبير ، و ٦,٥٨ ميجاواط. ومع ذلك ، عندما تستبدل دائرة الجسر الكامل بدائرة مضاعفة الجهد ، يزداد الجهد إلى ٣,٢ فولت و ٣,٨ فولت على التوالي على الرغم من أن التيار ينخفض إلى النصف. أظهر هذا

البحث قدرة حصادة الطاقة الهجينة على حصاد الطاقة بشكل فعال عند مدخلات التردد المنخفض. توفر نتائج هذا العمل إمكانية تلبية الطلب على الطاقة للأجهزة الإلكترونية القابلة للارتداء وتوليد الطاقة بكفاءة بتردد منخفض وعشوائي للحركة البشرية.

PROF. DR. MOHAMED HADI HABAEBI
Department of Electrical and Computer Engineering
Kulliyyah of Engineering
International Islamic University Malaysia

ABSTRACT IN BAHASA MALAYSIA

Penjanaan tenaga dari sumber persekitaran telah menarik minat yang besar terhadap potensinya untuk menghidupkan alatan electronik berkuasa rendah dan mengurangkan sisa electronic. Penjanaan tenaga dari getaran sangat sesuai untuk jenis penjanaan tenaga mikro ini. Penuaian tenaga secara hibrid adalah salah satu pendekatan untuk penjanaan tenaga yang tinggi dari sumber getaran dan mampu menghidupan kebanyakkan peranti electronic. Walau bagaimanapun, kebanyakkan penjana tenaga melalui hybrid menderita akibat pergerakkan rawak dan pergerakkan sehala kerana mereka hanya dapat menuai tenaga secara efisien pada frekuensi tetap dan satu arah gerakan. Penyelidikan ini menyiasat keupayaan penuai tenaga elektomagnetik dan penuai tenaga piezoelekrik untuk peranti dipakai, terutamanya ketika beroperasi pada julat frekuensi rendah antara 1 Hz hingga 5 Hz pada arah gerakan secara rawak. Gerakan linear iaitu gerakan manusia diubah menjadi gerakan putaran menggunakan jisim eksentrik. Setiap kali jisim eksentrik melepasi bilah PZT, magnet saling menolak satu sama lain, sehingga bilah PZT memesong ke pesongan maksimum. Teknik ini dikenali sebagai teknik pemesong magnetik dan secara serentak, menukar fluks magnet di sekitar gegelung tembaga untuk menghasilkan jumlah arus elektrik yang besar. Apabila jisim eksentrik berputar pada frekuensi tetap 5 Hz, voltan DC yang dihasilkan adalah 1.5 V, 4.9 mA dan 7.35 mW. Sebaliknya, apabila diputar secara manual menggunakan tangan, ia menghasilkan 1.4 V, 4.7 mA dan 6.58 mW. Namun apabila litar pengubah ditukar kepada litar mengganda voltan, voltan meningkat menjadi 3.2 V dan 3.8 V masing-masing. Penyelidikan ini menunjukkan kemampuan penjana tenaga hibrid untuk menjana tenaga secara berkesan, tanpa mengira input frekuensi rendah (1-5 Hz), kerana frekuensi dominan bilah PZT adalah 16 Hz. Hasil kajian ini memberikan kemungkinan untuk memenuhi permintaan tenaga untuk peranti elektronik yang boleh dipakai dan menjana tenaga secara efisien pada frekuensi pergerakan manusia yang rendah dan rawak.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Engineering.

…………………………………..
Noor Hazrin Hany Mohamad Hanif
Supervisor

…………………………………..
Azni Nabela Wahid
Co-Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Engineering.

…………………………………..
External Examiner
Hanim Salleh

…………………………………..
Internal Examiner
Nor Hidayati Diyana Nordin

This thesis was submitted to the Department of Mechatronics Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science in Engineering.

…………………………………..
Ali Sophian
Head, Department of Mechatronics Engineering

This thesis was submitted to the Kulliyyah of Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science in Engineering.

…………………………………..
Sany Izan Ihsan
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Mohamad Safiddin bin Mohd Tahir

Signature .... Date 4/4/2022 ....

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

DECLARATION OF COPYRIGHT AND AFFIRMATION OF FAIR USE OF UNPUBLISHED RESEARCH

HYBRID ENERGY HARVESTER FOR RANDOM DIRECTION MOTION

I declare that the copyright holders of this thesis are jointly owned by the student and IIUM.

No part of this unpublished research may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without prior written permission of the copyright holder except as provided below

1. Any material contained in or derived from this unpublished research may be used by others in their writing with due acknowledgement.

2. IIUM or its library will have the right to make and transmit copies (print or electronic) for institutional and academic purposes.

3. The IIUM library will have the right to make, store in a retrieved system and supply copies of this unpublished research if requested by other universities and research libraries.

By signing this form, I acknowledged that I have read and understand the IIUM Intellectual Property Right and Commercialisation policy.

Affirmed by Mohamad Safiddin bin Mohd Tahir

……..…………………….. 4/4/2022 ………………………..
Signature Date

ACKNOWLEDGEMENTS

In the name of Allah, Most Gracious, Most Merciful

First and foremost, Alhamdulillah, praise Allah for giving me the strength throughout my journey to complete my master's study, specifically during this pandemic COVID-19.

On 15th July 2021 and 4th February 2022, I was diagnosed with COVID-19 two times and was quarantined for 10 days. Alhamdulillah, I am grateful to survive this pandemic and to continue my master's research.

My deepest appreciation to my parents, Mohd Tahir bin Abg Embit and Masni binti Bujang, for keeping me motivated during this challenging journey and, by extension, to all my family members (Norita, Mastura, Mohammad Din Al-Hapis, Muhammad Zulfiqah) for their unconditional love and support.

I would like to express my special gratitude to my supervisors, Dr. Noor Hazrin Hany Mohamad Hanif and Dr. Azni Nabela Wahid, for guiding and advising me throughout this project. Without their supervision, I would not have been able to complete the study well.

I would also like to express my greatest gratitude to all my friends: Wan Ahmad Wan Azhar, Nadzaratul 'Ainina Kassim, and Mizan Izzati Mat Zin, for guiding and supporting me directly and indirectly throughout completing this study. Further thanks to all DDPG staff, lab technicians, and engineers who had helped me during this study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

DC	Direct current
AC	Alternating current
PZT	Lead zirconate titanate
IC	Integrated circuit
NdFeB	Neodymium magnet
MEMS	Micro-electromechanical systems
PVDF	Polyvinylidene fluoride
EH	Energy harvester
DOF	Degree of freedom
SSHI	Synchronized switch harvesting on inductor
FBR	Full bridge rectifier
VDR	Voltage doubler rectifier
AIN	Aluminium nitride
$Ba_2NaNb_5O_{15}$	Barium sodium niobate
DSA	Digital signal analyser
PA	Power amplifier
MATLAB	Matrix laboratory
COMSOL	Cross platform finite element analysis and solver
SOLIDWORK	Solid modeling computer aided design\
DAQ	Data acquisition
PWM	Pulse width modulation
IDE	Integrated development environment
TDSM	Technical data management streaming

LABVIEW	Laboratory virtual instrument engineering workbench
3D	Three dimensional
2D	Two dimensional
FFT	Fast Fourier transform
PCB	Printed circuit board

LIST OF SYMBOLS

V_o	Output voltage
N	Number of turns
Φ	Magnetic flux
t	Time
B	Magnetic field
A	Area
S	Mechanical strain
E	Electric field
T	Applied mechanical stress
D	Electric displacement
s	Matrix of elasticity under conditions of a constant electric field
ε	Permittivity matrix at constant mechanical strain
d_t	Piezoelectric coefficient matrix
d_{33}	Mechanical stress applied perpendicular to the beam
d_{31}	Mechanical stress applied at direction one
Y_{max}	Maximum deflection
F	Force
E_p	Young’s modulus of PZT
I	Moment of inertia
l	Length of the PZT beam
b	Width of the PZT beam
h	Height of the PZT beam
v_n	Eigenvalue for fundamental vibration

m	Mass of the proof mass
f_r	Resonant frequency
m_e	Mass of the PZT beam
K	Stiffness of the beam

CHAPTER ONE

INTRODUCTION

1.1 RESEARCH BACKGROUND

Energy harvesting, alternatively referred to as energy scavenging, is a technique for harnessing energy from ambient sources and converting it to electrical energy. Until now, we have obtained energy through solar panels, wind turbines, hydroelectric generators, and various other sources. This macro-scale energy harvesting technologies have been able to meet our energy demands successfully. However, the miniaturisation of electrical components such as sensors has developed rapidly for wearable and portable devices. Thus, the popularity of new electronics paradigms has increased significantly during the last several years.

Furthermore, integrated circuits (IC), wearable electronics devices, low-power circuit design, and networking approaches have all advanced due to these new technologies. These technologies are used in various applications on the human body, including glucose level sensors, blood pressure sensors, heart monitoring, oxygenation sensors, and medicine administration systems (P. Pillatsch et al., 2013). Diminutive sizes enable it to be comfortably fastened to human body parts. Additionally, the size reduction also resulted in a decrease in power consumption.

While electronics have advanced rapidly over the last few years, battery technology has remained stagnant. The majority of electronic devices use a traditional battery, which has a limited lifespan and must be replaced (Khaligh et al., 2008).

Moreover, batteries are the largest world's largest source of electronic waste. These traditional batteries contain hazardous substances that can be lethal to human health and the environment if not properly disposed (Huda et al., 2019). Other than that, the reduction in power consumption mentioned earlier also supports the idea of replacing batteries as a power source.

Micro energy is a term that refers to energy on a microwatt scale. One feasible solution is to build self-powered gadgets capable of generating electricity, which is commonly known as energy harvesting. Energy harvesting can be used to harvest energy from a variety of sources, including vibration, wind, sound, sun, and human motion (P. M. Y. Fan et al., 2015; Nguyen & Amirtharajah, 2018; Sang et al., 2012). Numerous sorts of energy harvesting studies have been conducted during the last decade. Despite this, when it comes to micro-scale energy generation, vibration energy harvesting has topped the chart due to a wide range of applications, accessibility, and minimal constraints in utilization, abundance in the environment, and availability of straightforward power generation mechanisms. Three techniques exist for harvesting vibration energy from the environment: piezoelectric, electromagnetic, and electrostatic (Ab. Rahman et al., 2013).

1.2 PROBLEM STATEMENT

Hybrid vibration energy harvesting can have high power density and power up most low power devices as compared to single mechanism energy harvesting. However, most hybrid vibration energy harvesters suffer from unidirectional sensitivity.

1.3 RESEARCH OBJECTIVES

The aims of this research work are:

1- To investigate the performance of energy harvester due to piezoelectric and electromagnetic interactions when subjected to low-frequency input.
2- To develop a hybrid energy harvester that combines piezoelectric and electromagnetic energy harvester.
3- To analyze and evaluate the performances of the developed hybrid model, including when subjected to random direction of motions.

1.4 RESEARCH METHODOLOGY

The research methodology is developed to achieve all the objectives. As shown in Figure 1.1, the first phase(red) is to select the suitable piezoelectric material for the design. Then, a simulation of piezoelectric deflection and electromagnetic energy harvester is conducted. The integration between both harvesters is simulated to identify the effect of electromagnetic energy harvester on the piezoelectric energy harvester. All the simulations are carried out using MATLAB, COMSOL, and SOLIDWORK software. If the design is optimum, which produces a higher voltage than a single energy harvester, the project continues into the second phase.

In the second phase (green), the hybrid energy harvester is fabricated. The test rig for the experiments is built. The final phase (orange) is to evaluate and verify the performance of the hybrid energy harvester as compared to the simulation data.

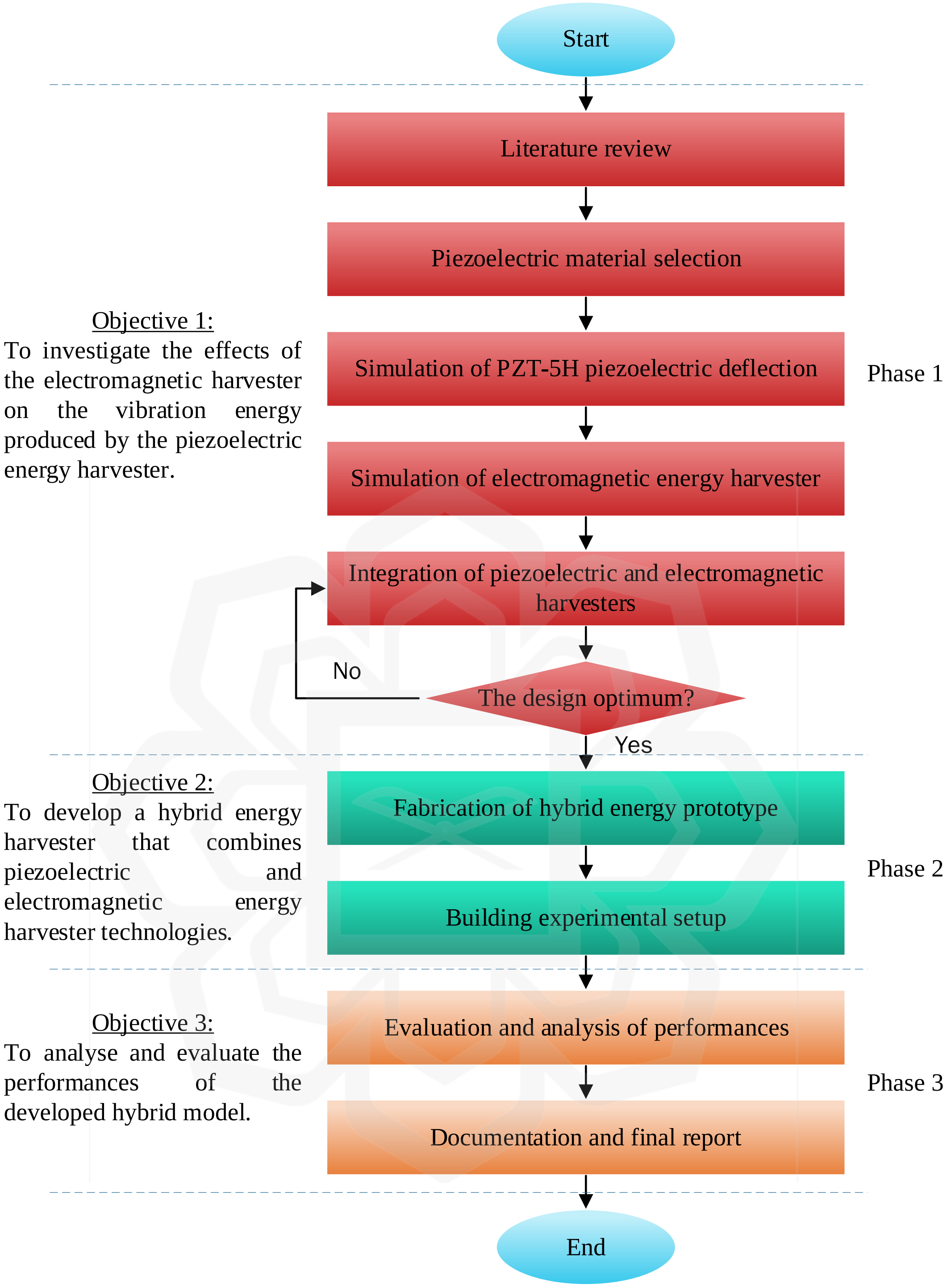

Figure 1.1 Flowchart of methodology

1.5 RESEARCH SCOPES

The research primarily focuses on harvesting energy using piezoelectric and electromagnetic approaches from the random direction of motions, representing human motion. The range of the low frequencies are between 0 Hz to 13 Hz. PZT-5H piezoelectric beam and neodymium (NdFeB) permanent magnets, which are readily available, are utilized in this research work.

1.6 SIGNIFICANCE OF THE STUDY

The development of the hybrid energy harvester is significant to cater to the energy demand for wearable and low-powered electronic devices. By integrating both vibration energy harvesters, the voltage generated is increased as compared to a single energy harvester. Additionally, the charging time is reduced significantly. The research also shows the capability of a hybrid energy harvester that can harvest energy at random directions, which is the frequency of human motion. Furthermore, the plucking method shows the method can convert low-frequency input into high-frequency input. Both energy harvesters are always simultaneously activated to produce high voltage.