



AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Electronics Engineering and Electrical Communications

Design and Implementation of Hybrid Energy Harvesting System for Medical Wearable Sensor Nodes

A Thesis Submitted in Partial Fulfillment of the Requirements of the
Degree of

Doctor of Philosophy in Electrical Engineering

Electronics Engineering and Electrical Communications

by

Saeed Mohsen Abosreea Hassan

Master of Science in Electrical Engineering

Electronics Engineering and Electrical Communications

Faculty of Engineering, Ain Shams University, 2016

Supervised by

Prof. Abdelhalim Abdelnaby Zekry

Dr. Mohamed Abdelhamid Abouelatta

Dr. Khaled Youssef Kamel

Cairo – Egypt – (2020)



AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Electronics and Communications Engineering Department

**Design and Implementation of Hybrid Energy Harvesting
System for Medical Wearable Sensor Nodes**

by

Saeed Mohsen Abosreea Hassan

Master of Science in Electrical Engineering

Electronics Engineering and Electrical Communications

Faculty of Engineering, Ain Shams University, 2016

Examiners' Committee

Name and Affiliation

Signature

Prof. El-Sayed Mahmoud El-Rabaie

.....

Electronics and Communications Department

Faculty of Electronic Engineering - Menoufia University

Prof. Mohamed Amin Dessouky

.....

Electronics and Communications Department

Faculty of Engineering - Ain Shams University

Prof. Abdelhalim Abdelnaby Zekry

.....

Electronics and Communications Department

Faculty of Engineering - Ain Shams University

Date of Examination: 14 / 11 / 2020

Statement

This thesis is submitted as a partial fulfillment of Doctor of Philosophy in Electrical Engineering (Electronics and Communications), Ain Shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

Saeed Mohsen Abosreea

Signature

.....

Date: / / 2020

Researcher Data

Name	: Saeed Mohsen Abosreea Hassan
Date of birth	: 18 / 10 / 1990
Place of birth	: Egypt
Last academic degree	: Master of Science in Electrical Engineering
Field of specialization	: Electronics and Communications
Name of University	: Ain Shams University
Date of issued degree	: October 2016
Current job	: Assistant Lecturer

Acknowledgment

A long way has passed until this moment; a way that was full of many ups and downs. And finally, it is the time to thank all those who have contributed to this final outcome.

First of all, I would like to thank **Allah** for giving me the capability to learn all what I have learned in my life and to give me the ability to write this thesis.

After Allah, I want to express my gratitude to **Prof. Abdelhalim Zekry** who's not only served as my supervisor but also encouraged me and provided me with valuable guidance and indispensable help. His words of advice, his trust, and his patience and understanding helped me to finish this work. He has been a role model to me.

Special thanks to my supervisors **Dr. Mohamed Abouelatta** and **Dr. Khaled Youssef** for their support till finalizing this research.

I grant all the success realized in my life to **my parents** to whom I owe all good things I learned and will learn till I die.

I'm also grateful to my wife **Eng. Sarah Oraby** for her support and continuous help all the way long. Also, I would like to dedicate this acknowledgement to all the people who helped me making it happen especially for my friends **Eng. Mahmoud Salem**, **Eng. Mohamed Saied**, and **Eng. Abanoub Mamdouh** for their continuous support and understanding without which I have probably quitted a long time ago, **my brothers** who sacrificed many happy moments I had to be busy away from them. Finally, I would like to dedicate thanking to **Dr. Ahmed Elkaseer** and **Dr. Ahmed Elshazly** for their help.

It is always impossible to personally thank everyone who has facilitated successful completion of this thesis. To those of you who I didn't specifically name, I also give my thanks for moving me towards my goal.

November 2020

Abstract

One of the solutions used for supplying low-power medical applications is the photovoltaic energy harvesting system (PEHS). In this thesis, the proposed PEHS is composed of a photovoltaic panel, a DC-DC boost converter, a fixed resistive load, and an analog control algorithm. This algorithm is designed based on the output load current. It is implemented using the multisim tool. This algorithm is simple, low cost, and low power consumption because it measures only the output current parameter and does not need multipliers. The power consumption of the proposed load is approximately 39.24 mW. Therefore, the expected working duration of the load is 20.9 hours under continuously operation of the light for 4 hours. Finally, the simulation results illustrate the transient characteristics of the proposed PV system.

In this thesis, an autonomous wearable sensor node is developed for long-term continuous healthcare monitoring. This node is used to monitor the body temperature and heart rate of a human through a mobile application. Thus, it includes a temperature sensor, a heart pulse sensor, a low-power microcontroller, and a Bluetooth low energy (BLE) module. The power supply of the node is a lithium-ion rechargeable battery, but this battery has a limited lifetime. Therefore, a photovoltaic energy harvesting system (PEHS) is proposed to prolong the battery lifetime of the sensor node. This PV energy harvesting system is practically tested outdoor under lighting intensity of 1000 W/m^2 . Experimentally, the overall power consumption of the node is 4.97 mW and its lifetime about 246 hours in active-sleep mode. The experimental results demonstrate long-term and sustainable operation for the sensor node.

In this thesis, a self-powered Internet of Things (IoT) wearable sensor node is proposed for healthcare monitoring. This node enables doctors of measuring the heart rate, blood oxygen saturation (SpO_2), and body temperature. This node is based on NodeMCU board that includes a microcontroller with a Wi-Fi chip. A solar energy harvester is developed as power supply to provide a solution for prolonging the lifetime of the node. This harvester is designed of two flexible photovoltaic (PV) panels, a charging controller, and a lithium-ion battery. The harvester is practically tested outdoors under direct sunlight and partly cloudy conditions. Experimentally, the IoT wearable sensor node consumes an average power of 20.23 mW over one hour and the lifetime of the node is 28 hours in a wake-up-sleep mode.

In this thesis, a wearable medical sensor system is designed for long-term healthcare applications. This system is used for monitoring temperature, heartbeat, blood oxygen saturation (SpO₂), and the acceleration of a human body in real-time. This system consists of a temperature sensor, a pulse oximeter sensor, an accelerometer sensor, a microcontroller unit (MCU), and a Bluetooth low energy (BLE) module. Batteries are needed for supplying energy to this sensor system, but batteries have a limited lifetime. Therefore, a photovoltaic-thermoelectric hybrid energy harvester is developed to power a wearable medical sensor system. This harvester provides sufficient energy and increases the lifetime of the sensor system. The proposed hybrid energy harvester is composed of a flexible photovoltaic (PV) panel, a thermoelectric generator (TEG) module, a DC-DC boost converter, and two super-capacitors. Experimentally, in active-sleep mode, the sensor system consumes an average power of 2.13 mW over one hour and works without the energy harvester for 46 hours.

Keywords

Photovoltaic (PV), Thermoelectric Generator (TEG), Multisim, Medical Wearable Sensor Nodes, Healthcare Monitoring, DC-DC Boost Converter, Super-capacitors, Internet of Things (IoT), Bluetooth Low Energy (BLE).

Contents

List of Figures -----	i
List of Tables -----	iv
List of Abbreviations -----	v
List of Symbols-----	vi
Chapter 1: Introduction-----	1
1.1 Overview-----	1
1.2 Problem Definition -----	2
1.3 Thesis Objectives -----	2
1.4 Thesis Contributions -----	3
1.5 Methodology -----	3
1.6 Thesis Outlines-----	4
Chapter 2: Literature Review and Background for Energy Harvesting Systems -----	6
2.1 Introduction -----	6
2.2 Energy Sources -----	6
2.3 Energy Harvesting Systems-----	7
2.4 Photovoltaic Energy Harvesting System -----	8
2.5 Photovoltaic Panel-----	9
2.5.1 Photovoltaic Panel Types -----	10
2.5.2 Photovoltaic Panel Model-----	11
2.5.3 Photovoltaic Panel Current-Voltage Curve-----	12
2.5.4 PV Panel Efficiency -----	12
2.5.5 Light Intensity Effect -----	13
2.6 Thermoelectric Energy Harvesting System-----	13
2.7 Mechanical Energy Harvesting System -----	15
2.7.1 Piezoelectric Energy -----	15

2.7.2 Electromagnetic Energy -----	16
2.7.3 Electrostatic Energy-----	16
2.8 Ultrasonic Energy Harvesting System-----	17
2.9 Radio Frequency Energy Harvesting System -----	18
2.10 Energy Harvesting Applications -----	18
2.11 Maximum Power Point Tracking (MPPT) Algorithms-----	19
2.11.1 Perturb and Observe (P&O) Algorithm -----	21
2.11.2 Incremental Conductance (IC) Algorithm -----	21
2.11.3 Other MPPT Algorithms-----	22
2.12 DC-DC Converter Types -----	23
2.12.1 Buck Converter -----	24
2.12.2 Boost Converter-----	25
2.12.3 Buck-Boost Converter -----	26
2.13 Energy Storages -----	26
2.14 Wearable Devices-----	27
2.15 Medical Wearable Sensor Nodes -----	27
2.16 Vital Data and Biomedical Sensors -----	268
2.16.1 Body Temperature-----	268
2.16.2 Body Temperature Sensors-----	269
2.16.3 Heart Rate-----	29
2.16.4 Heart Rate Sensors -----	30
2.16.5 Blood Pressure -----	30
2.16.6 Blood Pressure Sensors -----	31
2.16.7 Respiration Rate -----	31
2.16.8 Respiration Rate Sensors -----	31
2.17 Other Vital Signs and Wearable Sensors -----	32
2.18 Wireless Communication Technologies -----	34

2.19 Summary	35
Chapter 3: Proposed Architectures for Energy Harvesting Systems.....	36
3.1 Overview.....	36
3.2 Proposed One: PV System with Analog Control Algorithm	40
3.3 Proposed Two: Wearable Sensor Node Based on Battery.....	40
3.3.1 Power Calculations without Photovoltaics	41
3.3.2 Power Calculations with Photovoltaics	41
3.4 Proposed Three: IoT Wearable Sensor Node.....	42
3.4.1 Energy Budget of the Solar Energy Harvester	43
3.5 Proposed Four: Hybrid Energy Harvesting System	44
3.5.1 Energy and Lifetime Calculations	45
Chapter 4: Computer Aided Simulation of Energy Harvesting Systems.....	48
4.1 Simulation of the PV System with Analog Control Algorithm for the Proposed One	48
4.2 Simulation Results of the Analog Control Algorithm	51
4.3 Discussion	53
4.4 Simulation Model of the Hybrid Energy Harvester for the Proposed Four	54
4.5 Simulation Results of the Hybrid Energy Harvester.....	55
Chapter 5: Realization of the Proposed Energy Harvesting Systems	56
5.1 Realization of the Wearable Sensor Node Based on Battery for the Proposed Two	56
5.1.1 Hardware Implementation	56
5.1.2 Software Implementation	58
5.1.3 Results of the Wearable Sensor Node Based on Battery	59
5.2 Realization of the IoT Wearable Sensor Node for the Proposed Three	60
5.2.1 Hardware Implementation	60
5.2.2 Software Implementation	62
5.2.3 Results of the IoT Wearable Sensor Node.....	62

5.3 Realization of the Hybrid Energy Harvesting System for the Proposed Four --	63
5.3.1 Hardware Implementation -----	63
5.3.2 Software Implementation -----	66
5.3.3 Results of the Hybrid Energy Harvesting System -----	68
5.4 Discussion -----	74
Chapter 6: Conclusions and Future Work -----	78
6.1 Conclusions -----	78
6.2 Future Work -----	79
References-----	81
Publications -----	102

List of Figures

Fig.2.1 Photovoltaic Energy Harvesting Systems for Wearable Sensors: (a) a Bracelet with a PV Panel; (b) a Flexible Panel for a Node; (c) a Wearable T-Shirt	8
Fig.2.2 PV Panel Structure-----	9
Fig.2.3 Polycrystalline PV Panel-----	10
Fig.2.4 Monocrystalline PV Panel -----	11
Fig.2.5 Amorphous PV Panel -----	11
Fig.2.6 The Electrical Model of a PV Panel-----	12
Fig.2.7 I-V and P-V Curves of a PV Panel -----	12
Fig.2.8 I-V Curve Shifts with the Light Intensity -----	13
Fig.2.9 Thermoelectric Generator-----	14
Fig.2.10 Thermoelectric Generator Principle -----	14
Fig.2.11 The Temperature Gradient of a TEG -----	14
Fig.2.12 The Electrical Model of the TEG -----	15
Fig.2.13 Shoes with a Piezoelectric Harvester -----	16
Fig.2.14 Energy Harvesting Applications -----	19
Fig.2.15 I-P-V Curves with the MPP-----	20
Fig.2.16 Step-Down (Buck) Converter-----	24
Fig.2.17 Step-Down Converter Waveforms of the Inductor Current and Voltage-	24
Fig.2.18 Step-Up (Boost) Converter-----	25
Fig.2.19 Boost Converter Waveforms of the Inductor Current and Voltage -----	25
Fig.2.20 Buck-Boost -----	26
Fig.2.21 Wearable Devices -----	27
Fig.2.22 Medical Wearable Sensor Nodes-----	28
Fig.2.23 A Screenshot of a MAX30205 Body Temperature Sensor-----	29
Fig.2.24 A Screenshot of a Pulse (PPG) Sensor -----	30
Fig.2.25 A Screenshot of a Blood Pressure Sensor-----	31

Fig.2.26 Wearable Sensors-----	32
Fig.2.27 Wearable Sensor Systems-----	33
Fig.3.1 The Generic Block Diagram of the Energy Harvesting System -----	36
Fig.3.2 Block Diagram of the Proposed PV System -----	40
Fig.3.3 Block Diagram of the Sensor Node with a PEHS -----	40
Fig.3.4 Wearable Sensor Node with the IoT Cloud Service -----	42
Fig.3.5 Architecture of the Proposed IoT Wearable Sensor Node -----	43
Fig.3.6 The Proposed Architecture of the Hybrid Energy Harvester with the Sensor System -----	45
Fig.3.7 Generic Power Profile of the Sensor System -----	45
Fig.4.1 The PV System Design-----	48
Fig.4.2 The Overall PV System Design with the Proposed Analog Control Algorithm -----	50
Fig.4.3 The Flowchart of the Proposed Algorithm -----	51
Fig.4.4 Photovoltaic Panel Voltage-----	52
Fig.4.5 Capacitor Charging-----	52
Fig.4.6 Load Voltage -----	52
Fig.4.7 Resistance Sense Voltage-----	53
Fig.4.8 Duty Cycle-----	53
Fig.4.9 Circuit Configuration of the PV Panel and TEG Module with the DC-DC Converter -----	55
Fig.4.10 Three Curves of the Simulation of the Hybrid Energy Harvester -----	55
Fig.5.1 Hardware Components of the Developed Wearable Sensor Node -----	57
Fig.5.2 The Setup for the Developed Wearable Sensor Node -----	57
Fig.5.3 The Software Flowchart of the Node -----	58
Fig.5.4 The 24 Hour Operation Time of the Battery Voltage Monitoring-----	59
Fig.5.5 Discharging Curves of the Battery: (a) at Active Mode; (b) at Active-Sleep Mode-----	60

Fig.5.6 Hardware Components of the IoT Wearable Sensor Node with the Solar Energy Harvester-----	61
Fig.5.7 The Implementation of the IoT Wearable Sensor System -----	61
Fig.5.8 The Flowchart of the IoT Wearable Sensor Node -----	62
Fig.5.9 The Monitored Physiological Data of a Patient on the Ubidots Cloud Service -----	63
Fig.5.10 The Wearable Sensor System: (a) Hardware Components; (b) The Sensor System Prototype-----	65
Fig.5.11 The Software Flowchart of the Sensor System -----	66
Fig.5.12 The Developed Android Application: (a) GUI Design; (b) The Software Flowchart-----	67
Fig.5.13 I-V and P-V Characteristic Curves of the Flexible PV Panel at 1000 W/m ² -----	68
Fig.5.14 Output Voltage and Power Characteristic Curves of the TEG at $\Delta T=20$ °C -----	69
Fig.5.15 The Discharging Curve of the 50 F Super-Capacitor Bank -----	70
Fig.5.16 The Charging Curve of the 50 F Super-Capacitor Bank -----	70
Fig.5.17 The Charging Curve of the 50 F Super-Capacitor Bank from the TEG Module-----	71
Fig.5.18 The Measured Current Consumption Profile for the Sensor System -----	72
Fig.5.19 Heartbeat Readings Monitored Over an Active Time -----	72
Fig.5.20 The Collected Data of the Accelerometer in the X,Y, and Z Directions of the Sensor System-----	73
Fig.5.21 Screenshot of the Monitored Vital Data in the Developed Android Application (My Health)-----	74
Fig.5.22 Comparison of the Power Consumption and Lifetime between This Work and Previous Studies-----	75

List of Tables

Table.2.1 Different Energy Sources -----	7
Table.2.2 MPPT Algorithms -----	23
Table.2.3 Different Energy Storage Elements -----	27
Table.2.4 Wireless Communication Technologies -----	35
Table.3.1 Power Densities of Different Energy Sources -----	36
Table.3.2 Properties of Different Energy Storages -----	37
Table.4.1 Comparisons of Analog Control Algorithms -----	53
Table.5.1 The Proposed Electronic Components in the Developed Wearable Sensor Node -----	57
Table.5.2 Conversion Efficiencies of the Photovoltaic (PV) Harvester-----	69
Table.5.3 Charging Rate of the Bank -----	70
Table.5.4 Comparisons of the Recent Sensor Systems with Energy Harvesters----	76
Table.5.5 Comparisons of the Proposed Realized Systems-----	77