POWER CONDITIONING OPTIMIZATION FOR ULTRA LOW VOLTAGE WEARABLE THERMOELECTRIC DEVICES USING SELF-SUSTAINED MULTI-STAGE CHARGE PUMP

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Dedicated in great appreciation for encouragement, support and understanding to my beloved father, mother, lecturers, brothers, sisters and friends.

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ABSTRACT

Waste heat energy recovery from human body utilizing the thermoelectric generator (TEG) has shown potential in the generation of electrical energy. However, the level of heat source from the human body restricts the temperature deviation as compared to ambient temperature (approximately 3~10 °C in difference), thereby yielding an ultra-low voltage (ULV) normally less than 100 mV. This research aims at generating power from the TEG by harnessing human body temperature as the heat source to power up wearable electronic devices realizing a self-sustain system. However, power conversion of the TEG has typically low efficiency (less than 12%), requiring proper design of its power regulation system. The generated ULV marked the lowest energy conversion factor and improvement is therefore required to validate the use of ULV generated from human body temperature. This problem was addressed by proposing an improved solution to the power regulation of the ULV type TEG system based on the DC-DC converter approach, namely a multi-stage charge pump, with specifications restricted at the ULV source. Performances of the TEG connected in multiple array configurations with the generated source voltage fed into fabricated charge pump circuit to boost and regulate the voltage from the ULV into the low voltage (LV) region were analyzed. The maximum source voltage (20 mV) was referred and simulated in the LT Spice software and used as a benchmark to be compared with the voltage generated by the fabricated charge pump circuits. Error performances of the fabricated charge pump circuits were further analyzed by manipulating the circuits' parameters, namely, the switching frequency and the capacitance values. It was found that the proposed method was able to handle the ULV source voltage with proper tuning on its component parameters. The overall power conversion efficiency of 26.25% was achieved based on the performance evaluation values for components applied in this research. Hence, this proved the viability of thermoelectric applications in ULV using the proposed power regulation system.

ABSTRAK

Kitaran semula tenaga haba terpakai daripada badan manusia dengan menggunakan penjana termoelektrik (TEG) telah menunjukkan potensi dalam penjanaan kuasa elektrik. Namun, kandungan haba dalam badan manusia mengehadkan perbezaan suhu berbanding dengan suhu persekitaran (kira-kira perbezaan 3~10 °C). Kajian ini bertujuan menjana kuasa daripada TEG dengan menggunakan suhu badan manusia sebagai sumber haba untuk menghidupkan peranti boleh-pakai dan melengkapkan suatu sistem swakekal. Namun, TEG mempunyai kecekapan penukaran tenaga yang rendah (kurang daripada 12%), menyebabkan ia memerlukan suatu sistem kawalan kuasa yang sesuai. Ini mengakibatkan voltan teramat rendah (ULV) yang dijana biasanya mempunyai nilai kurang daripada 100 mV. Penjanaan ULV tersebut merupakan faktor penukaran kuasa terendah dan penambahbaikan diperlukan bagi mengesahkan penggunaan ULV yang dijana daripada suhu badan manusia. Masalah ini ditangani dengan cadangan solusi penambahbaikan terhadap kawalan kuasa bagi sistem TEG jenis ULV berasaskan kaedah pengubah DC-DC menggunakan cas pam berperingkat, dengan spesifikasi yang terhad pada sumber ULV. Hasil janaan tenaga daripada TEG yang disambungkan dalam konfigurasi yang berbeza dan voltan janaan yang dialirkan ke litar cas pam yang difabrikasi untuk meningkat dan mengawal voltan daripada ULV kepada lingkungan voltan rendah (LV) telah dianalisis. Sumber voltan maksima (20 mV) dirujuk dan disimulasikan dalam perisian LT Spice untuk dijadikan sebagai rujukan dan dibandingkan dengan voltan janaan daripada litar cas pam yang difabrikasi. Ralat keputusan bagi litar cas pam yang difabrikasi dilanjutkan analisisnya dengan mengubah parameter litar merangkumi frekuensi pensuisan dan nilai kapasitor. Kajian ini telah menunjukkan bahawa cadangan yang dikemukakan dalam kajian ini berupaya untuk menangani sumber voltan ULV dengan penalaan yang sesuai dalam perameter komponen. Kecekapan penukaran kuasa secara keseluruhannya mencapai 26.25% berdasarkan keputusan bagi nilai komponen yang digunakan dalam kajian ini. Kajian ini telah membuktikan kelayakan aplikasi penjana kuasa terma dalam lingkungan ULV dengan sistem kawalan kuasa yang dicadangkan.

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LIST OF ABBREVIATIONS

TEC	-	Thermoelectric Cooler
TEG	-	Thermoelectric Generator
ZT	-	Figure of merit
BJT	-	Bipolar Junction Transistor
FET	-	Field Effect Transistor
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
CMOS	-	Complementary Metal Oxide Semiconductor
MPPT	-	Maximum Point Power Tracking
SEPIC	-	Single Ended Primary Inductance Converter
PV	-	Photovoltaic

LIST OF SYMBOLS

V	-	Voltage
A	-	Ampere
W	-	Power
F	-	Farad
Hz	-	Hertz
η	-	Efficiency
f	-	Frequency
H	-	Inductance
Ω	-	Resistance
%	-	Percentage

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Portable devices are becoming more of a necessity rather than a luxury. These devices have been upgraded from stationary devices that are bulky and heavy that limit both their portability and usage. Instead, they have been designed to be as small as possible to ensure portability so that users are able to enjoy the functions that the devices have to offer wherever and whenever they want. Typically, a portable device is powered up by a power source that requires a charging and discharging process to maintain the function of the device. The power source is a restricting factor where the utilization of dry cells can only support the functions of these devices for a specific time [1]. Additionally, the disposal of old dry cells also pollutes the environment as there are acidic elements within the cells. Problems posed by the use of dry cells have been studied over the years with the intention of not only resolving the limitations of the dry cells but also attempting to eliminate their use entirely.

The idea of harvesting energy from existing abundant natural resources has promoted the viability of a whole day long standby portable device. Thus, green energy has been proposed worldwide as a form of sustainable new generation of power, harvested from the environment. Among all natural resources, heat has probably received the most interest as heat can be obtained continuously from human daily activities. Additionally, heat energy can readily be converted into electrical energy through the use of the thermoelectric generator (TEG). The TEG is attractive by its concise design with no moving parts and low maintenance [2].

Previous studies have shown that heat could be used as a power generation source. These studies have assisted in eliminating the need for charging and replacing batteries in applied applications [1]. At the same time, heat power generation has also assisted in the overall cost savings in terms of maintenance and labor. The evolution of technology, particularly the development of wireless technologies and low powered electronics, has further encouraged the TEG to be applied in autonomous systems [3].

Power supply is always a critical determination when dealing with autonomous systems. This critical determination excites researchers to invest in studies on TEG modules applied within portable devices aimed at sustaining the operation of the device by the users themselves. In micro-scale applications for instance, there are suggestions that applying the TEG in medical devices could assist in continuous monitoring of patients while generating power from the patients' body [4]. In macro-scale applications, the TEG has been applied on aircrafts [3], glass melt ovens [5] and nuclear dry cast storage [6]. The motivation for the macro-scale applications is to reduce reliability of power source on carbon and oil emission.

The TEG is also known as a generator with low energy conversion not exceeding 12% [7]. However, a proper power management system is required to ensure that the generated power is able to sustain operation of the whole power generation module. It is thus the aim of this research to design a power management system with high accuracy of 26.25 % of energy conversion efficiency for TEG based wearable devices.

1.2 Problem Statement

The TEG is very attractive in terms of its application due to the simplicity of the system in which no moving parts are involved [6]. However, its low energy conversion makes the design of a TEG based system difficult as power is generated based on heat conversion [8]. Therefore, there is a need for power dissipation being determined in the design criteria. The low generated power will not be able to support even low power electronic operations, making power generation a wasteful process.

These days, portable devices are typically equipped with built in batteries that need to be charged within specific periods. The charging and discharging process reduces the life cycle of the batteries [9]. When the battery life expires, the compact design of the portable device needs to be disassembled to replace the battery. Such an action is an inconvenience. The situation can also cause a rise in the cost of the device in terms of maintenance and manpower, which is not cost effective for long term usage.

On the other hand, the thermoelectric power generation is directly proportional to the range of temperature gradient where the higher the temperature gradient, the more power is generated. However, this limits the application of the TEG in an open environment as temperature gradients are low all the time resulting in low power generation. Low power generation of the TEG results in voltage generation in a much lower voltage rating, typically classified as an ultralow voltage region that has not been discussed much in previous research [10]. This situation limits the regulation of generated voltage as it is hard to find compatible circuit operating in ultralow voltage region. Besides, temperature fluctuations also cause ripple in output power that is not suitable in Direct Current (DC) output systems. Unstable DC power will cause output systems to have swing operations, causing improper system operations. Therefore, a power regulation circuit is required to resolve the problems mentioned above. The circuit works to filter unstable DC voltage at ultralow voltage region and amplify it to a higher level.

As a conclusion, an ultralow voltage operated power management circuit is proposed to resolve the low energy conversion efficiency of TEG. The power management circuit will be utilizing TEG sensors generating energy from human body temperature. Meanwhile, the energy harvesting method is set to be low temperature gradient that realize a self-sustain system. Hence, this resolves the dependency of portable device on battery while improves the low energy conversion efficiency of TEG sensors in sustaining low powered electronic systems.

1.3 Research Objectives

This research aims to accomplish the following objectives:

i. To design an optimal power regulation system for a thermo-electric power harvesting system.

ii. To prototype a power regulation system for the thermo-electric power harvesting system.

iii. To characterize the system performance in terms of its efficiency by comparing the simulation results and bench marking it with other relevant methods mentioned in research scope.

1.4 Scope of Research

The followings represent the scope of this research:

i) TEG based power management system design development restricted at ultralow voltage region.

ii) Power management unit is simulated using LT Spice with 20 mV input voltage with temperature deviation of five to ten degree Celcius (to imitate the raw output adopted from the TEG by body temperature).

iii) Step up based power management unit design (charge pump or boost converter) restricted with oscillator operated at 1.5 V.

iv) Fabrication of the power management unit is based on the simulated design and results from both methods are compared.

v) Analysis and optimization are based on two control parameters (switching frequency and charge capacitance)

vi) Evaluation of power management system efficiency is aimed to achieve at least 12 percent to overcome low energy conversion of TEG.

1.5 Significance of Study

This study enhances the energy harvesting systems that operate to sustain low powered electronic systems. As sustained power cuts down the cost for battery replacement in electronic devices, this study explores the potential of using human body temperature as a power generation source. This further expands the possibility of power management systems obtained from this research to enhances the generated voltage from an ultralow voltage region to a low voltage region. Additionally, this study also encourages further development of portable devices as the self-power sustained concept is not only a feasible option, but could also act as an unlimited power generation source. Furthermore, it enhances the possibility of a continuous health monitoring system. By having such a self-power sustained system, the risk of power failure of hospital facilities where lives are dependent on continuous power supply could be reduced.

The contributions of this research are listed as follows:

1) Explore the ultralow voltage region applications by utilizing human body temperature as a source for renewable energy conversion.
2) Introduce power regulations in ultralow voltage region to further enhance the viability of ultralow voltage applications in renewable energy.
3) Improve energy conversion efficiency by taking consideration of the worst energy conversion factor (i.e. low temperature differences) and improve it to a reliable rating.

1.6 Thesis Outline

The thesis consists of five chapters that are categorized as follows:

Chapter 1 explains the viability of portable wearable thermoelectric devices, issues, motivation and scope of the study.

Chapter 2 includes the literature review of past studies of thermoelectric applications, theories and power management methods that are applied to portable wearable devices.

Chapter 3 reveals the proposed techniques, software and hardware in proceeding with the research study.

Chapter 4 analyses and characterizes the results of the performance of multiple sensors in array configurations.

Chapter 5 discusses the results for both simulation and practical model of the proposed power conditioning system.

Chapter 6 summarizes the research study with future recommendations for further improvement.

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