Faculty of Electronics and Computer Engineering

DESIGN OF A HIGH EFFICIENCY MULTIPLE-INPUTS SINGLE-OUTPUT SWITCH CAPACITOR-BASED DC-DC CONVERTER FOR ENERGY HARVESTING SYSTEM

Yap Jim Hui

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YAP JIM HUI

A thesis submitted
in fulfilment of the requirements for the degree of Master of Science
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DECLARATION

I declare that this thesis entitled "Design of A High Efficiency Multiple-Inputs Single-Output Switch Capacitor-Based DC-DC Converter for Energy Harvesting System" is the result of my research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature : ....

Name : Yap Jim Hui

Date : ....

APPROVAL

I declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science in Electronic Engineering.

Signature :

Supervisor Name : Associate Professor Dr.Wong Yan Chiew

Date :

DEDICATION

For my lovely parents, my supervisor, Associate Professor Dr. Wong Yan Chiew, my co-supervisor, Associate Professor Dr. Kok Swee Leong, my colleagues and my friends.

ABSTRACT

Thermoelectric generators (TEGs) module acts as a source to harvest thermal energy and convert the temperature gradient into DC voltage. Due to its low electricity produced, the DC-DC converter is the key module to boost minimal voltage to feasible electricity. The setback of existing converter topology such as inductor-based is the off-chip component makes fully integrated on-chip system a challenging task. Thus, the research focuses on the design of a cross-coupled charge pump in power management energy harvesting circuitry together with a start-up circuit and control circuit to form a regulated battery-less power management system. Multiple energy sources, RF and thermal energy have been used as the supply for the auxiliary circuitry and cross-coupled charge pump in the research. The proposed cross-coupled charge pump is designed based on an analytical approach that investigates the transistor's size, the switching pulse's frequency, the switching pulse's slew rate and the capacitor's size. The peak efficiency of the cross-coupled charge pump has been improved by analyzing these four main parameters. The proposed system can function at a minimum voltage of 30mV and achieve a step-up voltage of 1.2V in a fully integrated chip. The major contribution of this work is the design of the cross-coupled charge pump has successfully achieved an efficiency of 70.86%. RF and TEG signal are utilized as voltage supply and input for the entire power management system. Due to the multiple energy harvesting sources, auxiliary circuitries can be fully integrated to form an on-chip power management system without an external inductor, capacitor and antenna to support the power management system and only occupy a chip size of 1.9358 mm^2. Implementation of on–chip antenna for RF auxiliary circuitry achieves a more compressive fully integrated on-chip system. In overall, the entire design configuration has managed to reduce the mismatch of the off-chip component on the on-chip power management system as well as to reduce the package of the chip size.

REKA BENTUK SUIS KAPASITOR KEMASUKAN-BERBILANG KELUARAN-TUNGGAL BERKECEKAPAN TINGGI BERDASARKAN PENUKAR DC-DC UNTUK SISTEM PENUAIAN TENAGA

ABSTRAK

Modul penjana termoelektrik (TEG) bertindak sebagai sumber untuk menuai tenaga haba dan menukar kecerunan suhu menjadi voltan arus terus (DC). Oleh sebab tenaga elektriknya yang rendah, penukar DC-DC merupakan modul utama untuk meningkatkan voltan yang rendah. Kemunduran topologi penukar DC-DC yang sedia ada seperti penukar DC-DC yang berasas induktor adalah komponen off-chip dan menyebabkan system on-chip bersepadu sepenuhnya sebagai tugas yang mencabar. Oleh itu, penyelidikan ini berfokus pada reka bentuk pam cas bersilang dalam litar penuaian tenaga pengurusan kuasa bersama dengan litar permulaan dan litar kawalan untuk membentuk sistem pengurusan kuasa tanpa bateri yang diatur. Sumber tenaga berganda, RF dan tenaga haba telah digunakan sebagai bekalan untuk litar tambahan dan pam cas bersilang dalam penyelidikan. Kerja penyelidikan ini berfokus pada penyelidikan pam cas bersilang CMOS yang berkecekapan tinggi. Oleh itu, pam cas bersilang yang direka berdasarkan pendekatan analitik pada ukuran transistor, frekuensi daya, kadar kepantasan daya dan ukuran kapasitor. Keupayaan puncak pam cas bersilang telah bertambah berdasarkan analisis pada empat parameter utama ini. Sistem yang direka dapat berfungsi dengan voltan minimum 30mV dan mencapai voltan sebanyak 1.2V dalam cip bersepadu sepenuhnya. Sumbangan utama daripada penyelidikan ini adalah reka bentuk pam cas bersilang yang berjaya mencapai keupayaan sebanyk 70.86%. Tenaga RF dan TEG digunakan sebagai bekalan voltan dan input untuk keseluruhan sistem pengurusan kuasa. Disebabkan pelbagai jenis sumber penuaian tenaga digunakan, litar tambahan dapat digabungkan sepenuhnya untuk membentuk sistem pengurusan kuasa on-chip tanpa induktor luaran, kapasitor dan antena untuk menyokong sistem pengurusan kuasa dan hanya menempati ukuran cip yang hanya 1.9358mm^2. Implementasi antena on-chip untuk litar tambahan RF mencapai sistem cip bersepadu yang lebih mampat Oleh itu, konfigurasi ini telah mengurangkan ketidaksesuaian komponen off-chip pada sistem pengurusan kuasa on-chip dan dapat mengurangkan paket ukuran chip.

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LIST OF ABBREVIATIONS

AC	-	Alternating Current
CCM	-	Continuous Conduction Mode
CMOS	-	Complementary Metal-Oxide-Semiconductor
CP	-	Charge Pump
C_{store}	-	Storage Capacitor
DC	-	Direct Current
DCM	-	Discontinuous Conduction Mode
DRC	-	Design Rule Check
EMI	-	Electromagnetic Interference
FET	-	Field Effect Transistor
FSM	-	Finite State Machine
I_{in}	-	Inductor Current
IoT	-	Internet of Things
LC	-	Inductor-Capacitor
LVS	-	Layout Versus Schematic
MOSFET	-	Metal-Oxide Semiconductor Field Effect Transistor
MPPT	-	Maximum Power Point Tracking
NMOS	-	N-type Metal-Oxide-Semiconductor
PCE	-	Power Conversion Efficiency
PEX	-	Parasitic Extraction
PMOS	-	P-type Metal-Oxide-Semiconductor
Q	-	Quality Factor
RCI	-	Recursive Current Injection
RF	-	Radio Frequency
TEG	-	Thermoelectric generator
V_{in}	-	Input voltage
V_{dd}	-	Supply Voltage

V_{store}	-	Storage Voltage
WBAN	-	Wireless Body Area Network
WSN	-	Wireless Sensor Node
ZCS	-	Zero Current Switching

LIST OF PUBLICATIONS

JOURNALS

Yap. J. H., and Wong. Y. C., 2019. A 30mV Input Battery-less Power Management System. *Bulletin of Electrical Engineering and Informatics*, 8(4), pp. 1169–1179.

Yap. J. H., and Wong. Y. C., 2021. A Complete Design and Development of a Miniature Battery-less Power Management Unit for Powering Biomedical Implant. *Journal of Engineering Science and Technology*, 16 (5), October 2021.

CHAPTER 1

INTRODUCTION

1.1 Background

The concept or implementation of energy harvesting implies for implantable biomedical devices has been given interest for the researchers to gain new relevance. An implantable medical device is one of the bioelectronics that involving sensors, chips and tiny power sources. Examples of implantable devices are pacemaker, cochlear implants, brain neurostimulators, etc. In the consideration of the volume, usage flexibility and convenience, these appliances are basically with a tiny battery assembled on it as the power source. Due to the continuous growth and revolution of the integrated circuit, the integrated microsystem had been open up windows of hope to give a solution to the complete system in a tiny and lightweight form. Nonetheless, an issue occurs when a battery is depleted and has to be replaced or recharged. This becomes challenging work to replace or take out the batteries of the biomedical devices which have been put underneath human skin or inside of the human body. Furthermore, the replacement of a battery beneath the body is dangerous as the leakage of mercury of the battery has brought up a health issue in a long term. Therefore, researchers had been put huge efforts into finding an efficient and easy way to make autonomous power on and self-rechargeable power supplies for these wearable devices.

Energy harvesting has opened up great value and possibility in renewable alternatives for a conventional battery. The reason for its extensive development because renewable energy can transform into a useful power source that is easy to obtain, less-tedious replacement compares with battery and the most important is it produces clean, pollution-free energy. Energy harvesting system has the potential to be used in health applications that are severely all volume-constrained, limiting the use of external passives for power delivery. While, in recent, ultra-low voltage becomes a point of merit in a future market demand especially in biomedical implants. One of the renewable energy, thermal energy has been given focus by the researchers now. Thermoelectric energy harvesting can convert thermal energy from human skin or waste heat energy into a small amount of DC electricity. Due to its characteristic of resilience towards environmental change, TEG becomes an attractive solution in the energy harvesting field (Ogawa et al., 2016). There are some examples of good heat sources in our daily application such as the heat from the refrigerator, air conditioner and laptop as they are almost operated continuously (Bose, Anand and Johnston, 2018). A thermoelectric generator is used to generate an electrical voltage from thermal energy. It is small in size, cost-effective and portable which has high potential to give autonomous power to a miniaturized and wearable electronic gadget that operates at very low power. Heat energy is one of the forms of energy that can be harvested for use in medical appliances as it can be captured from the human body. Previous research studies showed that thermal heat from the body can give electrical voltage to power up wearable biomedical devices. The only well-known practical application of the TEGs on a human body is the Seiko Thermal Wristwatch. It is a great inventory of wearable device that contains a thermoelectric generator that withdraws thermal body heat and converts the thermal gradient into electricity. According to Selvarathinam and Anpalagan (2016), the exact amount of human thermal heat that can be drawn out is permitted by a phenomenon called Carnot Efficiency. The equation of Carnot Efficiency is as following:

$$Carnot\ Efficiency = \frac{Tbody - Tambient}{Tbody} \quad (1)$$

Where;

$Tbody$ = Body Temperature

$Tambient$ = Ambient Temperature

The Carnot Efficiency yields to roughly 3.2%, showing that the quantity of energy that is managed to be harvested from body heat is from 2.4 W to 4.8 W. Nonetheless, the amount of energy depends on the difference between the body and ambient temperature. From the previous research, the maximum amount of heat energy that can be extracted from the body is from the neck area, forehead, and wrist area as these parts are not covered by clothing. One study from Leonov (2011) indicates that a vast amount (~100 W) of heat energy is available on the body, and only electrical power in the milliwatt range can be retrieved from body heat. According to Rozgi (2017), for more efficient operation, to gain a 20mV, a temperature difference of 4 °C temperature is needed. The researcher carried out this experiment based on the thermal heat from a human arm. This small thermal variation is hard to power on the harvester as most of the existing thermal-based energy harvesters need significantly more than 1 or 2 °C to power on the harvesting circuit. In Jiang et al. (2017), a 3.5K of a temperature gradient from the body of a rat and thermoelectric generator was used to demonstrate a real environment condition. In the future, there is a possibility that WSN or the BAN are transmitted or received the data by using the power from the body heat.

In this work, we find out that 1°C can produce 30mV. Thus, only 30mV is used as the minimum voltage for the harvester.

1.2 Problem Statement

There are many kinds of voltage booster work together with energy harvesting sources. However, it is a challenging task to design a high-efficiency voltage booster that can accept an ultra-low input voltage as well as fully integrated on an on-chip system. In past research, most voltage booster is designed by the off-chip components such as an inductor, capacitor and kicked started via an external electrical startup (Ogawa et al., 2016). Although the existing architecture can achieve high efficiency, 92% converter efficiency but with the single-inductor topology (Rozgi, 2017). There is research presented a fully integrated boost converter by replacing the physical inductor with an integrated metal-track inductor and managed to give a regulated 1.1V but the drawback is the 39% low efficiency (Hernandez and Noije, 2015). Acceptance of low input voltage for a boost converter is also another concern. One of the existing cross-coupled charge pumps for a low-power on-chip application is able to achieve an efficiency of 58.72 % but with a 1.2V supply voltage (Jiang et al., 2017). In a summary, off-chip components, external start-up circuitries and the limitation of low input voltage acceptance become the motivation for designing a high-efficiency cross-coupled charge pump with low input voltage acceptance that can fully integrate into a battery-less power management system in the research.

1.3 Research Objective

This research aims to propose a multiple-input single-output DC-DC switched capacitor converter for energy harvesting system. Methodology focus on the design of DC-DC switch capacitor converter and the auxillary circuit such as RF rectifier and logic gate control circuitries that will impact on the efficiency of converter.