Faculty of Electronic and Computer Engineering

ON-CHIP POWER MANAGEMENT SYSTEM BASED CMOS RECONFIGURABLE SWITCHED CAPACITOR DC-DC CONVERTER FOR BATTERY-LESS IOT SOC

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DECLARATION

I declare that this thesis entitled "On-Chip Power Management System Based CMOS Reconfigurable Switched Capacitor DC-DC Converter for Battery-less IoT SoC" is the results 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	:	…………………………………
Date	:	…………………………………

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.

Signature	:	…………………………….
Supervisor Name	:	…………………………….
Date	:	…………………………….

DEDICATION

This thesis is affectionately dedicated to my beloved mother and father

ABSTRACT

In recent studies, Radio Frequency (RF) energy harvesting method showed a great potential for indefinite battery lifetime for Internet of Things (IoT) System on Chip (SoC) application which is a system with functional blocks that includes sensors, memory, processing, and data transmission unit. However, the harvested energy is not stable and could not supply enough energy as required by each functional block of IoT SoC. Thus, it needs to be regulated and reconfigured to different levels of Direct Current (DC) supplies. Switched Capacitor (SC) DC-DC converter can be used for this purpose since it can regulate the energy to a stable level by stepping it up or down. But this conventional design has a drawback in fix conversion ratio, thus limited only to either step-up or step-down mode at one time and not simultaneously. Another drawback is SC DC-DC converter is only suitable for low load current application which is only in µA range, thus it requires a Low Dropout (LDO) voltage regulator added as an additional block to fulfil the requirement for high load current in microampere (mA) range. Hence, this work presents the design of a reconfigurable on-chip power management system based on CMOS SC DC-DC converter that can operate in both step-up and step-down simultaneously for battery-less IoT SoC. A method to achieve reconfigurability is proposed based on switching frequency parameter that is generated by Current-Starved Voltage-Controlled Oscillator (CSVCRO). Based on the simulation result, the CSVCRO enables the SC DC-DC converter to operate in both step-up and step-down modes for an input voltage range of 0.9V to 1.5V. The LDO design consists of error amplifier, bandgap voltage reference, feedback network resistor and series-pass transistor. NMOS transistor has been proposed to replace conventional Bipolar Junction Transistor (BJT) in bandgap voltage circuit to overcome the error amplifier input transistor driving voltage problem. In the simulation, the LDO performance has achieved 90.85dB of open-loop gain, 76.39º of phase margin and 63.46dB of Power Supply Ripple Rejection (PSRR) respectively. The simulations had also been validated through fabrication, measurement analysis, and benchmarking with existing works. Furthermore, it can be seen that the stability of the proposed design is higher compared to the previous research work which is at 75º. It is hopeful that the contribution from this work can be used to achieve more advancement in power management unit development based on CMOS technology and be the future of the microelectronic field.

ABSTRAK

Dalam kajian terkini, kaedah penuaian tenaga Radio Frekuensi (RF) menunjukkan potensi yang besar untuk jangka hayat bateri yang tidak terbatas bagi aplikasi objek Rangkaian Internet (IoT) Sistem pada Cip (SoC) yang mana sistem ini terdiri daripada beberapa blok fungsi seperti sensor, memori, pemprosesan, dan unit penghantaran data. Walau bagaimanapun, tenaga yang dituai adalah tidak stabil dan tidak dapat membekalkan tenaga yang cukup seperti yang diperlukan oleh setiap blok fungsi di dalam IoT SoC. Oleh itu, ia perlu dikawal selia dan dikonfigurasikan kepada tahap bekalan voltan Arus Terus (DC) yang berbeza. Penukar DC-DC Pensuisan Kapasitor (SC) digunakan untuk tujuan ini kerana ia boleh mengawal selia tenaga kepada kuasa yang lebih stabil samada dengan menaikkan atau menurunkan tenaga tersebut. Namun, topologi penukar DC-DC SC konvensional mempunyai kelemahan iaitu nisbah penukaran yang kekal yang mana kelemahan ini telah menghadkan hanya kepada mod menaik atau mod menurun pada satu-satu masa dan tidak boleh secara serentak. Kelemahan lain pada penukar DC-DC SC ialah ianya hanya sesuai digunakan untuk aplikasi arus beban yang rendah dimana arus bebannya dalam lingkungan microampere (mA) sahaja, dengan itu pengatur voltan Keciciran Rendah (LDO) ditambah sebagai blok tambahan untuk memenuhi keperluan arus beban yang tinggi dalam lingkungan mA. Oleh itu, projek ini telah membentangkan satu reka bentuk pengkonfigurasian sistem pengurusan kuasa pada cip berasaskan CMOS penukar DC-DC SC yang boleh beroperasi untuk mod menaik dan mod menurun secara serentak untuk IoT SoC tanpa bateri. Kaedah konfigurasi dicadangkan berdasarkan parameter pensuisan frekuensi yang dihasilkan oleh Pengayun Voltan Terkawal Arus Kelaparan (CSVCRO). Berdasarkan keputusan simulasi, CSVCRO membolehkan penukar DC-DC SC untuk beroperasi pada mod menaik dan mod menurun secara serentak untuk masukan voltan dari 0.9V kepada 1.5V. Reka bentuk LDO terdiri daripada ralat penguat, rujukan voltan jurang jalur, perintang rangkaian maklum balas, dan transistor lulus siri. Transistor NMOS telah dicadangkan untuk menggantikan Transistor Persambungan Bipolar (BJT) konvensional dalam rujukan voltan jurang jalur bagi mengatasi masalah pemacu voltan masukan transistor pada ralat penguat. Berdasarkan keputusan simulasi, prestasi LDO telah mencapai 90.85dB gandaan gelung buka, 76.39º jidar fasa dan 63.46dB Penolakan Riak Bekalan Kuasa (PSRR). Simulasi telah disahkan melalui fabrikasi, analisis pengukuran dan ditanda aras dengan kerja sedia ada. Tambahan pula, kestabilan yang dilihat pada reka bentuk yang dicadangkan adalah lebih tinggi dibandingkan dengan kerja penyelidikan sebelum ini iaitu sebanyak 75º. Adalah diharapkan agar hasil daripada kerja ini dapat digunakan untuk mencapai lebih banyak perkembangan dalam pembangunan unit pengurusan kuasa berdasarkan teknologi CMOS dan menjadi masa depan bidang mikroelektronik.

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ADE	-	Analog Design Environment
BGR	-	Bandgap Voltage Reference
CP	-	Charge Pump
CTB	-	Charge Transfer Block
CMOS	-	Complementary Metal-Oxide Semiconductor
CSVCRO	-	Current-Starved Voltage Controlled Ring Oscillator
DRC	-	Design Rule Check
DVS	-	Dynamic Voltage Scaling
EDA	-	Electronic Design Automation
EMI	-	Electro-Magnetic Interference
FSL	-	Fast Switching Limit
ICMR	-	Input Common Mode Range
IP	-	Intellectual Property
IoT	-	Internet of Thing
LVS	-	Layout versus Schematic
LZT	-	Lead Zirconate titanate
LDO	-	Low Dropout
MPPT	-	Multi Point Power tracking
PEX	-	Parasitic Extraction
PMU	-	Power Management Unit
PSRR	-	Power Supply Ripple Rejection
PFM	-	Pulse Frequency Modulation

PSM	-	Pulse Skip Modulation
PWM	-	Pulse Width Modulation
SR	-	Slew Rate
SSL	-	Slow Switching Limit
SC	-	Switched Capacitor
SCN	-	Switched Capacitor Network
SoC	-	System on Chip
TC	-	Temperature Coefficient
VDRG	-	Velocity Damped Resonant Generator
W/L	-	Width/Length
WSN	-	Wireless Sensor Network

LIST OF PUBLICATIONS

The research papers produced and published during the course of this research are as follows:

1. Mohamad Khairul Mohd Kamel, Yan Chiew Wong, 2018. Reconfigurable CMOS Voltage-Controlled-Ring-Oscillator Design for Energy Harvesting Power Management Unit**,** *Journal of Telecommunication, Electronic and Computer Engineering (JTEC),* January 24. (Accepted)
2. Khairul, M. & Wong, Y.C., 2017. Evaluation of Charge Transfer Blocks in CP Circuit Topologies. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC),* 9(2), pp.161–166.
3. Mohamad Khairul Mohd Kamel, Yan Chiew Wong, 2017. Design of wide tuning CMOS voltage-controlled ring oscillator for reconfigurability dc-dc converter. *Proceedings of Mechanical Engineering Research Day 2017*, pp. 120-121, May 2017.
4. Mohamad Khairul Mohd Kamel, Yan Chiew Wong, 2017. Design of Low Dropout LDO Voltage Regulator for RF Receiver Module. *National Symposium on VLSI Technology and System on Chip 2017*, December 12-14. (Accepted)

CHAPTER 1

INTRODUCTION

1.1 Research background

An electronic system requires a power management unit (PMU) as the generation and control of regulated voltage to operate. The power supply design is required to be incorporated with the system design in order to keep up high efficiency (Shirmohammadli & Saberkari, 2016). Integrated circuit components such as linear regulators, switched capacitor voltage converters, and voltage references are typical elements of power management.

In spite of the fact that Internet of Things (IoT) System-on-Chips (SoCs) demonstrate extraordinary potential, they have numerous plan challenges that hinder their widespread development. A standout amongst the most basic issues is node lifetime. Energy harvesting from surrounding sources conceivably gives the uncertain lifetime. Solar, vibration, kinetic and RF energy are the example of energy sources that available in surrounding. Figure 1.1 demonstrates block diagram in the power management of energy harvesting system. Today, as telecommunication systems getting evolve, RF energy is widely spread to the surrounding from wireless broadcast system and tend to have advantages over other energy source. Besides, RF energy can be effortlessly provided when required in each place. This advantage gives great flexibility to the system compared to other energy sources. However, the drawback arises where the harvested energy is unstable and cannot be supplied precisely as required by each block inside the IoT SOC. Thus, regulation and reconfiguration are needed to transform to a different level of supply voltages. A switched capacitor SC DC-DC converter is utilized to transform the harvested energy to various voltage references as needed. In addition, it provides a steady and suitable power supply voltage for each functional block.

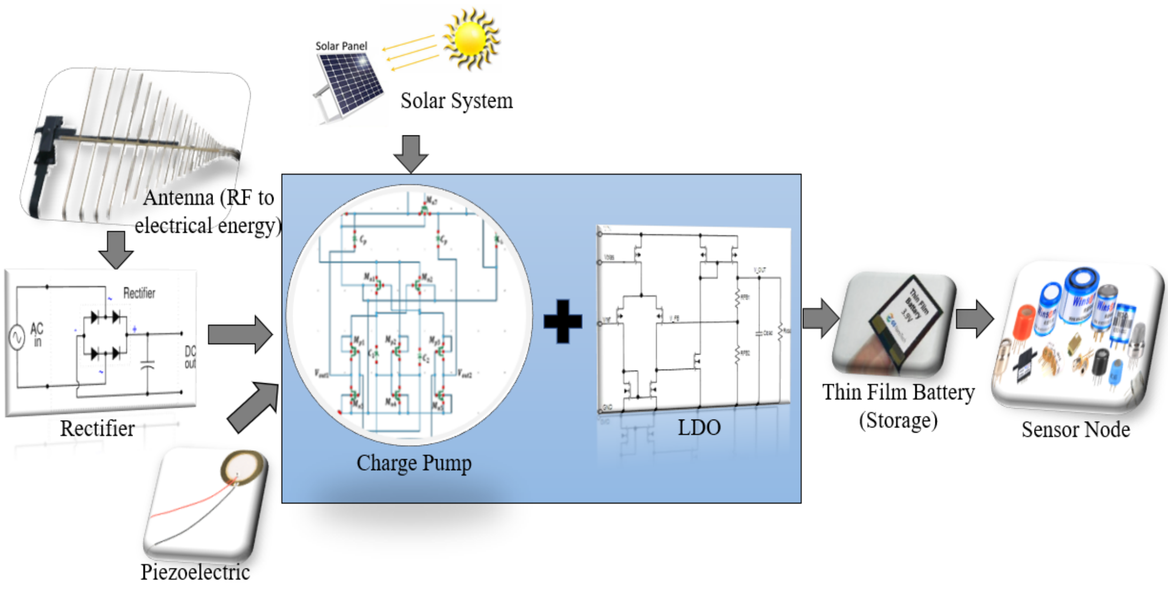

Figure 1.1: Block diagram of energy harvesting power management unit

SC DC-DC converters have been broadly utilized because of compatibility to a completely on-chip implementation (Sanders, 2008; Wei & Shih, 2013; Sathe, 2015). The abilities of SC DC-DC converter either step up or step down the input supply voltage by means of controlling different conversion ratios in the power stage is preeminent. Unfortunately, as stated by Retdian et al. (2016), the conversion ratio of conventional SC DC-DC converter is fixed for a given developed topology. The conventional SC DC-DC converter such as Dickson, Ladder, Fibonacci, voltage doubler etc. are all operates the charging and discharging process through a fix cycle of clock signal. Clock signal supply the switching frequency is the crucial parameter to perform reconfigurability of the conversion ratio in SC DC-DC converter. As the result, when there is requirement to supply a different level of output voltage to other functional block in IoT SoC, the different ratios of SC DC-DC converter should be used. Besides, the harvested energy come in at uncertainty voltage level. Therefore, a reconfigurable SC DC-DC converter is required to meet various operating voltage in the SoC.

Another important functional block in PMU is Low Dropout (LDO). The LDO comprises of error amplifier, bandgap voltage reference (BGR), pass series element and feedback network. The output voltage in LDO is scaled by having the power transistor that is controlled by a feedback network. The LDO provides a fast response as the feedback network is typically just constrained by the steady bandwidth of the error amplifier (Motkurwar & Ghodeswar 2016). The pass transistor is used to allow the power to the output flows through and its power density is restricted by the current of the pass transistor.

The SC DC-DC converter and the LDO voltage regulator forms as power management block in the energy harvesting PMU system. These blocks are designed based on specific design requirement. The proposed methodology is verified theoretically and compared with measurement results. This project has involved schematic designing, layout drawing, real chip fabrication and lab measurement.

1.2 Problem statement

Commonly, IoT SoCs use batteries, which limits node lifetime. This becomes a drawback in IoT SoC development because the necessity for charging or supplanting batteries has reduced user compliance. Energy harvesting from surrounding conceivably gives uncertain lifetime. Nonetheless, the power supply required by IoT SoC block does not precisely work as the harvested energy is unstable (Ali et al., 2013; Har et al., 2017). Thus, a DC-DC converter is desired to transform the voltage to the desired level. SC DC-DC converter is favourable as voltage converter module in the era of IoT which toward SoC industry trends over the other converter candidates such as inductor-based converter and linear regulator. Besides that, SC DC-DC converter is preferable for low-power handling application and provide high power efficiency.

SC DC-DC converters can either step up or step down the input supply voltage via controlling different conversion ratios in the power stage. The conventional topologies such as Dickson, Ladder, voltage doubler etc. have fix conversion ratio. The drawback had limiting the recent development application that require variation of conversion ratio performance. In conventional topologies, the generation of output voltage is controlled by a few parameters.

For example, the switching frequency has a role to control the charging and discharging process to achieve the desire conversion ratio. With the drawback as mentioned, when there is requirement to supply a different level of output voltage to each functional block in IoT SoC, different SC DC-DC converter should be integrated. Therefore, a reconfigurable on-chip power management-based SC DC-DC converter is needed to transform the power resources from the energy harvesting generator to various voltage references required by each functional block in the IoT SoCs.

1.3 Research objectives

The goal of this project is to design the SC DC-DC converter and LDO voltage regulator. Three objectives have been defined as below:

1. To design and fabricate the reconfigurable of SC DC-DC converter with input voltage range 0.9V to 1.5V for step-up and step-down configuration modes based on current-starved voltage-controlled ring oscillator (CSVCRO).
2. To design and fabricate an LDO voltage regulator with improvement of linearity and to provide a constant voltage reference.
3. To analyse and verify the performance of the proposed circuit.

1.4 Scope of research

The scope of research has been limited to a specific area. There are various energy sources available that can be used for energy harvesting, for example thermal, vibration, solar, etc. In this project, single energy source which is radio frequency RF energy source will be focused. Besides that, this project is only focused on designing SC DC-DC converter and LDO voltage regulator circuit. The proposed SC DC-DC converter is focused to have high pumping voltage and able to be reconfigured to perform step-up and step-down mode operation.