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Fully Integrated Switched-Capacitor PMU for IoT Nodes

Analysis and Design

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Preface

The IoT smart nodes deployment has been increasing rapidly in recent years, in a wide range of applications. These nodes are typically inserted in WSN, ranging from a few numbers to hundreds of nodes. Solutions using SoC have been proposed for the node implementation, due to their low production costs. These SoC are typically composed of sensors, to collect the data from the real world; an analogue front-end system for signal processing (S&H, Filter, and ADC/DAC) to convert the collected data to the digital domain; a microprocessor unit to do some signal processing of the data; a communication unit to transmit the treated data; and finally, a PMU, which is the focus of this book, to efficiently power all these blocks. Since the available energy is limited, efficient energy conversion is crucial to reduce maintenance costs. To this end, SC DC-DC converters have been proposed, since they can be fully integrated into CMOS technology, and offer a good trade-off between efficiency and power density. This book describes the design and test of a fully integrated PMU IC prototype, implemented in 130 nm bulk CMOS technology. The prototype is a fully integrated 16 mW PMU which includes a multi-ratio 1+3 binary-weighted SC converter, composed of three voltage CR 1/2, 2/3, and 1/1, covering an input voltage range of 1.1 V–2.3 V, and generating a 0.9 V output voltage. Time interleaved and capacitance modulation techniques were employed to completely remove the external decoupling capacitor. The output voltage ripple is further reduced by adjusting the number of active cells, according to the output power level and input voltage value, sensed through the average clock frequency. The PMU includes a set of auxiliary circuits to sustain the converter operation. These are a phase generator, a CR controller, the switch drivers, a cell controller, a voltage reference generator, and a start-up circuit. The total circuit active area is 5.12 mm^2 and a peak efficiency of 74.3% was measured.

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Contents

Acronyms

AC	Auxiliary SC cell
APS	Spectre Accelerated Parallel Simulator
ASM	Asynchronous state machine
ASP	Algebraic Series-Parallel
AVFI	Algorithmic Voltage-Feed-In
BOM	Bill of Materials
CMOD	Carrier Module
CMOS	Complementary Metal-Oxide-Semiconductor
CR	Conversion Ratio
CRS	Charge Redistribution Step
CTAT	Complementary to Absolute Temperature
EH	Energy Harvesting
ESD	Electrostatic discharge
ff	Fast-Fast
fnsp	Fast NMOS-Slow PMOS
FPGA	Field Programmable Gate Array
GBW	Gain-Bandwidth
IC	Integrated Circuit
IoT	Internet of Things
LDO	Low Drop-Out Regulators
MC	Main SC cell
MIM	Metal-Insulator-Metal
MOM	Metal-Oxide-Metal
MPPT	Maximum Power Point Tracking
MSC	Multiphase Soft-Charging
MUX	Multiplexer
NCG	Non-overlap Clock Generator
NSC	Negator-based SC
PCB	Printed Circuit Board
PDA	Dynamic Power Allocation

PG	Phase Generator
PMU	Power Management Unit
PSRR	Power Supply Rejection Ratio
PTAT	Proportional to Absolute Temperature
PV	Photovoltaic
PVT	Process, Voltage, and Temperature
QF	Charge-path folding
RC	Rational cell
RF	Radio Frequency
RSC	Recursive SC
SAR	Successive-Approximation-Register
SC	Switched Capacitor
SCW	Symmetric Cockcroft-Walton
snfp	Slow NMOS-Fast PMOS
SO	Stage Outphasing
SoA	State-of-the-Art
SoC	System-on-Chip
SOI	Silicon-On-Insulator
SP	Series-Parallel
SPCR	Scalable Parasitic Charge Redistribution
SR	Set-Reset
ss	Slow-Slow
tt	Typical-Typical
VFI	Voltage-feed-in
WSN	Wireless Sensor Network

Introduction

1

1.1 Motivation

The Internet of Things (IoT) plays an important role on the new generation of information technology, with a major impact in the human life in the recent and near future. This still recent technology aims to enable things to be connected anytime, anywhere, with anything and anyone, using any path/network or service [1]. This means that the objects in our environment would become smart, in the sense that they would be able to sense, interpret, share information, and react to events and human activities in the surrounding environment [2]. These smart objects, or smart nodes, are typically connected through a Wireless Sensor Network (WSN), where the node's number can vary from a few nodes, to hundred, or even thousand of nodes [3–5]. The production and maintenance costs must be as low as possible, for such large networks to be implemented. Hence, these nodes must be as autonomous and integrated as possible, and thus System-on-Chip (SoC) solutions have been proposed for their implementation [6–8]. These SoC are typically composed of sensors, to collect the data from the real world; an analogue front-end system for signal processing (e.g. S&H, Filters, ADC/DAC) to convert the collected data to the digital domain; a microprocessor unit to do some signal processing of the data; a communication unit to transmit the treated data; and finally, a Power Management Unit (PMU), which is the focus of this book, to efficiently power all these blocks.

As stated above, the PMU is responsible for powering the smart node. The node can be powered either by using a pre-charged energy storage device, like a battery or a supercapacitor, or by harvesting energy, Energy Harvesting (EH), from the surrounding environment, e.g. Photovoltaic (PV), piezoelectric, thermoelectric, or Radio Frequency (RF) energy [6–11]. Typically, a combination of both the EH and the energy storage device is used, where the harvested energy is stored in the energy stored device, to be then extracted by the PMU, for supplying energy to the system [6, 7]. However, generally the amount of available energy

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from the surrounding environment is reduced, typically only providing a fraction of the power needed for the system operation. Thus, these systems can spend a long time collecting energy and are only powered during small periods of time. For this type of operation, the energy storage device must withstand a large number of charge/discharge cycles without suffering from degradation. Hence, supercapacitors are an interesting solution for IoT nodes [10, 12, 13] because they have, ideally, a limitless number of charge/discharge cycles, and do not require a complex charging circuit, unlike batteries. Nonetheless, a rechargeable battery has the advantage of having a larger energy storing capacity, however, its lifetime is seriously reduced by the number of charge/discharge cycles (typically around 1000 cycles) [13–15]. Considering that typically the amount of available energy is limited, its extraction, either from the surrounding environment or from an energy stored device, must be made as efficient as possible. To this end, PMU using Maximum Power Point Tracking (MPPT) have been developed to efficiently extract the energy from the surrounding environment [6–8, 10, 11, 16, 17], and also PMU with high efficient voltage regulators have been developed to convert a variable voltage from an energy storing device to a constant supply voltage, suitable for the system operation [13, 18–20].

A constant DC voltage can be generated using a linear voltage converter, e.g. a Low Drop-Out Regulators (LDO), or by using a switched-mode DC-DC converter. The LDO have the advantage of being easily fully integrated and achieving high power densities [21, 22]. However, they are unable to step-up the supply voltage and only reach high energy efficiency values when their input voltage is close to its output voltage. As for the switched-mode DC-DC converters, they can be implemented using inductors—inductive converters [23–27]—or using capacitors—Switched Capacitor (SC) converters [19, 20, 28–32]. Both can step-up, or step-down, the voltage supply and can achieve high efficiency when using external inductors or capacitors. However, when fully integrating these converters, the inductive converters have their voltage conversion efficiency and power density reduced, due to the low quality factor and large area of the on-chip inductors [24, 27, 33]. On the other hand, capacitive converters can easily be fully integrated because they are only composed by transistors and capacitors, which are native in bulk Complementary Metal-Oxide-Semiconductor (CMOS) technology. In bulk CMOS technology, these converters achieve medium power density values, on the order of some milliwatts to hundred of milliwatts, and can achieve energy conversion efficiency values between 70 and 90% [19, 20, 28, 30–32]. The fully integration of these converters reduces the overall size of the system, since the discrete bulky capacitors and inductors are removed, thus reducing the Printed Circuit Board (PCB) space occupied by the PMU. This means that the Bill of Materials (BOM) is also reduced, and thus the fabrication and assembly costs are decreased. Furthermore, now the PMU is now much closer to its load. This proximity leads to better voltage regulation and better transient response. Considering this, the SC converters have attracted a significant interest in both the academia and the industry [34].

The working principle of the SC converters is easy to understand, a capacitor is used to transfer charge from the input to the output, where the frequency at which the charge is transferred, defines the converter's output voltage value. Typically, this charge transferring is controlled by two clock phase signals that allow for different circuit configurations on each clock phase. The SC converter has a finite output impedance, and thus the maximum power density is determined by the on-chip capacitance density. Due to the low capacitance density of on-chip bulk CMOS capacitors, there is a trade-off between the energy efficiency and power density [34, 35]. Furthermore, in fully integrated SC converters, minimizing the output voltage ripple comes at the cost of increasing the converter's area or circuit complexity, by using a large decoupling capacitor, or by using multiple cells in a time interleaving scheme, or by using other charge modulation techniques. This increases the design complexity of an SC converter making it a challenging task.

Finally, for an SC converter to operate properly, a set of auxiliary circuits are required. Typically, extra circuits like comparators, reference voltage generators, oscillators, digital circuits, and start-up circuits, are required. These must all be integrated together with the converter which further increases the design complexity of the PMU.

1.2 Outline

This book is composed of 7 chapters, including this introduction. A short description can be found below. In Chap. 2, an overview of the SC DC-DC converter fundamentals is presented. It starts with a detailed description of the passive implementation in 130 nm CMOS technology. Next, a theoretical step-by-step analysis used to size an SC DC-DC converter and determine its performance is depicted. The chapter ends with a brief description of the commonly used loop regulation techniques.

Chapters 3 and 4 cover the State-of-the-Art (SoA) of fully integrated SC DC-DC converters in CMOS technology. The first describes and analyses the performance of the most used topologies in multi-ratio SC converters. The second describes the techniques used to enhance the performance of fully integrated SC converters.

Chapter 5 shows the design process of a fully integrated PMU designed for a maximum output power of 16 mW, capable of converting a supercapacitor's variable input voltage from 1.1 to 2.3 V, whilst generating an output voltage of 0.9 V. The PMU includes a SC DC-DC converter that is dived into 1 + 3 binary-weighted cells, which are further divided into 32 smaller cells, where time interleaved was applied, to eliminate the external decoupling capacitor. The 3 binary-weighted cells can be enabled or disabled according to the power required at the output and the input voltage, sensed through the clock frequency. The PMU also includes a set of auxiliary circuits to ensure the correct behaviour of the converter, according to the input voltage and the output load. These auxiliary circuits include a phase generator, switch drivers, Conversion Ratio (CR) controller, cell controller, voltage reference generator, and start-up circuits.

Chapter 6 covers the implementation of the 16 mW PMU implementation in 130 nm CMOS bulk technology, to evaluate its performance and validate the theoretical equations through schematic simulations. The PCB test board and the test setup used for the circuit evaluation are also described. The measurement results of the prototype are presented, compared with the simulation ones, and conclusions are drawn.

Finally, in Chap. 7 conclusions are drawn and future work is discussed.

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