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Toru Tanzawa

Fully-Integrated Power Management Circuits for Thermoelectric Energy Harvesting

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To the memory of my family

Preface

As the number of IoT sensing modules for medical care, agriculture, infrastructure, retail distribution, etc., has rapidly increased worldwide, and a decrease in battery use has attracted increased amounts of research on energy harvesting. Energy harvesting is the technology used to harvest environmental energy, such as light, vibration, and thermal flow, to operate electronic devices. Because environmental energy fluctuates over time, power management circuits need to properly convert power from an energy harvester to IoT sensors. In addition to having high-power conversion efficiency over a wide input power range, power management circuits need to be cost effective and built with a small form factor.

This book describes fully integrated power management circuits for thermoelectric energy harvesting. Readers will learn about the applications, system design fundamentals, designs of building blocks, maximum power point tracking techniques, and design of battery chargers. The book will cover the following key topics: (1) minimizing the cost of a TEG by considering the maximum open-circuit voltage of the TEG and the dependence of the power conversion efficiency of the converter on the input voltage; (2) controlling the input voltage of the converter system to ensure that it remains higher than the minimum operating voltage; and (3) designing a charge pump operating in the subthreshold region, considering factors such as the clock frequency, stage capacitor size, rectifying device size, and number of stages. (4) Implement maximum power point tracking techniques with a small circuit area, and (5) design a fully integrated battery charger. Readers will gain a comprehensive understanding of these concepts and their practical applications.

Chapter 1 provides an overview of the IoT sensor edge module, TEG, and power converter. The target specifications of wearable electronic devices with TEGs are defined. TEGs are used in a wide variety of applications in terms of operating temperature and power level, ranging from high-power generation (over 1 kW at −160 °C and 800 °C) to low-power generation (on the order of μW at room temperature). This book focuses on TEGs for wearable electronics. One has three options for power converters for low-power applications: self-oscillation transformers, switching regulators, and charge pumps.

Wearable devices need to be provided with a small FF. Small numbers of bulky external components are needed. Thus, charge pumps with no external components are selected as fully integrated power management circuits.

Chapter 2 focuses on the design fundamentals of low-voltage charge pumps. The circuit structure and operation are overviewed. The circuit is composed of switches and capacitors. There are a variety of switches with different combinations of transistors. Several types of capacitors have also been fabricated in integrated circuits. The parasitic capacitance of the switches and the capacitors affects the characteristics of the charge pump. The circuit area is considered the cost. The area of the charge pump is mainly determined by the capacitor because a switch is nominally much smaller than a capacitor. The output current-voltage equation of a charge pump operating at low voltage is found as a function of the design and device parameters. One can estimate an output current at a specific output voltage once all the design and device parameters are given. Conversely, to design charge pumps operating at low voltage, a required output current at a specific output voltage is given, and then all the design parameters need to be determined in a specific CMOS technology where all the device parameters are given. The method for designing the charge pump to meet the required specification with a minimum circuit area is described. There is a trade-off between the circuit area and power conversion efficiency. As the power supply voltage decreases, the circuit area and the power efficiency tend to increase exponentially and decrease gradually, respectively. When the power supply voltage is one of the design parameters, one has to determine the operating voltage, the circuit area, and the power efficiency according to one's priority.

Chapter 3 discusses the optimum design for a system with an energy transducer and voltage multiplier. An equivalent circuit model is presented to help identify the relationship between the circuit parameters and the output voltage/current characteristics of the system. A maximum power point is then identified. When the parasitic capacitance in the charge pump is significant, the optimization can be expanded. Section 3.2 discusses the maximum output power point using an equivalent model. Section 3.3 validates the model by comparing it with the SPICE simulation results. This paper discusses the relationships among TEG electrical parameters, the power efficiency of converters, and the power consumption of loads in autonomous sensor modules. Based on the method discussed, one can determine the total number of TEG units together with the number of TEG arrays and the number of TEG units connected in series per array when the characteristics of the TEG unit, the minimum temperature difference in operation, the power conversion efficiency of the converter and the load conditions are given. A practical design flow to minimize TEG cost is proposed and demonstrated, taking the maximum open-circuit voltage of the TEG and the dependence of the power conversion efficiency of the converter on the input voltage of the converter into consideration. The entire system, including a TEG and a Dickson charge pump converter, which were designed through the proposed flow, was validated with SPICE.

Chapter 4 discusses the design of control circuits for low-voltage charge pumps, as illustrated in Fig. 4.1. V_S and V_{PP} are the input and output voltages of a charge pump, respectively. The V_S can vary due to variations in the open-circuit voltage of the TEG according to fluctuations in the environmental temperature or due to variations in the input current of the CP. On the other hand, the V_{PP} needs to be controlled to the target voltage required by a load, such as a sensor or RF IC, regardless of the variation in V_S. Even when the V_S is high enough for the CP to operate but not high enough for a bandgap reference or other analog circuits to operate, the power converter is required to work properly. Section 4.1 describes the use of an auxiliary voltage generator to supply a voltage for low-power analog and digital circuits in oscillators, regulators, and maximum power point tracking (MPPT) control circuits. A voltage regulator usually only controls the V_{PP}. However, when V_S approaches a critical voltage at which the CP flows current from the V_{PP} rather than to the V_{PP}, the CP operation needs to be suspended to hold the charges stored in the decoupling capacitor (which is not shown in Fig. 4.1). Thus, the TEG regulator is designed to detect both V_{PP} and V_S and to control the CP properly. The design of the regulator is presented in Sect. 4.2. In Chap. 3, the optimum design of charge pumps is discussed under the condition that V_S is at a certain voltage, particularly at the minimum voltage for design. When V_S varies, the optimum number of stages and capacitance per stage should be altered to maximize the output power from the charge pump. In Sect. 4.3, MPPT control is described.

Chapter 5 provides the design methodology for battery chargers powered by TEGs. To prevent the minimum open-circuit voltage from being limited by the operation of charge pumps, the clock generator is powered by the battery. Even though the clock generator consumes battery power, when the charge pump outputs more power than the consumed power, the net power can be positive. In Sect. 5.1, the system architecture is presented briefly. The design equations used to formulate an optimum number of stages and the required capacitance per stage are reviewed to minimize the open-circuit voltage of the TEG in Sect. 5.2. The impact of the output resistance of the TEG on the minimum open-circuit voltage is discussed. A design demonstration is conducted in Sect. 5.3. The minimum operation voltage is limited by the charge transfer switch (CTS) when a cross-coupled CMOS is used for the CTS. It is also shown that a simple MOS switch can reduce the open-circuit voltage below 100 mV.

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