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Ultra-Low-Power Circuits for Energy Harvesting Applications

Journal of Electrical Systems

Abstract: - Recent advancements in integrated circuit (IC) technology and design methodologies, particularly in the realm of ultra-low power circuits, have facilitated the fast expansion of fully integrated and portable electronics inside Internet of Things (IoT) smart nodes and wearable sensor systems on chip (SoC). IoT applications, such as biomedical sensors, body area networks, and wireless sensors, have leveraged this advancement. However, with the rising demands of individuals, several components must be included into the IoT SoC. Therefore, a small, efficient, and self-sustaining power management circuit (PMC) with a prolonged lifespan design is essential for IoT SoC. Consequently, energy scavengers, including solar cells (PV), thermoelectric generators (TEG), and electrostatic harvesters, provide an appealing approach for powering the PMC, enabling self-sustaining and extended lifespan systems.

The switched capacitor charge pump (SCCP) combined with low dropout (LDO) regulators is an effective solution for power management circuits (PMC) in energy harvesting systems (EHS) due to their on-chip integrability, eliminating the need for cumbersome off-chip inductors, particularly in implantable biomedical applications. Nevertheless, these regulators must be managed using a maximum power point tracking (MPPT) system to optimize energy harvesting and ensure optimal storage. The MPPT regulates whether to optimize power transmission according to load demand or to configure the regulator to extract the maximum available power from the energy harvester. Numerous MPPTs have been created to identify the maximum power point, hence enhancing tracking efficiency and/or conversion efficiency. Several criteria to be fulfilled include extensive input voltage handling, broad output load range coverage, output voltage control, and ultra-low power consumption. The latter is of significant significance to optimize the overall efficiency of the EHS and prolong its lifespan in the context of battery-powered PMCs.

Keywords: Low Energy Harvesting Systems; Energy Storage System; Power Management; Self- Sustainable Technologies; Transducer

INTRODUCTION

Recent advancements in integrated circuit technology and design methodologies, particularly in the realm of ultralow power circuits, have resulted in the emergence of fully integrated autonomous and implantable system-on-chip (SoC) solutions that exhibit superior performance in terms of power consumption, silicon area, and power efficiency. Numerous applications have leveraged this innovation, including Internet of Things (IoT) wearable devices, smart nodes, and biological sensors, which have emerged as significant technologies today (Figure 1-1) [6-16]. The quick proliferation of IoT devices and applications, driven by escalating human demands, amplifies the quantity of integrated components inside the IoT System on Chip (SoC). Consequently, the development of a small, completely integrated, and efficient power management circuit (PMC) is essential to adequately meet the power requirements of each component inside the IoT SoC.

Figure 1-2 illustrates a general block diagram of an IoT System on Chip (SoC). It comprises multiple components: a communication block, a signal processing unit, actuators, sensors, an energy supply, and a PMC. Each block requires a distinct supply amount based on its function. For an IoT SoC, several supply levels must be given for each block's requirements [24]. Consequently, a Power Management Controller (PMC) is essential to provide a controlled clean voltage level necessary for each component inside the Internet of Things System on Chip (IoT SoC). Nevertheless, the PMC architecture encounters several obstacles related to efficiency and power consumption. Therefore, to enhance the PMC design, two factors must be considered. Initially, the PMC operation

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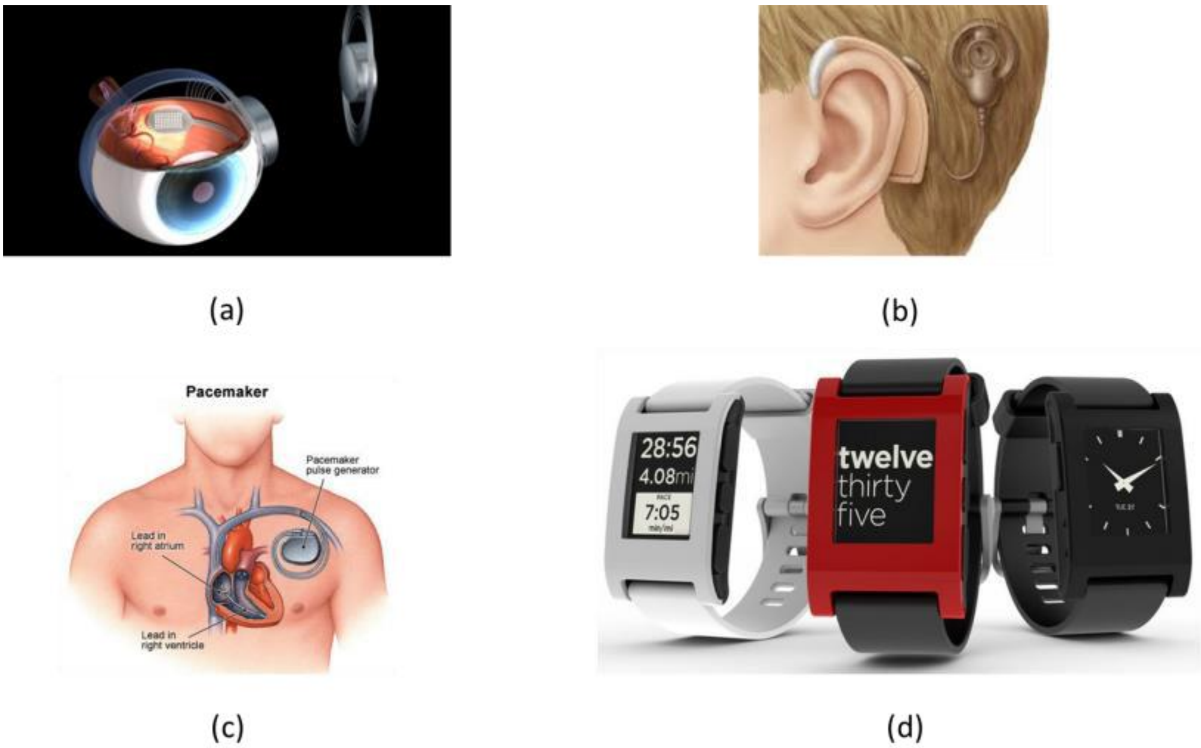

scheme should be conditioned regarding the power demand mode (i.e. heavy duty, light duty, stand-by or idle mode). Second, it should be flexible to operate under a wide 2 range of inputs powers, and to supply multiple output power one at a time or simultaneously [32].

LOW ENERGY HARVESTING DEVICES

Harvesting energy from the environment offers a persuasive alternative to battery-operated systems, particularly for low-power, extended-duration, and self-sustaining devices. Moreover, using electricity near the source may eliminate the need for substantial cabling and related transmission losses [34]. Its applications include energizing wireless sensor networks, wearable devices, charging mobile phones, lighting LEDs, and enabling cloud-based data transfer systems [35]. Nevertheless, several challenges arise in assessing and selecting the most appropriate low energy harvesting technology for certain applications [36].

Studies [37-39] have shown the effectiveness of low energy harvesting devices, such as piezoelectric, electromagnetic, electrostatic, and triboelectric transducers, in producing electrical power ranging from several tens to hundreds of μW. However, challenges remain, such as materials development and synchronization with ambient vibration frequencies, which may fluctuate due to temporal variables, application site, scalability, mass production, and energy conversion efficiency [37-39]. The major issue is whether energy harvesting devices can provide enough power considering the variability of energy sources. The costs related to the deployment and production of low energy collecting devices are substantial obstacles that hinder technical progress. Therefore, more research is essential to improve technology adoption. Enhancing the effectiveness of self-sustaining technology is a crucial endeavor. Luo et al. [42] underscore the paramount significance of selecting the suitable energy storage option, whether it be a battery or supercapacitor. The capacities and impedances of the energy storage system must align with the pulsed output of the energy harvesting device. Luo et al. [21] examined a triboelectric nanogenerator integrated with an energy storage device to provide power to commercial wireless sensors and other smart interconnected devices. A novel design of self-sustainable technology was introduced in the study by Luo et al. [43]. The system consists of a versatile self-charging power film (SCPF) that operates as both a self-sustaining information input matrix and a power generator integrated with an energy storage unit. The system may harness mechanical energy from finger movements via the interaction of electrification and electrostatic induction, while concurrently storing the accumulated energy. Luo et al. [36] devised a cost-effective and uncomplicated laser engraving method for a flexible self-charging micro-supercapacitor power unit (SCMPU). The SCMPU amalgamated a triboelectric nanogenerator with an electrochemical storage system into a unified device. Results demonstrate significant benefits, including remarkable durability and self-charging capability. The laser-induced graphene (LIG) demonstrated a peak power density of 0.8 W/m² with a loading resistance of 20 MΩ. The micro-supercapacitors (MSCs) demonstrated a capacitance of around 10.29 mF/cm² at a current density of 0.01 mA/cm².

ENERGY HARVESTING POWER MANAGEMENT CIRCUITS FOR IOT SOC

In the domain of IoT smart nodes and medical devices, the industry emphasizes size, weight, and energy consumption to minimize costs [32]. Advancements in solid-state circuits have resulted in a reduction in the size of System on Chip (SoC) technology. According to Moore's Law, technical advancements every 18 months lead to a reduction in supply voltage, resulting in diminishing dimensions, improved performance, augmented functionality, and ultimately decreased prices.

POWER MANAGEMENT

The integration of low energy harvesting, energy storage, and power management systems may leverage its potential and provide an ideal solution for enhanced efficiency and energy conservation via the statistical distribution of load durations. A critical technological challenge faced by self-sustainable technology is the effective storage of collected energy in an energy storage device. Due to the inherently high impedance of energy harvesting methods, the design often encounters significant impedance mismatch, particularly when the energy sources operate at low frequencies [82]. Moreover, the actual deployment of each integrated system seldom attains maximum performance when the self-charging power unit operates outside ideal circumstances [83]. Figure 2a illustrates the notion of a self-sustaining technology that integrates energy harvesting, power control, and energy storage systems. Figure 2b illustrates the energy management cycle for low-energy harvesting devices.

DC-DC POWER CONVERTERS FOR ENERGY HARVESTING SYSTEMS

Figure 1-1 illustrates that various components inside the IoT SoC need diverse voltage and power levels. Furthermore, contemporary mobile CPUs use the dynamic voltage scaling (DVS) technology to achieve reduced power consumption across various operational modes. Consequently, a DC-DC power converter is an essential component of the PMC inside EHS for IoT and biomedical applications. The DC-DC converter functions as a voltage regulator that can (i) manage varied input power voltage levels owing to the EHL's compact form size and inherent dependencies, and (ii) accommodate different on-chip voltage levels inside IoT SoCs. The DC-DC power converters in PMC may use linear regulators (such as low dropout regulators) or switching regulators (including buck/boost converters and charge pumps). Linear regulators, particularly low dropout regulators (LDOs), are regarded as excellent candidates for power management circuits within electronic health systems (EHS) due to their compact size, minimal noise (i.e., power supply rejection ratio), high bandwidth, design simplicity (i.e., cost-effectiveness), and potential for full integration on a chip. Nonetheless, switching regulators have attracted significant interest as a DC-DC power converter in EHS PMC for IoT applications [2, 7-9, 21, 26, 30, 31, 34, 36, 37, 39, 42-46, 65-68]. Generally, switching regulators have three primary benefits over linear regulators: (i) Switching efficiency can significantly improve as energy is stored rather than dissipated as a voltage drop (i.e., LDO); (ii) reduced energy loss necessitates smaller components and diminishes thermal management requirements; and (iii) the input voltage can be increased, decreased, or inverted, in contrast to linear regulators that solely reduce input voltage [41, 69]. The selection of the regulator within the PMC is contingent upon the application, the necessary efficiency, and the permissible output voltage fluctuations (i.e., noise).

3-PROPOSED LOW POWER ENERGY HARVESTING SYSTEM

As stated in the preceding chapter, in accordance with the International Technology Roadmap for Semiconductors (ITRS) and recent advancements in integrated circuit technology, IoT smart nodes, encompassing wearable devices, wireless electronics, and implantable sensors, are proliferating and gaining popularity. Furthermore, the intelligent nodes in IoT applications are projected to attain roughly 50 billion linked devices by 2020 [1-4]. These intelligent nodes are often realized as IoT System-on-Chip (SoC) and include a power management circuit (PMC), energy sources, signal processing units, communication modules, and sensors and/or actuators, as seen in Figure 1-1. Energy harvesting systems attract significant interest due to their provision of energy-autonomous IoT smart nodes, hence eliminating the maintenance costs associated with recharging and/or replacing batteries, as well as their cumbersome size [1, 4-10].

A variety of energy harvesters have been examined and analyzed in the literature, including photovoltaic (PV) systems [3, 5, 8, 11-14], thermoelectric generators (TEG) [15-17], and piezoelectric devices [18]. Among these energy scavengers, photovoltaic (PV) technology has garnered considerable interest and appeal as an energy source for autonomous Internet of Things (IoT) System on Chip (SoC) owing to its high power density and cheap cost. As stated in the preceding chapter, to optimize the harvesting of solar energy, the photovoltaic system is linked to a DC-DC converter regulated by a maximum power point tracker (MPPT) to ensure the system functions at peak efficiency. The need for MPPT, in conjunction with the DC-DC converter, arises from the dependent on the harvester's nature and the unpredictability of load power, particularly at a controlled output voltage. Solar energy may be captured via inductive-based [4, 16, 19, 20] or switched capacitor-based DC-DC converters [2, 3, 5, 6, 9, 13, 14, 21]. Nonetheless, the latter represents a more appropriate approach for fully-integrated IoT System-on-Chip (SoC) applications, such as smart nodes and body-area networks (BAN), therefore circumventing the need for cumbersome off-chip inductors.

Numerous hill-climbing-based Maximum Power Point Tracking (MPPT) approaches have been used to optimize the gathered power in accordance with load requirements. While they attain significant power efficiency (PE) at output loads of hundreds of microamperes, they exhibit a moderate PE (30%–40%) while delivering loads of hundreds of nanowatts in idle mode. Reference [4] indicated that the operational profile of IoT sensor nodes remains in idle mode for over 50% of their operational time. Furthermore, [23] illustrates a wireless operational scenario (Figure 3-1) that substantiates the previous assertion. The IoT wireless sensor activates just during intensive activities and mostly remains in idle or standby mode. As stated in [4], a standard wireless sensor node activates once per 60 seconds or longer, making the conversion efficiency during idle and standby (i.e., low load) mode the predominant factor in the total power efficiency of the energy harvesting system (EHS). Consequently, elevated PE at ultralight loads (i.e., hundreds of nA) is essential to prevent the deterioration of the EHS PE in IoT smart nodes and implanted sensors.

CONCLUSION AND FUTURE WORK

This thesis presents several designs, system and circuit-level methodologies, and innovative control algorithms to mitigate the primary limitations of tracking power efficiency, conversion power efficiency, and design area in the development of ultra-low power maximum power point tracking for energy harvesting systems inside IoT smart nodes. MPPT systems are a key component of EHS for biomedical and IoT applications, where power consumption, efficiency, and spatial constraints are paramount. This thesis introduces two MPPT designs with innovative tracking algorithms to meet the strict power budget inside EHS for IoT applications, which is constrained by the low input power from the EHL owing to its compact form factor. Their primary contribution is to enhance tracking and conversion power efficiency, sacrificing a negligible portion of the collected power, hence prolonging the peak output power that can be sustained with the same input gathered power. Chapter 2 presents a revolutionary time-based MPPT architecture that resolves the problem of tracking efficiency limitations. The suggested tracking method is an indirect, non-intrusive approach using a unique timing-based algorithm to enhance tracking efficiency. It lowers power consumption and design intricacy. It comprises a digital processing unit that implements the suggested tracking method, accompanied by ultra-low power auxiliary circuits. The manufactured chip underwent testing, and its operation was confirmed within an input voltage range of 0.4 V to 1.7 V. The test demonstrates a transient reaction time of under 100 ms at a minimum supply voltage of 0.8 V, with a peak tracking efficiency of 96.2% when powered by a photovoltaic micro-cell array within an irradiation range of 200 lux to 1000 lux.

Chapter 3 presents the development of an innovative 3D-MPPT that resolves the power efficiency constraints in wide-load range applications inside IoT SoC. The suggested MPPT enhances conversion efficiency over a broad load range with an innovative switch width modulation (SWM) approach. It has an innovative tracking algorithm that eradicates the trade-off between gate-driver and conduction power loss, demonstrating superior conversion efficiency across a broad load range in comparison to prior studies. The evaluated chip demonstrates anticipated outcomes, hence validating the suggested SWM approach. It attains a maximum power efficiency of 88% at 200 μA and maintains a power efficiency above 60% under ultra-light load conditions. Furthermore, an energy-conscious algorithm has been executed for a multiple-input-single-output energy harvesting system. Chapter 4 proposes a fully integrated, near-threshold digital low-dropout voltage (DLDO) regulator for ultra-low power IoT applications that need a reduction of the input EHL voltage by tens of millivolts. It pertains to the trade-off between speed and power. It comprises a load current-sensitive clock modulation method that delivers a rapid transient response just during load state changes. The suggested clock modulation (CM) regulates the clock frequency upon detecting a sudden load current change. A test chip is constructed with 65-nm CMOS technology, exhibiting a current efficiency of 99.7% with a load current ranging from 10 μA to 200 μA, and a quiescent current of 0.9 μA. 97.

FUTURE WORK WITHIN ENERGY HARVESTING SYSTEMS FOR IOT APPLICATIONS

As stated in the introduction, Chapter 1 highlights that the recent advancements in IoT devices, including portable electronics and wireless sensor nodes, necessitate the creation of an efficient self-sustaining PMC. Consequently, future endeavors should focus on the creation of a PMC powered by energy harvesters inside IoT smart nodes, which is crucial and promising for the development of self-sustaining systems and extended longevity. Numerous studies have investigated solar, thermal, and mechanical energy harvesters [2, 8, 39, 45]. Among these scavengers, mechanical energy is advantageous because to its ubiquitous presence in everyday life; it may be captured from the motion of humans, cars, and things. A unique mechanical energy harvesting known as a triboelectric nanogenerator (TENG) has been investigated among these harvesters. TENG has low weight, compact dimensions, and great power density. It produces electricity by the interplay of triboelectrification and electrostatic induction [107-117]. Consequently, future research will include a power management circuit (PMC) designed to gather energy from the triboelectric nanogenerator (TENG) and effectively charge a supercapacitor or battery to power different components inside the Internet of Things (IoT) system on chip (SoC).

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