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On-chip reconfigurable switched-capacitor DC-DC converter for indoor PV energy harvesting

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A reconfigurable switched-capacitor (SC) DC-DC converter is presented for indoor photovoltaic (PV) energy harvesting. The converter has three topologies to perform the energy transfer among the PV cell, the energy buffer and the load. A uniform hysteresis controller regulates the PV cell voltage at 1.5 V to extract the maximum power from the PV cell and regulates the load voltage at 0.9 V. To minimize the conversion loss, the energy is transferred from the PV cell to the load directly whenever energy is available in the PV cell. When the load voltage is high, the excess energy in the PV cell is stored in the buffer of 1.8 V. The load draws energy from the buffer when energy is not available in the PV cell. The proposed converter was fabricated in 0.18μm CMOS process and achieves peak efficiencies of 87%, 88% and 78% while delivering energy from the PV cell to the load, from the PV cell to the buffer and from the buffer to the load, respectively.

Introduction: Energy harvesting is a promising solution for powering miniaturized wireless sensor nodes that consume ultra-low power. Conventional energy harvesting systems store the harvested energy in an intermediate energy buffer (such as a rechargeable battery) and use additional conversion stages to deliver the energy from the buffer to the load [1, 2]. Moreover, the energy conversions are commonly performed by inductive DC-DC converters with off-chip inductors, which are not favourable for size constrained smart nodes [2, 3]. In this letter, a reconfigurable switched-capacitor (SC) DC-DC converter is proposed for indoor photovoltaic (PV) energy harvesting system. To improve the overall energy efficiency, the first converter topology transfers the energy from the PV cell to the load in one conversion stage when the PV energy is available and the load is demanding energy [3, 4]. When the load demands no energy, the excess energy in the PV cell is stored in the buffer through the second converter topology. The third topology acts as the backup converter, which is enabled to deliver the stored energy to the load when the PV energy is not available.

System architecture and converter implementation: The architecture of the energy harvesting system is shown in Fig. 1a. Here, a hysteresis controller regulates both the PV cell voltage V_{PV} and the load voltage V_{Load} to ensure maximum power extraction and provide the desired supply voltage to the load circuit. Fig. 1b illustrates the operating waveforms.

The PV voltage regulation is implemented by adaptively comparing the PV cell voltage with V_{MPP} (the voltage corresponding to maximum power extraction) and $V_{MPP} - \Delta V_{MPP}$, where ΔV_{MPP} defines the size of the hysteresis band. The comparison result PV_High decides whether the PV energy is available for extraction. When $PV_High = 0$, no energy is extracted from the PV cell, hence V_{PV} increases due to the photovoltaic current I_{PV} . When V_{PV} crosses V_{MPP} , PV_High becomes 1. As a result, the SC converter draws the energy from the PV cell and delivers the energy to the load or the buffer depending on the load condition. When V_{PV} falls below the lower threshold $V_{MPP} - \Delta V_{MPP}$ due to the energy extraction, PV_High returns to 0 and the energy extraction is stopped, allowing C_{PV} to be re-charged.

The load regulation is implemented by comparing the reference voltage with two different scaled versions of the load voltage, $\beta_1 V_{Load}$ and $\beta_2 V_{Load}$. The comparison result V_{Load_High} indicates the load condition. When $V_{Load_High} = 1$, no energy is delivered to the load, hence V_{Load} drops. When V_{Load} crosses its lower threshold, V_{Load_High} becomes 0. The power required by the load will be drawn from the PV cell when $PV_High = 1$ or from the energy buffer when $PV_High = 0$. The power transfer to the load is stopped when V_{Load} crosses its higher threshold. The energy in the PV cell will be transferred to the energy buffer when $PV_High = 1$, and $V_{Load_High} = 1$. In another scenario, when $PV_High = 0$, and $V_{Load_High} = 1$, the SC converter enters the idle mode, since there is no excess energy in the PV cell and the load is not demanding power.

The proposed SC DC-DC converter is shown in Fig. 2a. It provides three voltage conversion ratios of $\frac{2}{3}$, $\frac{4}{3}$ and $\frac{3}{5}$. In order for the multiple

Fig. 1 PV energy harvesting system architecture and operating waveforms

a System architecture

b Operating waveforms

configurations to share the total amount of on-chip capacitance, the capacitance is equally divided into six capacitors, denoted by C1-C6. The equivalent circuits of the converter topologies in both clock phases are shown in Fig. 2b. When transferring energy from the PV cell to the load, the PV voltage of 1.5 V is converted to a regulated load voltage of 0.9 V. The converter topology with nominal voltage conversion ratio of $\frac{2}{3}$ is selected. In the first phase, the voltages across the capacitors C1-C6 are charged from $\frac{1}{2} V_{Load}$ to $V_{PV} - V_{Load}$. In the second phase, C1 and C2 are connected in series, each capacitor is discharged from $V_{PV} - V_{Load}$ to $\frac{1}{2} V_{Load}$, releasing the charge to the load. Similarly, C3, C4, C5 and C6 are discharged. The current delivered to the load is given by

$$I_{out} = 9Cf_{sw}(V_{PV} - \frac{3}{2}V_{Load}) \quad (1)$$

where C is the size of each charge transferring capacitor and f_{sw} is the switching frequency. The current drawn from the PV cell is given by

$$I_{in} = 6Cf_{sw}(V_{PV} - \frac{3}{2}V_{Load}) \quad (2)$$

To implement the hysteresis PV voltage regulation, the switching frequency f_{sw} must be designed for $I_{in} > I_{PV}$ so that the converter is able to bring V_{PV} down when V_{PV} hits its higher threshold V_{MPP} . Similarly, I_{out} must be greater than the load current for load voltage regulation. The same analysis can be applied to converter topologies with conversion ratios of $\frac{4}{3}$ and $\frac{3}{5}$.

The excess energy in the PV cell is delivered to the buffer through the converter topology with conversion ratio of $\frac{4}{3}$, which converts V_{PV} of 1.5 V to V_{Bat} of 1.8 V. When the load voltage is low and the PV energy is not available, the converter topology with conversion ratio of $\frac{3}{5}$ is selected to convert the buffer voltage of 1.8 V to the load voltage of 0.9 V.

Measurement results: The reconfigurable SC DC-DC converter was fabricated in 0.18μm CMOS technology with active area of 0.8×0.78 mm², as shown in Fig. 3. The converter uses a total amount of 2.5 nF on-chip capacitance implemented as dual-MIM capacitors. The proposed PV energy harvester was tested with a commercial PV cell featuring a 2.5 cm² size. Fig. 4 shows the transient waveforms of the regulated PV cell voltage and the load voltage across a 100 kΩ load resistance under 400 lux light intensity. Fig. 5 shows the measured output power of the three converter topologies and the power conversion efficiencies versus switching frequency. When enabled, the converter topology with conversion ratio of $\frac{2}{3}$ (PV-to-Load) delivers 26 μW of power to the

Fig. 2 Proposed reconfigurable SC DC-DC converter

a Switched-capacitor power stage

b Equivalent circuits of the three converter topologies in both clock phases

load with peak efficiency of 87% at 100 kHz switching frequency. The $\frac{4}{3}$ -topology (PV-to-Bat) is designed to operate at the same switching frequency as the $\frac{2}{3}$ -topology, 88% peak efficiency is achieved while delivering 50 μ W of power from the PV cell to the energy buffer. The $\frac{3}{5}$ -converter-topology (Bat-to-Load) is designed with switching frequency of 300 kHz, at which the converter achieves a peak efficiency of 78% while delivering 32 μ W of power from the energy buffer to the load.

Fig. 3 Die microphotograph

Conclusion: In this letter, an on-chip reconfigurable SC DC-DC converter with three topologies for indoor PV energy harvesting is presented. Both the PV cell voltage and the load voltage are regulated by a uniform hysteresis controller for maximum power extraction and providing stable supply for the load circuit. To improve the overall energy conversion efficiency, the harvested energy is delivered to the load in one

Fig. 4 Measured transient waveforms

Fig. 5 Measured output power and efficiency vs switching frequency

conversion stage whenever PV energy is available and the load voltage is low. The excess energy from the PV cell is stored in the energy buffer, which powers the load circuit when PV energy is absent. The $\frac{2}{3}$, $\frac{4}{3}$ and $\frac{3}{5}$ converter topologies achieve peak efficiencies of 87%, 88% and 78% while processing power of 26 μ W, 50 μ W and 32 μ W, respectively.

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