A Ripple Voltage Sensing MPPT Circuit for Ultra-Low Power Microsystems

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Abstract
We propose a maximum power point tracking (MPPT) circuit for micro-scale sensor systems that measures ripple voltages in a switched capacitor energy harvester. Compared to conventional current mirror type MPPT circuits, this design incurs no voltage drop and does not require high bandwidth amplifiers. Using correlated double sampling, high accuracy is achieved with a power overhead of 5%, even at low harvested currents of 1.4μA based on measured results in 180nm CMOS.

Introduction
A number of miniature sensor nodes were recently proposed for use in new embedded application areas, including medical, security, and resource exploration. In general, miniature-scale systems are equipped with a harvesting unit (solar, thermal, etc) to recharge their battery. The small form factor of these sensors has led designers to opt for integrated switched capacitor boost converters (SCBCs) with a total capacitance in the range of 0.5 to 1.5nF [1,2]. Furthermore, the limited size of the harvesting unit makes efficient energy extraction from the energy source and up-conversion of the voltage a major priority. However, the type of energy source and its operating point can vary greatly. For instance, in office lighting a 1mm2 solar cell reaches its optimal energy efficiency at ~250mV and produces 45nA current. In sunlight, that same solar cell reaches its optimal energy efficiency at ~2–5V and produces 2μA. Clearly, the two conditions require vastly different capacitor switching frequencies, switch sizes, and voltage conversion ratios of the SCBC. A highly flexible SCBC is therefore needed that ideally performs maximum power point tracking (MPPT), allowing it to automatically search for and track the configuration that delivers maximum power to the battery.

In general, MPPT involves simultaneous measurement of both voltage and current delivered to the battery, which are multiplied and fed into a search algorithm. Given the small power budget of micro-sensors, the voltage/current measurement and search algorithm must be performed with minimum power overhead. A comprehensive MPPT method was proposed in [3] where the battery inflow current is measured (Fig. 1). While having the advantage of directly measuring energy delivered to the battery, it incurs a voltage drop over the current mirror transistor, resulting in significant energy loss. Furthermore, it requires a high bandwidth amplifier to track dynamic current influx.

This paper demonstrates a MPPT circuit that takes advantage of the unique structure of SCBC – it places a small sampling capacitor in parallel with the flying or decoupling cap in the SCBC that “eavesdrops” on the voltage transfer that occurs in the voltage converter. By integrating the small voltage fluctuations using correlated double sampling (CDS), the MPPT achieves a power overhead of 5%, even at low harvested currents of 1.4μA (Fig. 6). Fig. 7 shows example MPPT operation including the fine resolution of conversion ratio, switch size, and conversion ratio.

Proposed Circuit
Fig. 2 shows the circuit diagram of the proposed harvested energy monitor and its waveform. The SCBC has a ladder topology and its switches are driven by a set of non-overlapping clocks (Φ1 and Φ2). This switching function transfers charge from the energy source to the battery, generating ripple voltages at SCBC internal nodes. In one phase (Φ1), the flying capacitor of CFLY provides charge to the decoupling capacitor of CDIC by charge sharing while the flying capacitor of CFLY transfers charge to and recharges the battery. Thus, voltage across CDIC (VDIC) increases while voltage across CFLY (VFLY) decreases when energy is harvested. In the other phase (Φ2), charge moves from CDIC to CFLY due to VDIC > VFLY and VDC decreases while VFLY increases (Fig 2 waveforms). This voltages difference (VDIC – VFLY) is proportional to the amount of charge sent to the battery in a switching period. Hence, integrating the ripple voltages’ difference for a fixed time provides a measure of harvested energy.

We implement the proposed ripple voltage sensing circuit using a small sampling capacitor (CSAMPLE) that is placed in parallel with CFLY, a correlated double sampling integrator, two integration capacitors (CINT1 and CINT2), and a clocked comparator. To sample VDC and VFLY, CSAMPLE is alternatively connected in parallel to CDIC or CFLY. Its sampling frequency is divided down to ~1kHz from Φ1 to rebandwidth the requirement of the integrator and hence its power consumption. The small size of CSAMPLE, along with the fact it is decoupled from the SCBC only once in 138 cycles, results in negligible energy impact on SCBC (<0.91% efficiency degradation, measurement-based calculation including phase drivers).

One challenge in measuring energy transfer in the proposed method is the small magnitude of the ripple, which is a requirement in high efficiency voltage conversion. As a result, the integrator’s output voltage can easily saturate due to accumulation of the amplifier’s offset or low frequency noise over multiple integration cycles. To address this, we use CDS to integrate the differences of VFLY and VDC ripple and amplify it sufficiently for use in the comparator. CDS is achieved by changing the polarity of CINT1 and CINT2 with P1 and P2. The energy transfer is calculated for two configurations successively and stored on CINT1 and CINT2. These two capacitor voltages are then compared (READ and FIRE) to determine the optimal energy transfer configuration and the SCBC parameter combinations are updated accordingly.

The complete energy harvesting unit consists of a reconfigurable SCBC, harvested energy monitor, MPPT controller, look-up table, and a wide frequency range oscillator (Fig. 3). The MPPT controller can adjust four SCBC parameters through the look-up table: conversion ratio, switching frequency, switch size, and gate driving voltage. Mapping of switching frequency, switch size, and gate driving voltage is done in the programmable look-up table. This allows efficient or non-functional parameter combinations to be excluded from the search. The look-up table also sends the clock division ratio (HEMCLK, DIV) to the harvested energy monitor to set the integrator frequency.

The designed SCBC connects a successive approximation (SA) DC-DC converter [4] in series with a 1:6 converter (Fig. 4). Each switch has transistor size controllability (1 to 63) to optimize switching loss and conduction loss for different switching frequencies. The smallest switches have separate smaller flying capacitors while larger switches share larger ones since the SCBC does not require large switches for slow switching frequency, while capacitance from large switches deteriorates its efficiency [5]. AC coupling gate drivers enable the modulation of gate driving voltage by only changing the amplitude of Φ1 and Φ2. They level shift Φ1 and Φ2 to the proper voltages based on switch source voltages, which is stabilized by decoupling capacitors. Compared to the conventional AC coupling gate drivers for the SA converter, new gate drivers are proposed for the 1:6 converter because of its single-phase topology and the fixed ~0.6V between VDICH and VDLOW. This design requires only half the capacitors by reusing signals from the complementary type of gate driver in order to short gate and source of switch transistors to prevent DC drift. Also, devices connected to VDICH and VDLOW help reduce leakage via super cut-off when the switches are disabled.

Proposed Circuit
Fig. 5 shows that the fine resolution of conversion ratio enables > 94.6% tracking efficiency across 170 ~ 4100 incident lux despite inherent limitations of SCBC’s compared to inductive boost converters. The designed MPPT circuit consumes 35nW (avg. over light intensity) and achieves a power overhead of 5%, even at low harvested currents of 1.4μA (Fig. 6). Fig. 7 shows example MPPT operation including changing conversion ratios and switch sizes. From the last position, the MPPT searches for the updated maximum power point (MPP). The MPPT locks converter configuration once finding MPP while it checks other configuration periodically for improved energy harvesting. A comparison to recent work is given in Table 1, showing > 6x improvement in terms of MPPT circuit power. Die photo is given in Fig.8.

References
Figure 1. Conventional harvested energy monitor for maximum power point tracking (MPPT).

Figure 2. Proposed ripple voltage sensing harvested energy monitor and its waveform.

Figure 3. Block diagram of the designed energy harvesting unit.

Figure 4. Reconfigurable switched capacitor boost converter.

Table 1. Performance summary and comparison.