An OTA-based power sensing integrated circuit for MPPT in photovoltaic energy harvesting applications

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Abstract

In this paper, the design of a power sensing circuit based on the Operational Transconductance Amplifier (OTA) for photovoltaic energy harvesting applications is presented. The circuit extracts a series of pulses that have a frequency proportional to the measured power and can communicate with a digital processing unit that implements a Maximum Power Point Tracking (MPPT) algorithm. It can accommodate an input voltage range of 0.3-1 V and an adjustable input current range while consuming approximately 360 μW at a 3 V supply voltage. The circuit is suitable for integrated energy harvesting systems that include an MPPT unit, and it is compatible with photovoltaic energy harvesting systems.

1 Introduction

Maximum Power Point Tracking (MPPT) is a widely used technique in energy harvesting systems that harness the ambient available energy from the environment. By employing MPPT, an energy harvesting interface aims to extract the utmost possible energy from a source under varying conditions, and this is typically achieved by adjusting the load's electrical characteristics (current and voltage) to satisfy the Maximum Power Point conditions. More specifically, MPPT in photovoltaic systems, where a solar cell or panel converts the energy from solar irradiance to electrical energy, typically involves the measurement of the solar panel's output voltage and current to calculate the corresponding output power and the adjustment of the duty cycle of a DC-DC converter that is interposed between the transducer and the load, so that the maximum power is extracted from the former to be provided to the latter under varying temperature, solar irradiance, and shading conditions.

The prevalent MPPT algorithmic methods are Perturb and Observe (P&O) and Incremental Conductance [1-2] where the power or its derivative is calculated, and its behavior is studied for variations of the operating voltage or current, so that the MPP is tracked. By always operating at or around the MPP, the overall efficiency and performance of the system are enhanced, and the cost-effectiveness of the photovoltaic systems is improved. Both algorithms require knowledge of the behavior of the power in real-time to conduct the appropriate adjustments on the load characteristics. Typically, the voltage and the current are sensed separately, and the power is estimated by an analog or digital multiplier [3]. While voltage sensing is generally a non-complex process, current sensing [4-6] involves the employment of a shunt resistor and the measurement of the voltage drop across the resistor, which is proportional to the current that flows through it. The resistor's value sets the sensitivity and accuracy of the current sensing circuit; therefore, a larger value would result in higher sensing efficiency but also in higher power losses. In addition, analog multiplication suffers from linearity and accuracy issues and limited dynamic range, whereas digital multiplication increases computational complexity as well as processing power demands.

In this paper an integrated analog circuit that provides an indication on the variations of the output power of a solar panel, which can be utilized by an MPPT unit, is presented. The circuit extracts a digital signal in the form of a series of pulses with a frequency proportional to the power of the solar panel, while consuming little power and occupying a small silicon area.

2 Description of the MPPT interface

A conventional MPPT interface for a photovoltaic panel consists of a DC-DC converter that is responsible for the MPPT process, the control unit of the DC-DC converter that typically conducts the power estimation and adjusts the duty cycle of the control signals of the converter, and the load.

In Figure 1 the proposed MPPT interface is depicted along with the positioning of the power sensing circuit on the DC-DC boost converter and its communication with the digital MPPT unit. The power estimation is conducted before the digital processing, which in this case is responsible only for the creation of the control signals of the converter.

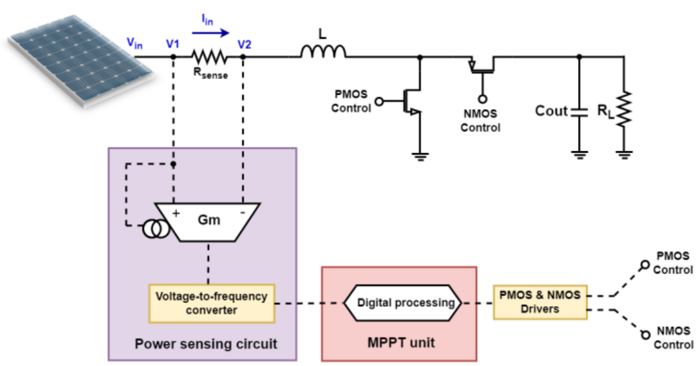

Figure 1. Proposed MPPT interface block diagram

The inputs of the power sensing circuit are the terminals of a shunt resistance that is inserted between the PV panel and the input inductor of the DC-DC converter. The voltage difference of the two terminals $\Delta V = V1 - V2$ is proportional to the input current of the DC-DC converter, I_{in}, according to:

$$\Delta V = I_{in} R_{sense} \tag{1}$$

and it is converted into a current by an Operational Transconductance Amplifier (OTA).

The input voltage is converted into a proportional current which is used as a bias current of the OTA. Since the output current of the OTA is proportional to both the voltage difference at its inputs and its transconductance, which in certain operating conditions is proportional to its bias current, the output current of the OTA is proportional to the output power of the PV panel. A current sensing and a power sensing circuit implementation using the OTA circuit were presented in [7] and [8], respectively, however the proposed circuit provides a less complex as well as more area-efficient solution. In Section 3 a more thorough mathematical analysis is presented.

3 Proposed power sensing circuit

Figure 2 depicts the proposed power sensing circuit which consists of a transconductor (Figure 2a) that converts the input voltage of the DC-DC converter (output voltage of the PV panel) into a proportional current, according to:

$$I_B = \frac{V1}{R_C} \tag{2}$$

The core of the power sensing circuit is the OTA circuit (Figure 2b), which converts the voltage difference at its inputs into a current, according to:

$$I_{OTA} = G_m(V1 - V2) \tag{3}$$

where G_m is the amplifier's transconductance. According to [9] the transconductance of the OTA has a linear dependence on the bias current when the amplifier operates at the weak inversion or with low currents. Thus, ideally:

$$I_{OTA} = kI_B(V1 - V2) \tag{4}$$

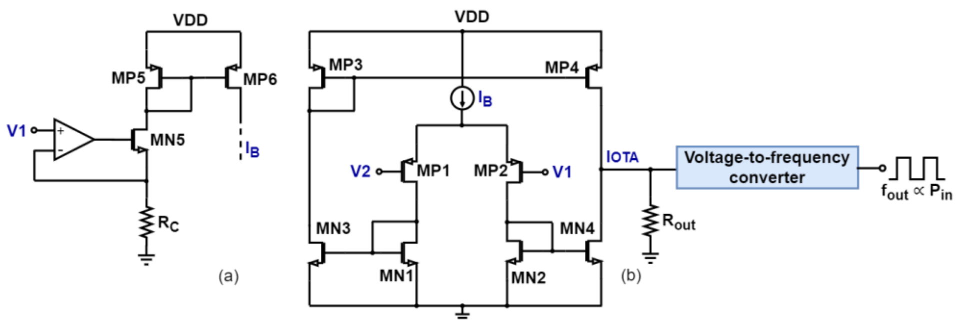

Figure 2. Proposed power sensing circuit (a) Transconductor (b) OTA and voltage-to frequency converter

And from (2) and (4):

$$I_{OTA} = k\frac{V1}{R_C}(V1 - V2) \tag{5}$$

Since *V1* is the input voltage ($V1 \equiv V_{in}$) and the voltage difference ΔV is proportional to the input current, I_{in}:

$$I_{OTA} \propto V_{in} \times I_{in} \propto P_{in} \tag{6}$$

The OTA's output voltage, V_{out}, which is inserted to the voltage-to-frequency converter's input, is the product of its output current and the load resistance, R_{out}:

$$V_{out} = I_{OTA} \times R_{out} \tag{7}$$

Finally, the frequency of the pulse series at the output of the voltage-to-frequency converter (Figure 3) – which is based on [10] - is proportional to the voltage at its input, which is V_{out}, therefore:

$$f_{out} = mV_{out} \propto I_{OTA} \propto P_{in} \tag{8}$$

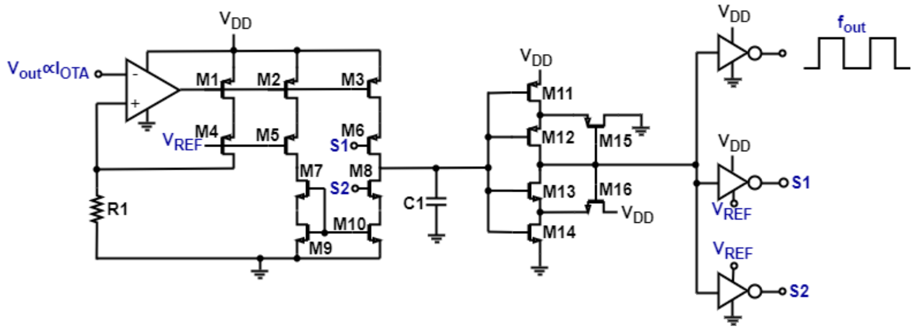

Figure 3. Voltage-to-frequency converter

Table 1 includes the component values of the power sensing circuit and the voltage to frequency converter and Figure 4 depicts the layout of the total power sensing circuit.

Table 1. Component values of the power sensing circuit and the voltage-to-frequency converter

Components	W/L (μm/μm)	Components	W/L (μm/μm)
MP1-MP2	10/8	M1-M10	40/2
MN1-MN2	20/2	M11-M12	10/1
MN3-MN4	20/2	M12-M13	10/3
MN5	10/0.35	M15	15/1
MP3-MP4	20/2	M16	2/1
MP5-MP6	10/4	C1	73.8pF
R_C	1MΩ	R1	2.4MΩ
R_{out}	2MΩ		

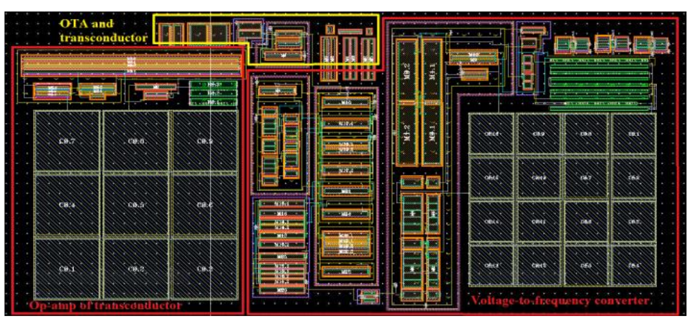

Figure 4. Physical design (layout) of the power sensing circuit (303 μm × 144 μm)

4 Post-layout simulation results

The specifications of the energy harvesting module appear in Table 2. The input voltage range can be adjusted by varying the value of R_C to maintain proper bias conditions of the OTA circuit (~0.2-1 μA) and the input current range can be adjusted by varying the value of the shunt resistor, R_{sense}, so that the voltage difference remains inside the measurable range of 0-100 mV. However, R_{sense} contributes to the power losses, so its value should be carefully selected in relation to the input current range.

Table 2. Specifications of the power sensing circuit

Technology	180 nm CMOS (XH018)
Input voltage	0.3-1 V (adjustable)
Input voltage difference	0-100 mV (fixed)
Input current @ Rsense=100 mΩ	0-1 A (adjustable)
fout (kHz)	2.55-14.11 kHz
Power consumption @ 3V	0.36 mW

The diagrams in Figure 5 depict the plots of the output frequency versus the voltage V1 for various voltage differences ΔV (Figure 5a) and the output frequency versus the voltage difference ΔV for various V1 values. In Figure 5c the post-layout results of the output frequency plotted against the product of the voltage difference $\Delta V \propto I_{in}$ and the voltage $V1 \equiv V_{in}$ are presented. The frequency is linearly dependent on this product and therefore on the input power of the DC-DC converter.

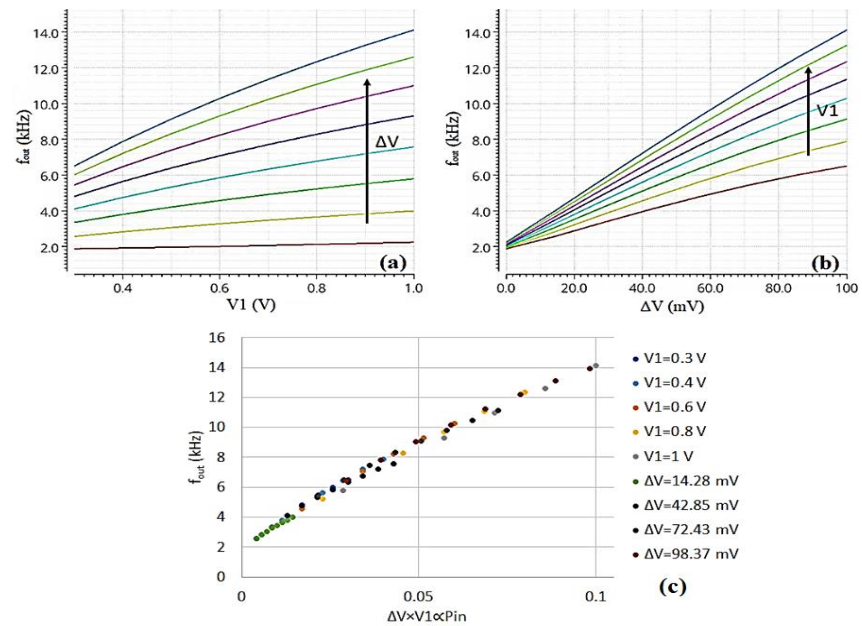

Figure 5. Output frequency vs. (a) V1, (b) ΔV and (c) the product of ΔV×V1

The derived straight-line equation is:

$$f_{out} = 123.08 \times n \times P_{in} + 2.5312\ kHz, \qquad R^2 = 0.989$$

which indicates that the output frequency is linearly dependent on the input power.

5 Conclusions

An integrated power sensing circuit was designed and simulated in XH018 CMOS technology using Cadence software. The power sensing circuit utilizes the linear relationship between an OTA's output current and the voltage difference on its inputs, as well as the linear relationship between an OTA's transconductance and its bias current when the amplifier operates in the weak inversion or low current region. The extracted voltage at the load of the OTA circuit is converted into a series of pulses with a frequency proportional to the input power of the DC-DC converter, allowing a digital MPPT unit to detect its behavior and adjust the converter's duty cycle accordingly. The final circuit occupies 0.0436 mm^2 and consumes 360 μW, which renders it feasible to be integrated in an energy harvesting system.

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