

A VCO-Based MPPT Circuit for Low-Voltage Energy Harvesters

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Abstract—Thermal energy harvesting has many key challenges such as getting a sufficient output power, while achieving maximum power efficiency from thermoelectric generators (TEGs). A new VCO-based MPPT circuit for low-power applications is introduced. The proposed MPPT circuit is used in conjunction with Pelliconi charge pump forming a low-power thermal energy harvesting system. This system models the temperature difference between TEG module layers by 0.25V that is boosted to 3V. A prototype is implemented using UMC 130nm technology process, which achieves 61.6 % power efficiency, with output voltage level approximately 3V at maximum load current of 60 μ A.

Keywords—energy harvesting, maximum power point tracking, VCO-based control, thermoelectric harvester, bio-medical applications

I. INTRODUCTION

Nowadays, many researchers are looking for harvesting electrical power from human energy resources or environmental energy sources for micro scale electronic systems such as bio-medical implants, and wireless sensor networks (WSNs). Most of these applications depend on a battery to power on. However, there are a lot of drawbacks for using batteries such as: 1) limited life time, and 2) May be fabricated from toxic/hazardous chemicals or metal. Therefore, it would be better if the batteries life is extended for several years through the micro-scale energy harvesting system.

Energy harvesting is collecting ambient energy in different forms (i.e. thermal, piezo, and solar) [1]. Then, the harvested energy is transformed into an electrical signal using a certain transducer. The transducer output voltage has to be stepped up to maintain the required supply voltage. Moreover, the excess energy is stored in an energy reservoir such as a super capacitor or a rechargeable battery.

A large number of maximum power point tracking (MPPT) techniques has been widely reported in the last few years. Some of these techniques are: 1) Perturb and Observe donated by P&O [2], an MPPT algorithm which is considered as one of the most commonly used algorithms in energy harvesting, 2) Three Point Weight Comparison [3], 3) Open Circuit Voltage [4], and

4) closed loop MPP [5-6]. These MPPT techniques are evaluated considering different types of isolation, irradiance variations, and the energy supplied by the whole system. In this paper, a new MPPT circuit is proposed to achieve a maximum power efficiency at maximum load current.

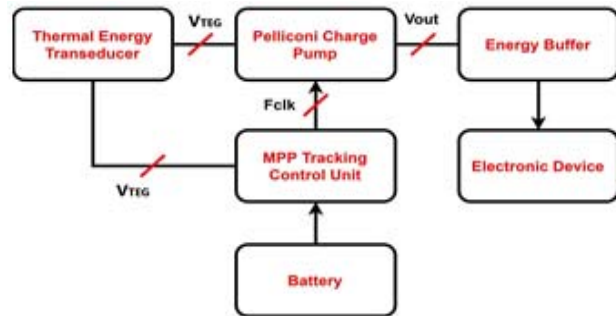


Fig. 1 System Block Diagram

The system, shown in Fig. 1, consists of thermoelectric generator (TEG) module, modelled as a DC voltage source, where the output power level of TEG is proportional to the difference in temperature on its plate. Then, the output of transducer (V_{TEG}) is used as an input source for Pelliconi charge pump that achieves maximum efficiency through the proposed VCO-based MPPT circuit. Finally, the output voltage from the charge pump is stored using a battery. Also, the output battery is used to act as an external supply voltage for supplying MPPT circuit. Since, the proposed MPPT circuits requires multiple supply voltage levels that are generated through voltage dividers with high resistance for less power consumption.

The rest of the paper is organized as following: in section II, charge pump operation principle is presented. Then, the proposed VCO-based MPPT circuit is introduced in section III, while the simulation results are given in Section IV. Finally, a conclusion is derived in Section V.

II. PELLICONI CHARGE PUMP OPERATION PRINCIPLE

The operation of Pelliconi charge pump, shown in Fig. 2, works as follows: 1) during the first half cycle, $\Phi 1$ is high, and $\Phi 2$ is low, so the transistors (M1 and M2) are ON and the transistors (M0 and M3) are OFF. Thus, C0 is charged to V_{TEG} through M1, V0 is set to V_{TEG} , and C1 is charged to $V_{DD} + V_{TEG}$ and discharges it to V_{OUT} through M2. 2) During the second half cycle, $\Phi 1$ is low and $\Phi 2$ is high, the transistors (M0 and M3) are ON and the transistors (M1, and M2) are OFF, C1 is charged to V_{TEG} through M0, so V1 is set to V_{TEG} , C0 is charged to $V_{DD} + V_{TEG}$, and discharge it to V_{out} through M3. Therefore, the output voltage equals $V_{DD} + V_{TEG}$ after first stage [7].

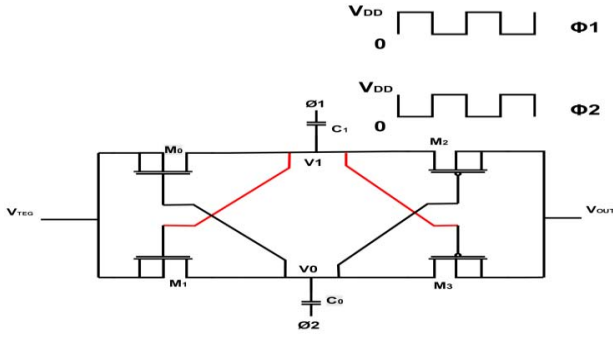


Fig. 2 Pelliconi Charge Pump Circuit Schematic

Cascading more than one stage is used to achieve the required voltage level, where the output voltage is multiplied n-times of the single stage charge pump, where n is the number of stages. Pelliconi charge pump has many advantages: 1) High gain, and 2) A completely symmetrical scheme and no extra output stage is needed. When $I_{out} \neq 0$, the voltage gain is reduced because of the stage output resistance and its value can be expressed by the following equation [7]:

$$\Delta V = V_{DD} \cdot \frac{C}{C+C_s} - I_{out} \cdot R_{out} \quad (1)$$

where $C_0=C_1=C$, C_s is the parasitic capacitance, I_{out} is the output load current, and the output resistance R_{out} is expressed as following [8]:

$$R_{out} = \frac{1}{2(C+C_s)f} \quad (2)$$

Where f represents the clock operating frequency. At very low voltage levels, cascading n-stages is necessary to obtain the desired output voltage (i.e., to obtain an output voltage of 3V from a 0.25V input; at least three stages are needed), assuming no losses the output will be $V_{TEG} + 3 \cdot V_{DD}$. However, the parasitic capacitance and output resistance reduces the output of the first stage to be $V_{TEG} + \Delta V$, making the output of the second stage $V_{TEG} + 2 \cdot \Delta V$, and finally, the output of third stage is $V_{TEG} + 3 \cdot \Delta V$. Therefore, the output will be $3.03V$, providing a voltage gain of 12.28.

Charge pump power efficiency is the significant performance metric in charge pump design. It is defined as the ratio between the output power and the power supplied from

the DC input voltage and the clock sources. The charge pump power efficiency can't reach 100%, since some of the input power is consumed by the MPPT circuit, and the circuit switches [9]. To evaluate the power efficiency of Pelliconi charge pump we have used the following expression [11].

$$Power\ Efficiency = \frac{P_{out}}{P_{in}} \cdot 100\% = \frac{P_{out}}{P_{out} + P_{loss}} \cdot 100\% \quad (3)$$

Where P_{out} is the delivered power to the load, P_{in} is the input power of supply, and clock generator, and P_{loss} is the consumed power through the output resistance of the charge pump, charging, and the MPPT circuit.

III. PROPOSED VCO-BASED MPPT CIRCUIT

In Fig. 3, The proposed MPPT circuit is shown, where it achieves a maximum output power from any module under certain conditions. It consists of three main blocks: a voltage controlled oscillator (VCO), an output digital buffer, and non-overlapping clock generator circuit. This MPPT circuit generates non-overlapping clocks for a charge pump to step up the output voltage from TEG module. The proposed MPPT circuit is shown in Fig. 3. The circuit consists of three main blocks: a voltage controlled oscillator (VCO), a digital voltage buffer, and non-overlapping clocks circuit generator.

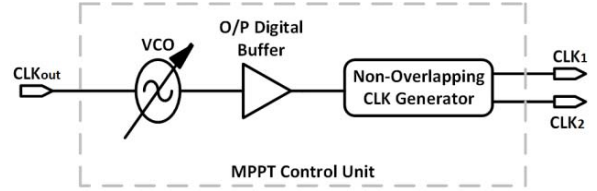


Fig. 3 Proposed MPPT block diagram

A. Voltage Control Oscillator

Fig. 4 shows that the VCO circuit is used to sense the input voltage from the output of the charge pump in order to track the output, and generate the input clocks. The output frequency of the generated clocks depends on the change in the input voltage. The input voltage from the transducer (i.e. V_{TEG}), is the input for a PMOS transistor gate, where the output current of the transistor is expressed as following [10]:

$$I_D = \frac{\mu_p C_{ox} W}{2L} ((V_{SG} - |V_{th}|)V_{SD} - \frac{V_{SD}^2}{2}) \quad (4)$$

Where μ_p is the charge-carrier effective mobility, C_{ox} is the gate oxide capacitance per unit area, V_{th} is the threshold voltage, V_{SG} is the source-gate voltage, and V_{SD} is the source-drain voltage. Therefore, the output current decreases due to increase of the input voltage. Moreover, the output frequency of the voltage controlled Oscillator is given by [11]:

$$F_{CLK} = \frac{1}{2N t_p} \quad (5)$$

where N: number of inverters and it should be odd to have oscillations, and t_p is the average propagation delay for each inverter. From the previous two equations: it's obvious the trade-off between t_p , and I_D . Since, the t_p increases with decreasing I_D either by decreasing W or increasing L.

For low power consumption, this circuit has to work at low frequency, so there are two different ways to decrease this frequency: 1) increase the number of inverters used in this circuit, but this will increase power consumption in circuit, and 2) increase the channel length to increase the average propagation delay for each inverter as shown in (6), (7) [12].

$$t_p = \frac{1}{2}(t_{pHL} + t_{pLH}) \quad (6)$$

$$t_{pHL} = t_{pLH} = \alpha \cdot \frac{C_l \cdot V_{DD}}{\frac{W}{L} \cdot \mu \cdot C_{ox} \cdot (V_{DD} - V_{th})^2} \quad (7)$$

Where C_l : parasitic load capacitance, α is a constant varies on the accuracy required for the application [12].

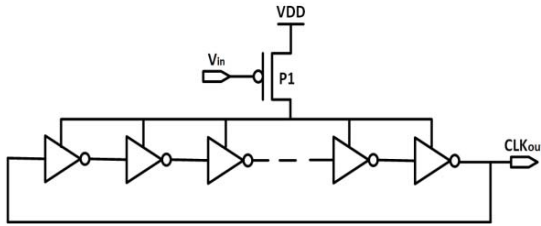


Fig. 4 Proposed VCO Circuit Schematic

B. O/P Digital Buffer

It is used to adjust the output voltage level of the generated clocks for the charge pump, and decrease the output ripples of VCO.

C. Non-Overlapping Clock Generator:

Using a non-overlapping clock generator, shown in Fig. 5, to control the charging and discharging of the capacitors used in the charge pumping circuits and prevents the switching leakage in the charge pump [13]. The two capacitors are alternately charged through a delay circuit connected to an oscillator with two MOSFET switches controlled by the non-overlapping signals instead of two MOS diodes.

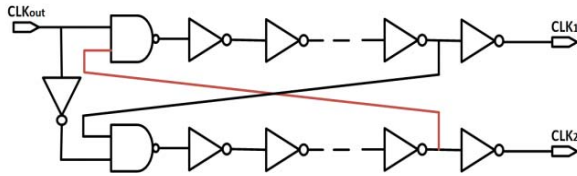


Fig. 5 Non-Overlapping circuit schematic

IV. SIMULATION RESULTS

A prototype is implemented using UMC 130 nm CMOS technology, where it is simulated using Cadence Virtuoso. The TEG module output voltage level is modelled to be 250 mV [14]. The output clock amplitude from the proposed MPPT circuit is adjusted to be 1V. The overall system is operating at clock frequency 6 MHz while using the charge pump capacitors of 25 pF, which can be implemented on a chip.

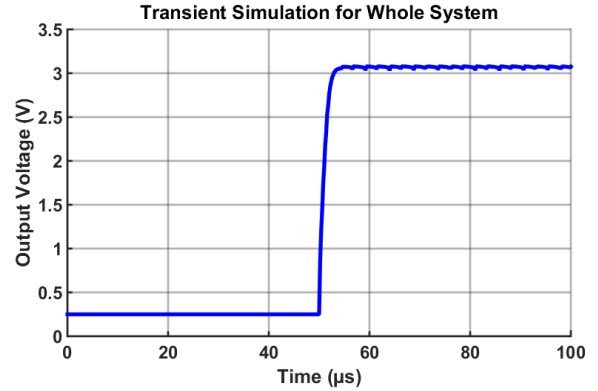


Fig. 6 V_{OUT} of the whole thermal energy harvesting system

Fig. 6 shows the output voltage of the whole system using three identical stages from Pelliconi charge pump. It is observed that the used charge pump circuit has the capability to step up the input voltage of 250 mV to 3.07 V.

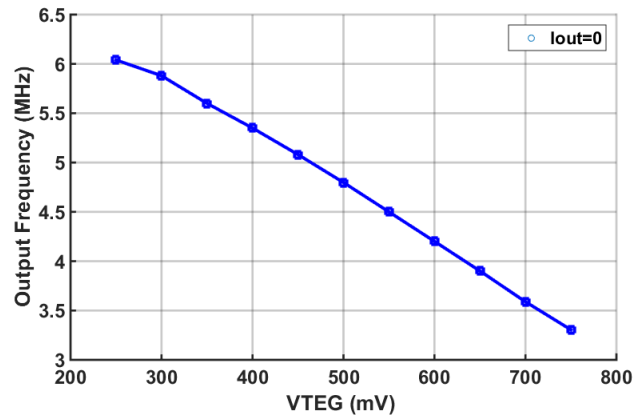


Fig. 7 output frequency versus different input voltage

Fig. 7 shows the output frequency variations for different input voltages, where the output frequency increases, as the input voltage decreases. When the input voltage increases, the output current decreases, so the output frequency decreases.

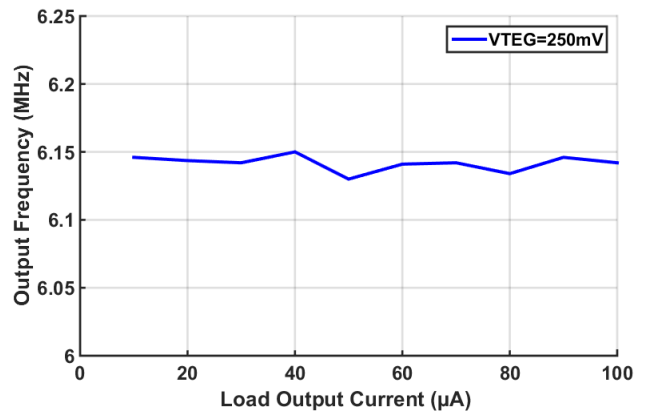


Fig. 8 output frequency versus different load current

Fig. 8 shows the output frequency versus different values of load current, where the output frequency slightly changes with the increasing of load current. the changes in the order of less than 0.5% variation in the output frequency, this is almost constant, so it shows a good performance in terms of frequency while increasing the load current to save the power.

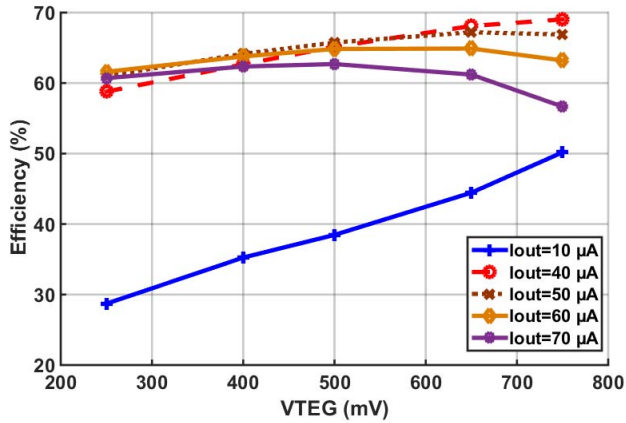


Fig. 9 Power efficiency versus input voltage to the whole thermal system

Fig. 9 shows the power efficiency versus input voltage to the whole thermal energy harvesting system for five different load current values (10 μ A, 40 μ A, 50 μ A, 60 μ A, 70 μ A) to determine the maximum load current with the maximum power efficiency occurs. It shows that the power efficiency peak value is 61.6% at $V_{TEG}=250$ mV and $I_{out} = 60$ μ A. In addition, the power efficiency increases with the increase of the input voltage (i.e., The power efficiency peak value is 69.03% at $V_{TEG}=750$ mV, and $I_{out} = 40\mu$ A).

Fig. 10 shows how the power consumption of the proposed VCO circuit decreases with the increase of the input voltage, so it shows a good performance in terms of power while increasing the input voltage (i.e., power consumption reaches to 4.16 μ W when the input voltage is 1V).

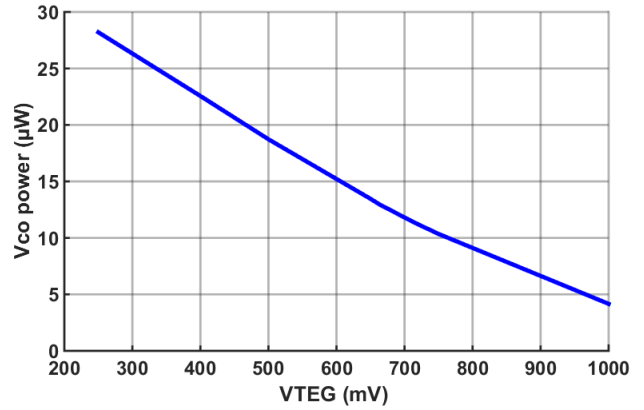


Fig. 10 power consumed in Proposed VCO Circuit versus input voltage

Finally, Table I shows a detailed comparison between this work and the recently published work presented in [7], and [15-19]. It shows that our proposed system using the proposed VCO-based MPPT circuit provides good results compared to others. The proposed system can operate from input voltage as low as 250 mV which makes it suitable for thermal energy harvesting applications, while [7], and [17-19] uses a higher input voltage. In addition, the simulation work of the proposed MPPT circuit provides a good permanence characteristics presented in a high-power efficiency reaches to 61.6% at load current 60 μ A. However, number of used stages in [15] is higher, but the output voltage in this work is higher with less number of stages. Finally, the power efficiency in [18-19] is higher, but the driving current capabilities of the proposed circuit is better.

V. CONCLUSION

This paper presents a new technique for maximum power locking of a thermal-based energy harvester. A thermal energy harvesting system is implement using UMC 130nm CMOS technology. In addition, utilizing the proposed VCO-based MPPT circuit, the system achieves 61.6 % efficiency at maximum load current for low voltage applications. The implemented system stepped up a low input voltage as 250 mV to be 3.07 V with a static load current of 60 μ A. This system is well suited for thermal energy harvesting for bio-medical implants, weather station sensors, etc.

TABLE I: A PERFORMANCE COMPARISON BETWEEN THE PROPOSED SYSTEM, AND THE STATE-OF-THE ART ENERGY HARVESTING SYSTEMS

Reference	[15]	[7]	[16]	[17]	[18]	[19]	This Work
Technology Process	250 nm	180 nm	130 nm	90 nm	180 nm	180 nm	130 nm
V_{in} (V)	0.3	1.8	0.2	1.2	1 \rightarrow 1.5	1 \rightarrow 1.5	0.25
V_{out} (V)	2.72	5	N/A	6.24 \rightarrow 7.4	3 \rightarrow 3.5	3.3	3.07
f_{clk} (MHz)	1	100	250	0.25	0.15	0.25	6
Efficiency at I_{max} (%)	57	54	52	56	88.7	86.4	61.6
I_{load} (μ A)	2.8	350	30	55	16	12	60
MPPT Circuit	Not Included	Not Included	Not Included	Not Included	Included	Included	Used
Number of Stages	6	3	N/A	7	3	3	3

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