Autonomous ultra-low power DC/DC converter for Microbial Fuel Cells

Salah-Eddine Adami, Nicolas Degrenne, Christian Vollaire, Bruno Allard, François Buret, François Costa

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S-E. Adami, N. Degrenne, C. Vollaire, B. Allard, F. Buret
Ampère Laboratory
University of Lyon, Ecole Centrale de Lyon
Lyon, France
Salah-eddine.adami@ec-lyon.fr

F. Costa
SATIE Laboratory
University of Paris, ENS de Cachan
Cachan, France

***Abstract*—In this paper, an ultra-low voltage and power DC/DC converter is presented. This converter harvests energy from a Microbial Fuel Cell (MFC) in order to feed another circuit such as an autonomous wireless sensor. The MFC behaves as a voltage generator of 475mV open-circuit voltage with a 600Ω serial internal impedance. The maximum delivered power is therefore around 100µW. The DC/DC converter provides output voltage in the range 2-7.5V and performs impedance matching with source. The converter achieves when associated with the MFC, 60% peak efficiency. Furthermore, this DC/DC converter is self-operating without the need for external power source of start-up assistance.**

I. INTRODUCTION

Energy harvesting is a new field that researchers are more and more interesting in. It consists in collecting small amounts of energy from the environment using special transducers in order to feed an external standard circuit. There are various sources for energy harvesting [1]: solar, vibration, electromagnetic, thermal and organic. The typical application of energy harvesting is supplying autonomous wireless sensors. It avoids the use of batteries and the maintenance, enabling long life expectancy. Most of these transducers deliver a very low voltage (below 1V) and a very low power (below 1mW). A voltage level of few volts is essential in order to supply conventional electronic circuits (wireless sensors in particular). Voltage step-up can be achieved with power electronics, but again, conventional commercial DC/DC converters need at least 1V input voltage and require a minimum power in order to start-up functioning. Special new low voltage and power structures are necessary.

Most ultra-low voltage and power converters (ULVPC) need an external power source. It can be either the external output rechargeable battery or a storage capacitor charged to a sufficient level. In [2] a DC/DC boost converter powered by the external output battery is presented. It harvests low RF energy (>10µW). Another ultra-low power boost converter is presented in [3]. Output capacitor has to be charged to 650mV in order to supply the control circuit.

Self-powered converter topologies are more interesting, in particular for autonomous wireless sensors. In fact, a battery-less system does not require any maintenance, because batteries have a limited charge/discharge cycles. Furthermore, energy harvesting systems do not contribute to a good battery health because of the non-regulated available energy for most of sources. Batteries are space consuming and they take a large part of the system size. For these reasons, a self-powered system is very interesting and offers more application opportunities.

Self-powered topologies use a special self-oscillating circuit in order to start-up from low voltage. Armstrong oscillator [4-9] is commonly used in this field. This oscillating circuit is often used as a start-up part of a principal converter because of the need of an external regulated voltage. Most self-oscillating circuits operate for milli-watts power levels. In [6] a 100mW boost converter using the Armstrong oscillator as a start-up stage is presented. Similar topologies are presented in [7-8] for 17mW and 1mW respectively.

The aim of this study is to present a self-powered DC/DC converter for a 100µW MFC. It is a novel topology inspired from the Armstrong oscillator. The part II describes the used MFC and the details of its electrical characteristics. Next, in part III, the DC/DC converter and its performances are presented. In part IV, the converter is powered by the MFC in order to evaluate the global performances of the system.

II. MICROBIAL FUEL CELLS

A. Description

Microbial fuel cells (MFCs) produce electrical energy from organic matter through the action of bacteria [10]. Domestic wastewater can advantageously be used as a fuel, while the process advantageously permits its treatment at the same time. A laboratory prototype was built using a carbon fiber brush anode and an air cathode like described in [11]. The volume of the reactor is 0.9 liter and the cathode area is 32cm^2.

The MFC (Fig.1) was inoculated with wastewater from a wastewater treatment plant (Limonest, Grand Lyon). 10 hours before running the polarization curve and testing the DC/DC converter, it was fed with 0.1g of acetate and loaded with a 200Ω resistor.

Figure 1. The used Microbial fuel cell

B. *Electrical characteristics*

Voltage-current curve (Fig.2) was acquired at 26°C by decreasing the load resistance from open-circuit to short-circuit. The resistance values were set with a resistor box. We waited 2 minutes for each resistance value before acquiring the voltage (stabilization time because of high MFC time constant).

C. *Simplified electrical model*

The polarization curve can be approximated as a straight line. The basic equivalent circuit is a voltage source (475mV) serially connected to a 600Ω resistor. This model is also confirmed by the graph in Fig.3. In fact, the MFC output power is maximal for a 600Ω load resistance. Hence, impedance matching between the source and the converter is essential in order to maximize the MFC output power. As regarding the very low available power, a simple impedance matching technique based on the adjustment of the converter input impedance will be used.

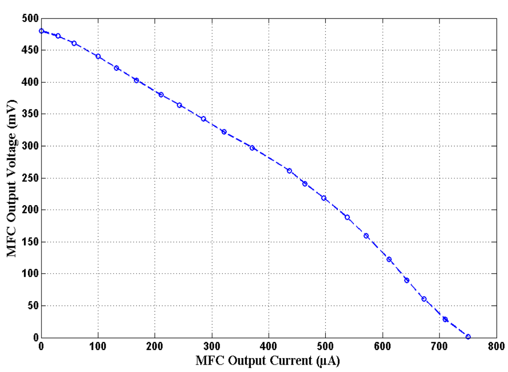

Figure 2. Voltage-current MFC characteristic

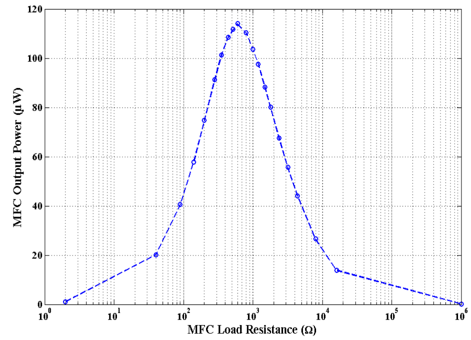

Figure 3. MFC output power vs. load

III. ULTRA-LOW VOLTAGE AND POWER DC/DC CONVERTER

A. *Description and operation*

The DC/DC converter in Fig.4 is a novel topology inspired from the Armstrong oscillator [4-9]. It is based on the use of a step-up transformer and a normally-on N-channel JFET transistor.

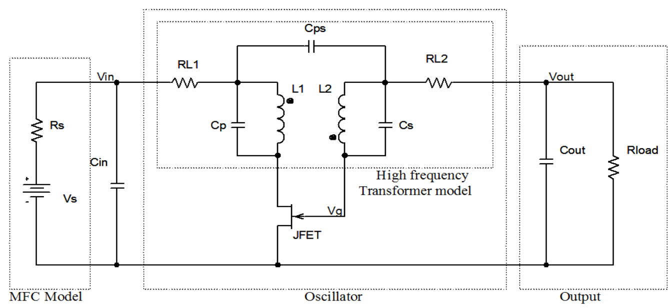

Figure 4. The DC/DC converter topology (JFET = 2N4338 and Transformer = Coilcraft LPR6235-253PML)

When the converter is connected to the MFC, the current increases in the primary winding. The secondary winding applies a positive voltage on the gate of the JFET which is ON. The JFET gate-source PN junction is conducting, and the output capacitor is charged with a negative voltage. The output voltage is therefore negative. When the primary current reaches saturation, the voltage across the primary winding cancels and the negative voltage of the output capacitor is applied on the gate of the JFET pinching it off. The current in the primary winding decreases and a negative voltage is applied by the secondary winding on the gate of the JFET, which leads to its switching off. This peak of voltage that switched off the JFET falls back to zero and the oscillation process starts again.

The optimal commercially available JFET is the 2N4338 device thanks to its low gate-source cutoff voltage ($V_{GS(off)}$ from -0.5 to -1 V). This allows the converter to start-up with a small input voltage. The transformer turn-ratio (1:20) is a trade-off between efficiency and step-up ability. It was determined using simulation optimization.

A JFET is used rather than a MOSFET because JFET's gate cutoff voltage is very low compared to the MOSFET's one. Moreover, JFET's gate capacitor is very small which reduce switching losses. However, JFET cannot be used as a principal power switch with conventional DC/DC converter because of the high value of its drain-source resistance (R_{ds}) [8].

The high frequency transformer model has been established (from 40Hz to 1MHz) using an impedance meter (Agilent 4294A) and using the model described in [12]. This model includes: serial coils resistances, coupling coefficient and stray capacitances. The DC/DC converter was simulated using Pspice with the parameters indicated in Tab.1

TABLE I. DESCRIPTION OF THE USED COMPONENTS

Symbol	*description*	*value*	*Unit*
Vs	Voltage source (open circuit)	475	mV
Rs	Source input serial resistance	600	Ω
Cin	Input capacitance	4.7	µF
L1	Primary inductance	23.74	µH
L2	Secondary inductance	9.65	mH
m	Turn ratio	20	-
Cp	Primary stray capacitance	3.13	nF
Cs	Secondary stray capacitance	13.9	pF
Cps	Primary to secondary stray capacitance	50.9	pF
RL1	Primary coil resistance	155	mΩ
RL2	Secondary coil resistance	54.8	Ω
Cout	Output DC filter capacitance	100	nF

B. Simulation and experimental results

Simulations and experimental measurements using the simplified MFC model were performed in order to evaluate the performances of the converter.

1) Impedance matching

Impedance matching between the source and the converter is essential in order to maximize the source output power. Fig.5 shows the ratio between the real power extracted from the source and the maximum possible extracted power from the source (94µW). A perfect impedance matching is observed around $R_{optimal}$=280kΩ. This optimal impedance will thus be used in further measurements. Furthermore, the matching is acceptable (ratio > 85%) over a decade of output load (100kΩ to 1MΩ).

2) Optimal Converter efficiency

In order to evaluate the performances of the converter as regard to the input power, the source voltage level is swept from 0.2 to 2V (the source impedance is kept 600Ω and the load resistance is equals to $R_{optimal}$=280kΩ). Fig.6 presents the converter output voltage versus the input voltage and Fig.7 presents the converter efficiency versus the input power.

The converter step-up ratio is around 18 and is constant over all input voltage levels (0.1 to 0.9V). Furthermore, simulation and measurement results are very close.

The efficiency is equal to 58% for the MFC power level (100µW). It decreases for lowest power levels and reaches 32% for 16.5µW. The efficiency increases with input power and reaches 68% for 1000µW. For higher input powers, the efficiency decreases (47% at 1620µW). Simulations are quite close to the measurements except for the lowest and for the highest power level. For this last one, the ferrite losses have to be integrated in the simulation model.

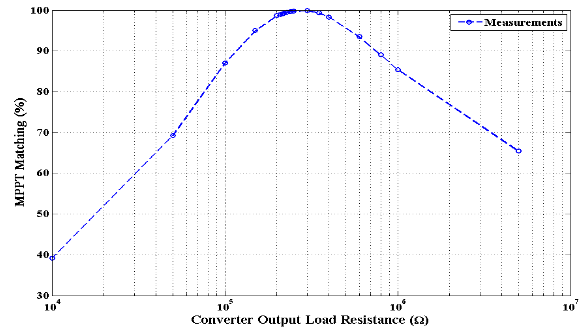

Figure 5. Impedance matching between the source and the converter

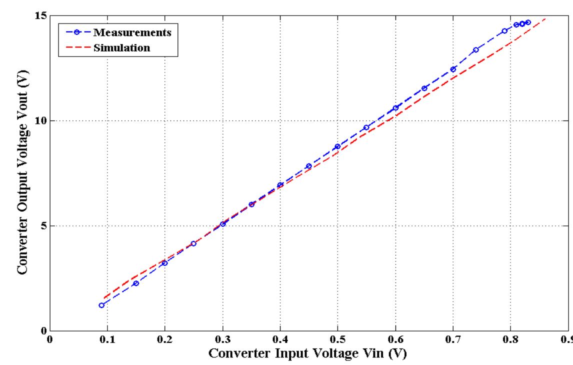

Figure 6. Converter output vs. input voltages (Simulation and measurements)

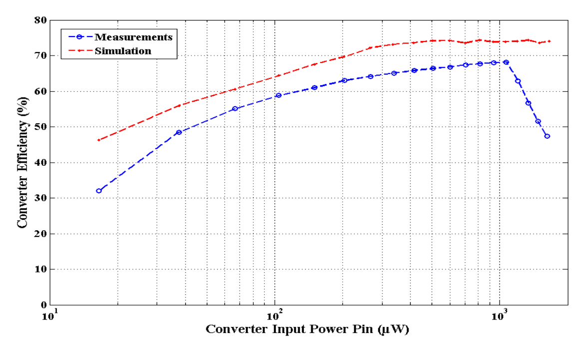

Figure 7. Converter efficiency vs. input power (Simulation and measurements)

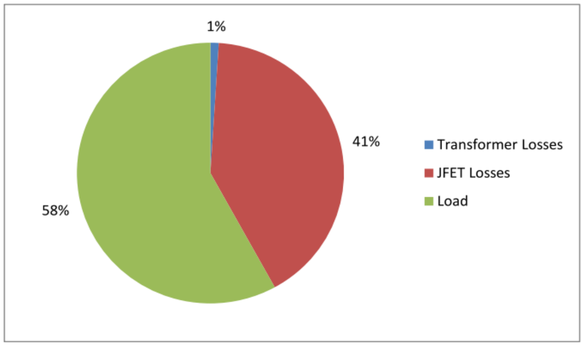

Figure 8. Converter losses repartition

Fig.8 shows the converter losses repartition. Most converter losses are due to the JFET: the JFET on-resistance (50Ω) and the gate input capacitance (5pF). However, most losses are due to the JFET on-resistance which is high because of the low gate threshold voltage (the drain-source channel is weakly doped).

IV. Energy Harvesting from a Microbial Fuel Cell

In this part, the converter is associated with the MFC described in part II.

A. *Experimental protocol*

The converter is tested with the MFC as a source and with a variable resistance at the output. Because the time-constant of the MFC is quite large (about 1 minute), a 2 minute interval is taken between each measurement. The ambient temperature is 26°C.

B. *Results*

The converter efficiency (Fig.9) is higher than 50% over a decade of output load resistance (from 60kΩ to 600kΩ). It reaches a maximum of 60% for a 200kΩ load resistance. This is the same result using the MFC model for a 100µW power level (Fig.7).

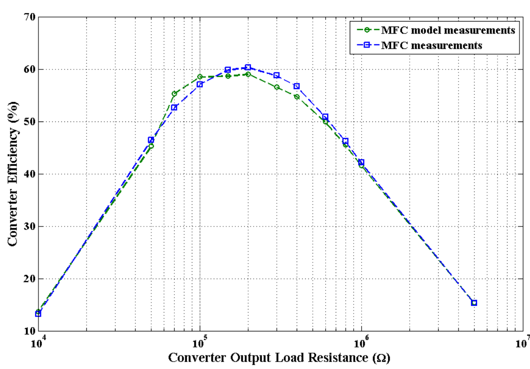

Figure 9. Converter efficiency vs. Load resistance

C. *Discussion*

The impedance matching (>85%) between the MFC (600Ω) and the converter is achieved over a wide range of converter load resistance (100kΩ to 1MΩ). High efficiency (>50%) is achieved between 60kΩ and 600kΩ. Therefore, high efficiency and impedance matching are both achieved in the range 100k-600kΩ which corresponds to an output power level of 53-68µW and an input power level of 95-113µ.

V. Conclusion

A novel self-powered high efficiency DC/DC converter has been introduced. It harvests 100µW from a microbial fuel cell, steps-up low voltage (below 300mV) to a conventional 2-7.5V output voltage level and is designed for impedance matching over a wide range of output load resistance (100k-600kΩ). Furthermore, this converter is very compact (<0.15cm^3) and has a very low cost (<1 USD for 1k units), which is suitable for industrial applications. Although it was designed for MFCs, this converter can be adapted and used with other energy-harvesting sources.

References

[1] J. Colomer-Farrarons, P. Miribel-Catala, A. Saiz-Vela, and J. Samitier, "A Multiharvested Self-Powered System in a Low-Voltage Low-Power Technology," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 9, pp. 4250-4263, Sep. 2011.

[2] T. Paing, J. Shin, R. Zane, and Z. Popovic, "Resistor Emulation Approach to Low-Power RF Energy Harvesting," *IEEE Transactions on Power Electronics*, vol. 23, no. 3, pp. 1494-1501, May. 2008.

[3] E. Carlson, K. Strunz, and B. Otis, "20mV Input Boost Converter for Thermoelectric Energy Harvesting," *Symposium A Quarterly Journal In Modern Foreign Literatures*, vol. 2, 2009, pp. 162-163.

[4] D. Grgić, T. Ungan, M. Kostić, and L.M. Reindl, "Ultra-low input voltage DC-DC converter for micro energy harvesting," *PowerMeMs*, 2009, pp. 265-268.

[5] H. Yu, H. Wu, and Y. Wen, "An Ultra-low Input Voltage Power Management Circuit for Indoor Micro-light Energy Harvesting System," *Cell*, 2010, pp. 261-264.

[6] J.M. Damaschke, "Design of a low-input-voltage converter for thermoelectric generator," *IEEE Transactions on Industry Applications*, vol. 33, 1997, pp. 1203-1207.

[7] L. Mateu, M. Pollak, and P. Spies, "Analog Maximum Power Point Circuit Applied to Thermogenerators," *iis.fraunhofer.de*, pp. 1-4.

[8] M. Pollak, L. Mateu, and P. Spies, "Step-up DC-DC-Converter with coupled inductors for low input voltages," *Fraunhofer IIS*, 2008.

[9] M. Pollak, L. Mateu, and P. Spies, "DC-DC Converter With Input Polarity Detector For Thermogenerators," *Design*, 2009.

[10] Y. Yang, G. Sun, and M. Xu, "Microbial fuel cells come of age," *Journal of Chemical Technology & Biotechnology*, vol. 86, May. 2011, pp. 625-632.

[11] J. Middaugh, S. Cheng, W. Liu, and R. Wagner, "How to Make Cathodes with a Diffusion Layer for Single-Chamber Microbial Fuel Cells,"2006. http://www.engr.psu.edu/ce/enve/logan/bioenergy/pdf/Cathode_093008.pdf. [Accessed June 23, 2011]

[12] H.Y. Lu, J.G. Zhu, S. Member, and S.Y.R. Hui, "Experimental Determination of Stray Capacitances in High Frequency Transformers," *Power*, vol. 18, 2003, pp. 1105-1112.