Step-up DC-DC Converter Supplied by a Thermoelectric Generator for IoT Applications

José Almeida
Academia Militar
Lisboa, Portugal
josesalmeida@tecnico.ulisboa.pt

Pedro Santos
Academia Militar
Lisboa, Portugal
pedro.santos@lx.it.pt

João Vaz
Instituto Superior Técnico
Lisboa, Portugal
joaovaz@tecnico.ulisboa.pt

***Abstract*—Autonomous and portable electronic circuits are typically powered by a battery. Since batteries have a limited life span there is a need to study an alternative to replace batteries with low-cost energy harvesting sources.**

This work reports the design and prototype of a DC-DC converter to step-up the low voltage of a small low-power thermoelectric generator (TEG), with an output voltage of hundreds of mV, to attain a system output voltage of 1.2V. After the theoretical analysis and simulation of the converter, several possibilities for sizing the converter are evaluated, to be implemented only with components off-the-shelf (COTS).

In order to be a standalone system, it was also necessary to design an oscillator to drive the MOSFET with a switching frequency of a few MHz. A super-capacitor wasv also introduced in the circuit to retain the TEG input for a reasonable time.

Finally, with the inclusion of a Low-dropout regulator and the experimental validation of the final prototype, it was possible to observe a regulated voltage at the output of 1.2 V.

***Index Terms*—DC-DC converter, energy harvesting, thermoelectric generator.**

I. INTRODUCTION

The idea of IoT (Internet of Things), where devices with embedded electronics, sensors, actuators, and software are connected and interact over the internet, has gained wide attention [1]. Wearable applications are also the target of growing interest for personal health monitoring and the use of various electronic sensors. A combination of IoT and wearables can improve quality of life by reducing the cost of [2] healthcare, as well as monitoring daily training and performance.

Thermoelectric generators, TEG, together with photovoltaic cells, are promising *Energy Harvesting* (EH) sources for very low voltage and low power applications. The output power and voltage available from the TEG generally ranges from $10\mu W$ to $10mW$ and from 50 to 600 mV respectively. The actual values depend on the differences in temperature and size of the TEG [3]. To power a battery or IoT device, it is necessary to convert the output voltage of the TEG, to a standard output voltage (1.2V, 2.4V, etc.) [4] [5].

II. STATE-OF-ART

Table I presents topologies of converters proposed in the scope of energy harvesting. The parameters under analysis for comparing the different typologies are the input and output voltage, the prototype area, the converter switching frequency, its efficiency, the presence of external coils, the manufacturing process, and the topology of the step-up DC-DC converter.

The works in Table I are from the step-up DC-DC converter. All the works present variations to improve the performance of the designed converter, raising the output voltage as much as possible with very low input voltages. Some systems require an external source for the start-up, like a piezoelectric [6] or a super-capacitor [7]. Some of the developed systems often featured Maximum Power Point Tracking, control circuits, and the use of transformers as a solution to startup the circuit [8] e [9]. The circuit presented in [10] and [11]is based on a charge pump topology.

III. THERMOELECTRIC GENERATOR - TEG

The thermoelectric generator (TEG) is a device that produces electrical energy from the difference in temperature applied between two surfaces. This process was discovered by Thomas Johann Seebeck in 1821 [12]. According to Seebeck, it is possible to obtain an electrical potential difference by applying a temperature difference to two types of materials. As a result, this phenomenon is known as the *Seebeck* effect. The TEG was tested and characterized in order to evaluate the voltage available to supply the voltage step-up system. The reference temperature was set to 25ºC. When an heating plate of T_h=230ºC was applied to the TEG hot zone a voltage around 0.5V was obtained at the TEG output terminals.

IV. SYSTEM DESIGN

A. Step-up DC-DC Converter

The step-up system was based on a inductor type hard-switch boost converter, as can be seen in Figure 1, with L = 150 uH, C = 4.7 nF and a load R_L = 100 kΩ. Figure 2 shows a 2.2V at the output of the DC-DC converter as a function of time, for an external supply voltage of 0.5 V, and with a square-wave generator driving the *gate* of the MOSFET (0-5V, D = 50% and f_C = 1 MHz).

B. Colpitts LC Oscillator

The driving of the MOSFET gate was based on a LC oscillator, according to the schematic present in Figure 3. The values for the designed oscillator circuit were L = 470 uH,

TABLE I
COMPARISON OF DIFFERENT VOLTAGE BOOSTING DC-DC CONVERTER TOPOLOGIES USED IN ENERGY HARVESTING.

Parameters	Articles					
	[7]	[8]	[6]	[9]	[10]	[11]
Year	2010	2012	2015	2019	2019	2019
Vin (mV)	20	40	16	20	57	11
Vout (V)	1	2	1,32	1.2	-	-
Area (mm2)	4,5	-	-	0,46	0,96	0,93
Frequency	0,22 - 3,1 MHz	439 kHz	1 kHz	80 kHz	25 KhZ	3,9 MHz
Efficiency	75%	61%	40%	81,5 %	-	85% @140 mV
L (uH)	4,7	-	37	100	220	-
Process	CMOS 130nm	CMOS 130nm	-	CMOS 180nm	CMOS 180nm	CMOS 130 nm
Architecture	Inductive Boost	Transformer	Inductive Boost	Transformer	Inductive Boost	Inductive Boost
Source	TEG	TEG	Piezoelectric	TEG	TEG	TEG

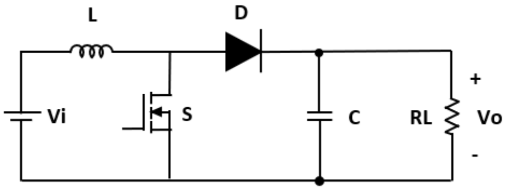

Fig. 1. Schematic of the Step-up DC-DC Converter.

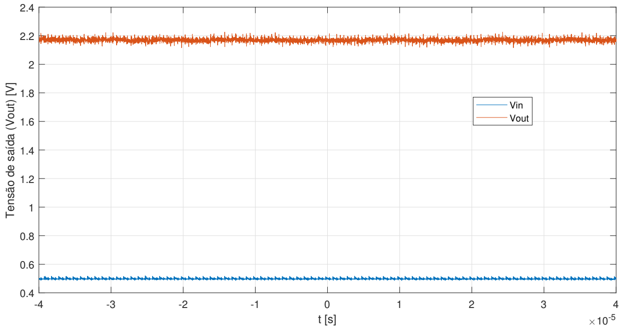

Fig. 2. Time diagram of the output voltage of the Step-up DC-DC Converter (orange) for Vin = 0.5 V (blue), f_c = 1 MHz, D = 50%.

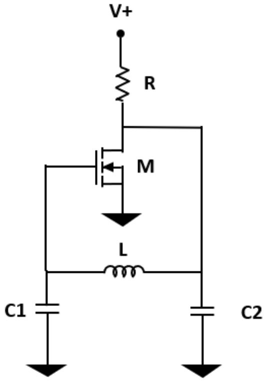

Fig. 3. Schematic of Colpitts LC oscillator.

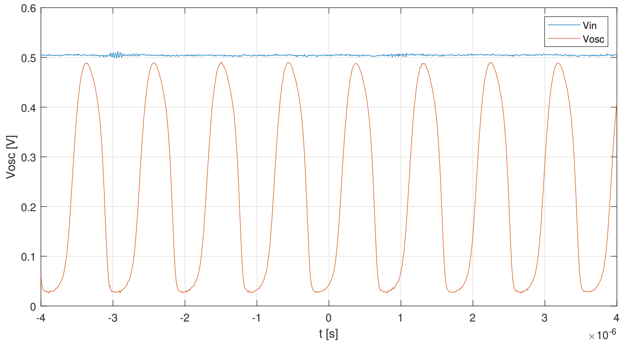

Fig. 4. Waveforms from the experimental setup, on the test board, showing the LC oscillator output voltage for an input voltage of 0.5 V.

R = 1.2 kΩ, C_1 = 10 pF, C_2 = 47 pF. Figure 4 shows the 1 MHz waveform obtained from the oscillator output assembled on the test board.

With the oscillator working for the desired low supply voltage of 0.5 V, it is also possible to supply this block with the TEG, which is fundamental for the circuit to be autonomous.

V. SYSTEM PROTOTYPE

Figure 5 shows the final prototypes of the boost converter with and without a super-capacitor at the input. The systems were designed to have an implantation area below 4.8 cm^2, with a maximum of nine COTS.

In Figure 6 the timing diagram is presented for the two final prototype cases, without and with a super-capacitor of 0.1 F. The circuit is fed by an ideal input voltage of 0.5V, with R_L = 100kΩ and observing the voltage at the boost converter's output and the low-dropout (LDO) regulator output for both cases. Note that we observe a much higher value in the boost converter with the super-capacitor than that observed without the super-capacitor. This difference is explained by the fact that the super-capacitor acts as a battery and allows the current in the circuit to be higher. It is also important to verify that the voltage regulator is working as foreseen in the specifications,

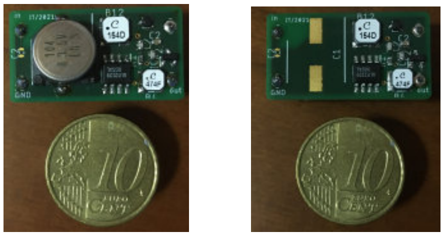

Fig. 5. Final prototypes of the *boost* converter with (left) and without (right) super-capacitor.

with a voltage regulated at 1.2 V.

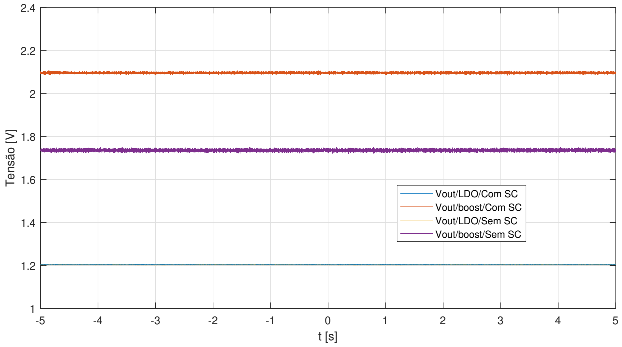

Fig. 6. Time diagram for the two final prototype cases, with and without super-capacitor. Being the circuit fed by an ideal input voltage of 0.5V, with R_L = 100kΩ and observing the voltage at the output of the converter boost and at the LDO output for both cases.

A. Analysis of the influence of the load resistance in the final prototype

Figure 7 shows the system output volatge for several load values. For higher resistances the voltage at the output of the converter is increasing, as expected. However, zooming in near 1.2 V, we see that for a 22 kΩ load the regulator no longer offers 1.2V, which can be explained by the fact that the output voltage of the converter is below the 1.4 V, the minimum value indicated in the datasheet for a efficient voltage regulation.

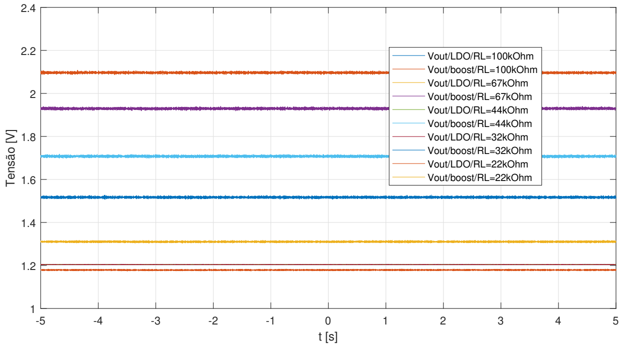

Fig. 7. Time diagram for the analysis of the influence of the load resistance R_L in the final prototype with super-capacitor, with the circuit fed by an external supply voltage of 0.5V and observing the voltage at the output of the converter and the LDO.

B. Analysis of the influence of the input voltage on the final prototype

As expected, the higher the input voltage, the higher the output voltage at the boost converter. For values of output voltage in the boost lower than 1.4 V, the output voltage in the LDO is no longer regulated at 1.2 V, as we can see in Figure 8. It was experimentally measured that for input voltages values above 400mV the boost converter remains functional. However, for this input values the boost converter output is not sufficient to deliver the necessary LDO regulator input voltage. This is another boundary condition for the prototypes.

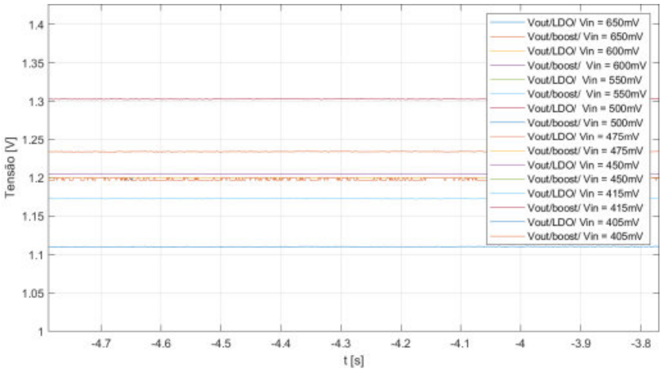

Fig. 8. Time diagram for the analysis of the influence of the input voltage on the output voltage of the LDO.

C. Analysis of the final prototype supplied by the TEG

Figure 9 shows the output voltage of the boost converter and the output voltage of the LDO when the system is powered by the TEG. Initially, a temperature difference was applied to the TEG in a time frame of about twenty seconds. Then the TEG is disconnected from the board by a push button. After the TEG is switched off, the output voltage on the LDO remains regulated for another fifteen seconds, which is a sufficient time span for numerous electronic system applications. In Figure 10 unlike the previous case, the super-capacitor is absent in the circuit. Therefore, when the temperature difference is no longer present (17 seconds), the output voltage of the *boost* drops abruptly. Consequently, the output voltage at the LDO only remains constant for another two seconds.

VI. CONCLUSIONS

A step-up voltage DC-DC converter was designed and prototyped to be powered with a TEG. The converter switch is controlled by an LC oscillator at a frequency of 1 MHz. For a oscillator duty-cycle of 50% a standard output voltage of 1.2 V was obtained with the cascade of an LDO voltage regulator. This LDO is capable of regulating a variable input voltage between 1.4 V and 5.5 V at a fixed voltage of 1.2V.

The imposition of a super-capacitor at the input of the *boost* converter was also studied, which allowed a higher converter output voltage and, at the same time, the remaining of the regulated 1.2V signal above 20 seconds, which is a reasonable time to communicate with other sensors and IoT nodes.

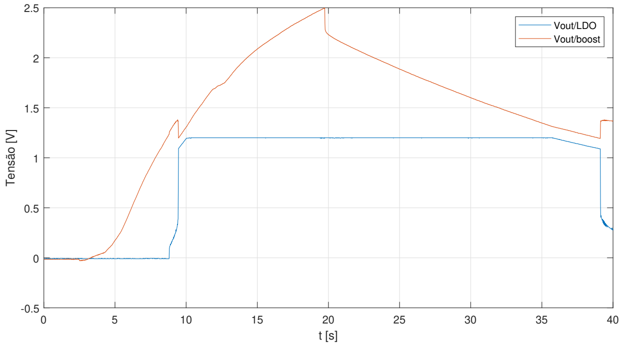

Fig. 9. Time diagram for the analysis of the influence of the super-capacitor in the final prototype with R_L = 100 kΩ, when the input voltage is supplied by the TEG. Voltage at the output of the *boost* converter and the LDO.

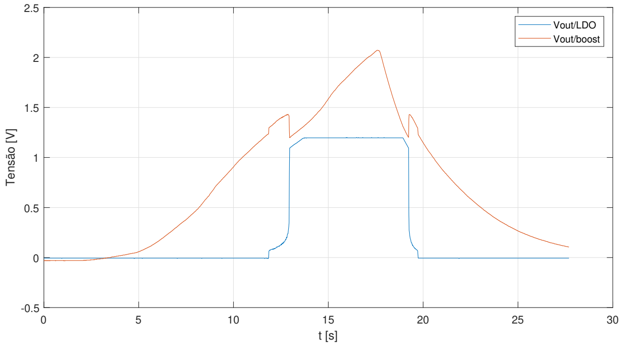

Fig. 10. Time diagram for the analysis of the influence without super-capacitor in the final prototype with R_L = 100 kΩ, when the input voltage is given by the TEG. Observing the voltage at the output of the *boost* converter and the LDO.

ACKNOWLEDGMENT

A special thank to the Instituto de Telecomunicações for funding this work, as well as for providing the laboratory facilities for prototyping.

REFERENCES

[1] A. Nozariasbmarz, H. Collins, K. Dsouza, M. H. Polash, M. Hosseini, M. Hyland, J. Liu, A. Malhotra, F. M. Ortiz, F. Mohaddes, *et al.*, “Review of wearable thermoelectric energy harvesting: From body temperature to electronic systems,” 2020.

[2] H. Liu and C. Zhao, “Wearable electrochemical sensors for noninvasive monitoring of health-a perspective,” *Current Opinion in Electrochemistry*, 2020.

[3] S. Bandyopadhyay and A. P. Chandrakasan, “Platform architecture for solar, thermal, and vibration energy combining with mppt and single inductor,” *IEEE Journal of Solid-State Circuits*, vol. 47, no. 9, pp. 2199–2215, 2012.

[4] N.-M. Sze, F. Su, Y.-H. Lam, W.-H. Ki, and C.-Y. Tsui, “Integrated single-inductor dual-input dual-output boost converter for energy harvesting applications,” in *2008 IEEE International Symposium on Circuits and Systems*, pp. 2218–2221, IEEE, 2008.

[5] M. B. Ammar, S. Sahnoun, A. Fakhfakh, and O. Kanoun, “Design of a dc-dc boost converter of hybrid energy harvester for iot devices,” in *2020 IEEE 6th World Forum on Internet of Things (WF-IoT)*, pp. 1–4, IEEE, 2020.

[6] A. Romani, A. Camarda, A. Baldazzi, and M. Tartagni, “A micropower energy harvesting circuit with piezoelectric transformer-based ultra-low voltage start-up,” in *2015 IEEE/ACM International Symposium on Low Power Electronics and Design (ISLPED)*, pp. 279–284, IEEE, 2015.

[7] E. J. Carlson, K. Strunz, and B. P. Otis, “A 20 mv input boost converter with efficient digital control for thermoelectric energy harvesting,” *IEEE Journal of Solid-State Circuits*, vol. 45, no. 4, pp. 741–750, 2010.

[8] J.-P. Im, S.-W. Wang, S.-T. Ryu, and G.-H. Cho, “A 40 mv transformer-reuse self-startup boost converter with mppt control for thermoelectric energy harvesting,” *IEEE Journal of Solid-State Circuits*, vol. 47, no. 12, pp. 3055–3067, 2012.

[9] S. C. Chandrarathna and J.-W. Lee, “A dual-stage boost converter using two-dimensional adaptive input-sampling mppt for thermoelectric energy harvesting,” *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 66, no. 12, pp. 4888–4900, 2019.

[10] S. Bose, T. Anand, and M. L. Johnston, “Integrated cold start of a boost converter at 57 mv using cross-coupled complementary charge pumps and ultra-low-voltage ring oscillator,” *IEEE journal of solid-state circuits*, vol. 54, no. 10, pp. 2867–2878, 2019.

[11] R. L. Radin, M. Sawan, C. Galup-Montoro, and M. C. Schneider, “A 7.5-mv-input boost converter for thermal energy harvesting with 11-mv self-startup,” *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 67, no. 8, pp. 1379–1383, 2019.

[12] C. Gould, N. Shammas, S. Grainger, and I. Taylor, “A comprehensive review of thermoelectric technology, micro-electrical and power generation properties,” in *2008 26th International Conference on Microelectronics*, pp. 329–332, IEEE, 2008.