Multiple-Input Multiple-Output Energy Processing for Energy-Harvesting Applications

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Abstract— **This article deals with energy harvesting field, which is a method of collecting energy from the environment to power small devices. This type of energy use is growing exponentially due to the appearance of many of these devices.**

The objective is to design and implement an ultra-low-power boost converter, designed for energy harvesting applications, which is able to add different types of energy coming from the environment to charge a battery or to feed another electronic device. It is a very innovative project and therefore, the methodology used has contemplated a lot of time for studying, doing simulations, optimizing and testing a prototype. This has allowed us to carry out a study of great value and usefulness which establishes the basis to construct a device that adds energies of our surroundings. Finally, to verify the feasibility of the application, a two-input boost converter is built to add energy coming from two different sources (with the possibility of expanding this number) and also offers different types of output storage elements.

In conclusion, the work has confirmed the possibility of adding energy from our environment and has shown the great potential of the application studied through a functional prototype.

Index Terms— **Boost Converter, Energy Harvesting, Harvester, Power Module, Solar Cell, Supercapacitor, Thermoelectric Generator.**

I. INTRODUCTION

Energy is more and more required for human living and electronic devices are rapidly increasing as well as their consumption. Furthermore, *IoT* (Internet of Things) has born, a concept that defines the connection of small devices to the Internet. These devices are receivers and generators of data (a constant exchange of information is produced) and they need energy to be used. In order to power all these devices, renewable energy is becoming more important than finite non-renewable sources and future exaggerates this difference. Due to this society changing, energy harvesting phenomena has obtained relevance without so much effort; power collection from the environment to make some devices work without being plugged to the electricity network can be a real revolution (see [2]), since this energy is free (and clean) and the devices can be autonomous (no need to connect them to the network or charge their batteries).

In energy harvesting applications, it is recommended to use multiple energy sources (see [3]). This way, the powered device can continue to function when the place or time makes access to one of the sources limited (such as solar energy at night). In most projects, the most powerful source of energy is used at each moment (see [5] and [6]). However, much more energy could be obtained if all the energy provided by the different sources was used. This can be seen in [1] and it is also what the project described in this article intends to do.

The main hypothesis to demonstrate is that energy harvesting power can be easily added and environment low-power can be converted to a power supply for electronic devices. This lets us to design and build a multiple-input circuit to show that this design is feasible and to obtain real results coming from previous simulations, calculus, planning and programming. The article is organized in the following manner. In the *System Architecture* section, the design will be presented and described. Next, the results of the simulations will be shown in the *Simulations* section. The next step will be to build the prototype and verify that the experimental results are good. This will be seen in the *Experimental Results* section. Finally, the conclusions of the project will be presented. The main purpose is to determine if the final product would be possible and viable.

II. SYSTEM ARCHITECTURE

A. General View

The block diagram in Fig. 1 illustrates the circuit studied represented as modules and the energy flow path through them.

First, harvesters collect energy coming from the environment or from anywhere it can be used, in this case, renewable energies used will be the sun and the heat, which are the most common and used ones. So, the harvesters that obtain the power to the circuit are a photovoltaic solar cell and a thermoelectric generator (TEG), one harvester for each input. They are responsible of converting renewable energies to voltage or electrical energy.

Then, module 1 will adjust energy coming from TEG input,

this means being as much efficient as possible to later sum up this energy with other inputs.
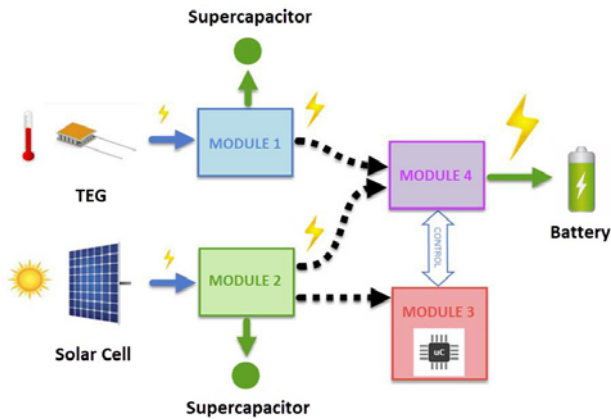

Figure 1. General Block Diagram.

Module 2 will do the same thing with the energy coming from the solar cell. Both modules will boost voltage (using a similar topology as the one described in [4] or [8]) and will adjust the impedance according to harvester's features and power. In other words, these modules are to be computed to optimize efficiency and power tracking. To do so, it is important to know each harvester's behaviour in deep and its electrical model and responding. Later, these modules will be explained in detail.

Module 3 will be the one in charge of thinking and making the decisions on the circuit. In first place, changing the way of summing the inputs and also optimizing the circuit depending on energy type and quantity. Module 3 will contain the microcontroller to this job.

After having input energy boosted and adapted, the real innovation part comes with the power summing. Module 4 will be a boost converter, controlled by module 3, which do the real power adding of the two input sources.

Finally, the last part of the circuit could be a battery to store the energy somewhere, or can be a load representing another device that takes the energy from this MIMO boost converter.

B. Module 1

The first part of the circuit consists on a DC boost converter configuration working in optimal conditions for the Thermoelectric Generator (TEG) harvester. This module is based on the ultra-low boost converter BQ25505 and it has a specific application for TEG sources giving 0.5V maximum in real cases to be boosted up to 4.2V of voltage.

C. Module 2

This module is working similar as the one already mentioned, but designed and focused on solar application. A solar cell is giving the up to 5V voltage input to BQ25505 boost converter, which gives 4.2V in the output. Configuration in the IC is taking into account the MPPT and furthermore, it has a battery management feature. That is, it can use an external primary battery to keep the system working without interruption.

D. Module 3

Each electronic system has to be controlled and in this case, the switching in the final DC converter takes a very important role. Therefore, the MSP430FR5969 microcontroller unit (MCU) is responsible for switching the signals on module 4 and voltage states in module 1 and 2 treating. In addition, its working voltage is 3.3 V, so the whole system does not start until the system's brain is awake.

E. Module 4

The real innovation part of the circuit comes up with the idea of adding all energy collected from the harvesters and amplified from the BQ25505 boosts. This 4th module is designed to add that two powers with any losses using a DC boost converter with double input switched by MOSFET transistors. Its schematic can be seen in Fig. 2.

Talking about really low power coming from a solar cell and a thermoelectric generator, this PWM generation must consume as less as possible so that CSD18542KTT MOSFETs are used in it.
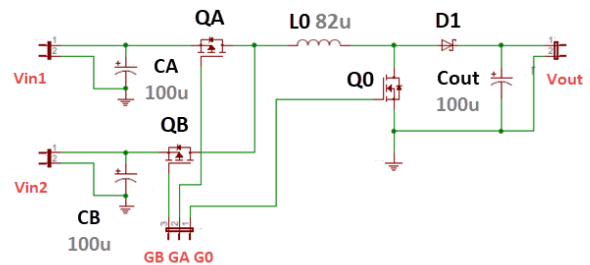

Figure 2. Module 4 Schematic Diagram.

F. Circuit Start-Up

Two types of operation should be differently considered: the transient operation; from when the system is turned on until it works normally, and the stable operation which means the circuit is working as it is supposed to. The MIMO boost converter, with all its 4 modules, it is designed for becoming stable without any user intervention.

Transient Operation will work as:

1st. All modules and devices are turned off and harvesters start collecting energy.

2nd. BQ25505 from modules 1 and 2 start boosting that energy to a similar output voltage.

3rd. Part of voltage from module 2 is accumulated in a supercapacitor in module 3.

4th. When that voltage reaches 3.3V, the controller starts working and generating the PWM signal.

5th. Module 4 controlled by module 3 sums the two voltage

inputs from 1 and 2.

6th. This amount of power allows charging a battery and supplying energy to some electronic device.

Stable Operation will work as:

1st. Once the circuit is stabilized, module 4 adds the powers coming from the harvesters and adjusted by module 1 and module 2 and the result power goes directly to the load or secondary battery.

2nd. During stable operation, all modules are working continuously and together: module 3 gives the three PWM signals to the switches in module 4, modules 1 and 2 gives the energy to the supercapacitors in the outputs and through the module 4 to the final load or battery if the harvesters are giving enough energy from the sources.

3rd. In the case the circuit is not giving enough power to keep module 3 working, the energy missing will be supplied by the primary source to guarantee that the circuit's 'brain' is always 'awake'.

III. SIMULATIONS

Module 3 needs to be connected to MOSFET transistor's gates in module 4; this way it can control the switching. This innovative module requires indispensable simulations to understand its behavior and to determine which switching strategy works better. One potentially good switching technique is the one presented in [7]. However, in order to reduce the computational power required, two easier switching strategies will be proposed. The input signals of the module 4 are simulated in PSIM software following two switching options: non-complementary switching and complementary switching.

Complementary switching is a switching strategy in which a harvester is connected at any time to module 4. That is why for each power source (and therefore, harvester) added to the system, this switching will have to be modified to adapt it to the new structure. In addition, it is possible that the capacitors of the system do not have time to discharge and, therefore, not all the energy is added up. Finally, a non-ideal switching would contribute to a loss of static energy. However, this strategy ensures that the connected device always has power. The system clock, the activation signal of the first harvester and the activation signal of the second harvester have been simulated and the result can be seen in Fig. 3.
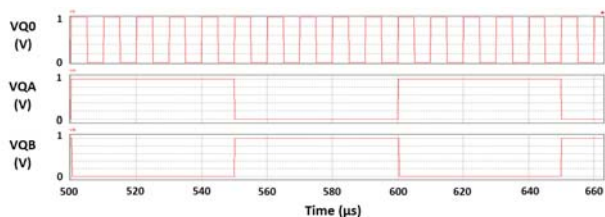
Figure 3. Complementary Switching. From top to bottom with respect to time: system clock, activation signal of first harvester and activation signal of second harvester.

Non-complementary switching is a switching strategy in which the different harvesters are connected to the system one by one and with a set time between them without connection. This allows the capacitor to have more time to discharge. It also adds flexibility to the system (a harvester can be added without modifying the switching) and avoids the loss of energy due to a bad switching, since no harvester is connected at the same instant that another is disconnected. However, with this strategy there is a certain risk that the connected device will run out of power. The same three signals that in the previous switching strategy have been simulated and the result can be seen in Fig. 4.
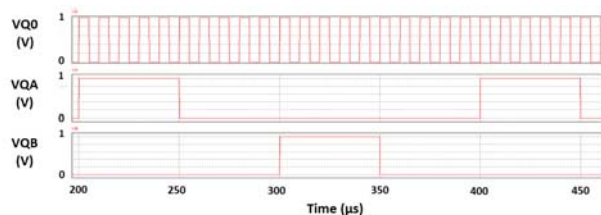
Figure 4. Non-complementary Switching. From top to bottom with respect to time: system clock, activation signal of first harvester and activation signal of second harvester.

The ideal strategy is potentially a mixture between the two. The switching system must be adapted to each situation, so that the time without any connected harvester is minimum to guarantee that the connected device always has power. However, this time should not be null (the change between harvesters should not occur at the same time) to avoid the effects of a non-ideal switching.

The fact that the circuit is adding power needs to be demonstrated. So, three different circuits are evaluated and the results can be seen in Table 1.

These results demonstrate how energy coming from disconnected inputs is stored in the capacitors and then reincorporated to the boost converter. Energy got on the output is higher than the results in previous simulation profiles. Therefore, with this simple circuit simulated, energy-adding is theoretically demonstrated and almost all energy coming from the input is transferred to the output. Furthermore, the capacitor in the input stabilizes input voltage.

Once the previous fact is demonstrated, it is necessary to optimize the circuit and make it as efficient as possible. To do

TABLE I
SIMULATION NUMERICAL RESULTS

Circuit Configuration	Input Voltage (V)	Output Voltage (V)	Output Power (mW)
Normal Boost Converter	5.00	16.10	259.18
2-input Boost (without capacitors)	5.00	16.17	261.47
2-input Boost (with capacitors)	4.56	19.79	391.57

so, different circuits are simulated following calculated values to verify the functioning and behavior. From the simulation, we can say that the input capacitor only affects on delaying the signal to reach its maximum point, RC delay. It does not affect voltage values. Then, output capacitor only affects the ripple in the output. It does not affect voltage values. Also, the lower the inductor, the greater the output voltage is. Finally, the higher is the duty cycle in NMOS transistor, input voltage decreases. That happens because the circuit's equivalent resistance is lower as the MOSFET is connected to GND a major period of time. Then the following affirmation is accomplished:

100% of duty cycle; Q0 = ON; Rcircuit is 0.
0% of duty cycle; Q0 = OFF; Rcircuit is 1K.

IV. EXPERIMENTAL VERIFICATION

All 4 modules were tested once they were implemented. Their correct functioning was crucial for getting reasonable results and conclusions. Circuits were first checked and tested individually and later on they were connected and tested together with all modules.

Module 1 and 2 were implemented and tested following the BQ25505 instructions and steps in its datasheet.

For Module 3, two different programs were designed with *Energia* software from *Texas Instruments*. The aim is to check if what is in the program happens also from a practical point of view; that is the theoretical values being close to the experimental results. To do so, an oscilloscope is used to monitor the 3-pulse width modulated (PWM) signals supposed to control MOSFET transistors in Module 4. The last module was tested as a normal one-input boost converter.

Once the modules are checked separately, it is time to test the complete circuit functioning. The experimental results from MIMO boost converter are compared with the simulations to show similar conclusions. To do so, modules must be connected following *Figure 1*. The results of this test show that the system is adding energy, and that therefore, the implemented design works. However, it does not show the same results of the simulation due to the loss of energy involved in the connections in a PCB. The final system should be implemented in an ASIC to take advantage of all the features of the design.

V. CONCLUSIONS

Multiple-input boost converter design for energy harvesting applications has been a tough and promising project. The possibility of adding energy coming from different sources in our environment becomes a new world where autonomous devices are increasing more and more.

Once the project is done and the prototype is tested, we can conclude that the designed boost converter circuit presents correct results and overcomes our expectations. This success brings the authors to find a path to follow and continue the project. It is important to say that the main goal of the final project was implementing a prototype which demonstrates that power coming from different sources can be added to be stored in a battery, a supercapacitor, or to feed another electronic device. This hypothesis has been accomplished with merit.

There have been many problems; the majority related with the fact that energy harvesting requires caring a lot about energy losses, even if they are small. This has affected on the simulations as power values were low and time intervals were minimal, so values were not the same as in reality. Regarding implementation, ASIC would be the only option as energy harvesting applications requires low distances between components and low-power techniques. Also, the microcontroller has to work in fast time response to be effective, and components chosen must consume the less as possible. There have been problems during experimental results too, even when measuring parameters as the circuit requires very high-quality instrumentation and because of the losses in the PCB connections.

Nevertheless, all these obstacles have been overcome and goals have been achieved with positive results. Improving the device reducing losses and using a considerable number of inputs, the circuit would be able to charge a smartphone battery.

REFERENCES

[1] Shi, C., Miller, B., Mayaram, K. and Fiez, T. (2011). A Multiple-Input Boost Converter for Low-Power Energy Harvesting. *IEEE Transactions on Circuits and Systems II: Express Briefs*, 58(12), pp.827-831.

[2] Tan, Y. (2013). Energy harvesting autonomous sensor systems. 1st ed. Boca Raton: CRC Press, Taylor & Francis Group.

[3] Carli, D., Brunelli, D., Benini, L. And Ruggeri, M. (2011). An Effective Multi-Source Energy Harvester for Low Power Applications. Design, Automation & Test in Europe Conference & Exhibition (DATE), IEEE.

[4] Wang, S.-W., Im, J.-P. and Cho, G.-H. (2011). Dual-Input Dual-Output Energy Harvesting DC-DC Boost Converter for Wireless Body Area Network. Biomedical Circuits and Systems Conference (BioCAS), IEEE.

[5] Khruatiew, T., Chalermyanont, K., Prasertsit A. and Wichakool, W. (2013). An Integrated Multiple-Input Multiple-Output Converter with Battery Charger for Low Power Applications. The 6th PSU-UNS International Conference on Engineering and Technology, 12 (1.4), pp. 1-5.

[6] Behjati, H. and Davoudi, A. (2012). A MIMO topology with series outputs: An interface between diversified energy sources and diode-clamped multilevel invertir. Applied Power Electronics Conference and Exposition (APEC), IEEE.

[7] Onwuchekwa, C. N. and Kwasinski, A. (2012). A Modified-Time-Sharing Switching Technique for Multiple-Input DC–DC Converters. *IEEE Transactions on Power Electronics, vol. 27, n. 11, pp. 4492-4502.*

[8] Dobbs, B. and Chapman, P. (2003). A multiple-input DC-DC converter topology. *IEEE Power Electronics Letters*, 99(1), pp.6-9.