UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola d'Enginyeria de Barcelona Est

FINAL DEGREE PROJECT

Degree in Industrial Electronics and Automation Engineering

MULTIPLE-INPUT MULTIPLE-OUTPUT ENERGY PROCESSING FOR ENERGY-HARVESTING APPLICATIONS

Volume I

Report

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Call: January 2017

Resum

Aquest projecte s'emmarca en l'àmbit de "l'energy harvesting", que és un mètode de recol·lecció d'energia de l'ambient per a alimentar petits dispositius de baix consum. Degut al naixement de molts d'aquests dispositius (sensors, "wearables"...) aquest tipus d'aprofitament d'energia està creixent exponencialment.

L'objectiu d'aquest projecte és dissenyar i construir un convertidor elevador de tensió de baix consum, pensat per a aplicacions "d'energy harvesting", que sigui capaç de sumar diferents tipus d'energia de l'entorn per a carregar una bateria o alimentar una càrrega. És un projecte molt innovador i per això la metodologia emprada ha contemplat molt de temps d'estudi, simulacions, optimització del disseny i proves experimentals amb un prototip. Això ha permès portar a terme un estudi de gran valor i utilitat que estableix la base sobre la que construir un dispositiu que sumi energies del nostre entorn. Finalment, per a verificar la viabilitat de l'aplicació, s'ha construït un convertidor elevador capaç de sumar dues entrades d'energia (amb possibilitat d'ampliar aquest nombre) i que ofereix diversos tipus de sortides.

Com a conclusió, el treball realitzat ha confirmat la possibilitat de sumar energies del nostre entorn i ha mostrat el gran potencial de l'aplicació estudiada mitjançant un prototip totalment funcional.

Resumen

Este proyecto se enmarca en el ámbito del "energy harvesting", que es un método de recolección de energía del ambiente para alimentar pequeños dispositivos de bajo consumo. Debido al nacimiento de muchos de estos dispositivos (sensores, "wearables"…) este tipo de aprovechamiento de energía está creciendo exponencialmente.

El objetivo de este proyecto es diseñar y construir un convertidor elevador de tensión de bajo consumo, pensado para aplicaciones de "energy harvesting", que sea capaz de sumar diferentes tipos de energía del entorno para cargar una batería o alimentar una carga. Es un proyecto muy innovador y es por eso que la metodología utilizada ha contemplado mucho tiempo de estudio, simulaciones, optimización del diseño y pruebas experimentales con un prototipo. Esto ha permitido llevar a cabo un estudio de gran valor y utilidad que establece la base sobre la que construir un dispositivo que sume energías de nuestro entorno. Finalmente, para verificar la viabilidad de la aplicación, se ha construido un convertidor elevador capaz de sumar dos entradas de energía (con posibilidad de ampliar este número) y que ofrece diversos tipos de salidas.

Como conclusión, el trabajo realizado ha confirmado la posibilidad de sumar energías de nuestro entorno y ha mostrado el gran potencial de la aplicación estudiada mediante un prototipo totalmente funcional.

Abstract

This project belongs to 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 (sensors, wearables...).

The objective of this project 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.

Greetings

There are many people who helped during the performing of the project, each of them contributing with some issue or knowledge. We wanted to put on record all names and institutions in the report to thank them for all their support.

First of all, it must be said that it is a great pleasure to work with Herminio Martínez García as a project director. His support has been very helpful and the encouragement of reporting an energy harvesting project has been wonderful. Continuing with the personnel from the university, technical service has been also really pleasant. Soldering and testing has been easier and faster thanks to them.

We are glad of having the support from our close friends in the university, especially those coming from electronics and automation engineering team. Their advice, spirit and constructive criticism have been essential while doing the project. In particular, Julia Nueno and Sergi Lloret let us try their material related to energy harvesting as their project was also similar.

Related to the project motivation, and contributing with the majority of founding, we would like to thank a lot the jury from Texas Instruments Innovation Challenge 2016. In general, all Texas Instrument Company has collaborated in many aspects and let us get many samples of chips and transistors needed.

Regarding other companies there are some which has also offered their product samples and support. Some of them are well-known brands as: *TE connectivity, Fairchild/ON Semiconductor, Coilcraft, Wurth Electronic, Copper/Eaton, Enocean, Hershey Power, Europavia, PowerFilm, Ceramtec, ICN-CSIC, OTEGO, MEGGIT, NOLIAC, CEDRAT-TEC* and *TechIdeas*.

Some other useful pieces of advice and recommendations came from Santiago Gómez Gómez, motion developer in Omron ATC Europe. Also, as a consequence regarding our methodology with daily reunions, library stuff has helped everyday with book references and room reservations in FME faculty from UPC University.

Last but not least, it is important to thank the respective families for their personal support and help.

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1. Introduction

This first chapter describes the final project expressed as a report. A basic ingredient is for sure the motivation for what the project is done and developed. Once there is a good and powerful reason to do the project, there is the need of fixing some goals to achieve. After that it is important to think on how the project will be and what is the project going to include, defining the limits coordinated with the execution time. Before starting, a good planning is the key point for having success; during the project it has to be checked and updated every time in a while. All this factors are explained in detail below.

1.1. Motivation

Energy is more and more required for human living, electronic devices are rapidly increasing as well as their consumption. Furthermore, renewable energy is becoming more important than finite non-renewable sources and future exaggerates this difference (this fact will be demonstrated in Theoretical Background, section 2). 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.

Energy harvesting topic, initially proposed by our director, is studied in first term and developed as a final university project. The information through internet and coming from some interesting articles and references made us think in a power adding design; a multiple input device to gather low power from different sources to get as much energy as possible to be converted in longer autonomy. Our most important motivations are the followings:

a) The project is ambitious and rigorous, with innovative processes and interesting results, based on teamwork. Both project's authors are entrepreneurs and the project can be planned as the beginning of more investigations together; of course if all goes as planned and with success.
b) The Texas Instruments Innovation Challenge has been the main motivation. A worldwide contest where our electronic device can be exposed in front of enterprises like TI and the possibility of being founded if winning the challenge is a powerful aim.
c) The topic is a good one for being part of the final university project. All time spent in the report and prototype will for sure have its reward and can be then reflected in the academic record.
d) Personal satisfaction is also a motivation to go further in the project. Learning to do all processes, approaches, conclusions and overcoming problems ourselves are skills that can only be learned by working hard on something you like.

1.2. Objectives

Regarding the objectives to achieve, we have listed all of them divided in two sections; fixed steps to accomplish with the design application and general goals related with the project.

Circuit design goals:

- Design a multiple input boost converter which allows power adding.
- Simulate the circuit to demonstrate how different kind of energies coming from different input sources can be summed up.
- Implement the circuit in PCB format to show real values.
- Build a prototype to evaluate the circuit's possibilities and test the application.

General goals:

- Be part of the project from the start, continue the whole process and see its own conclusions.
- Learn and experience how to design, simulate, implement and test a self-made circuit.
- Overcome all problems and obstacles during the project.
- Teamwork rapport and planning to reach the same purposes.

1.3. Scope

The project itself requires a lot of work related with investigation, so it is crucial to take into account what is going to be part of the project and what will not be on the scope. The path and ambitions must be realistic and clear.

The main hypothesis to demonstrate is that energy harvesting power can be easily added and convert the environment low-power to a power supply for electronic devices. This lets us to design and build a multiple-input circuit to show that it really works; to obtain real results coming from previous simulations, calculus, planning and programming. Everything mentioned determines in the project, if the final product would be possible and viable. Furthermore, we will see how real applications would affect each of the report's part.

1.4. Methodology

In every project, methodology followed is one of the most relevant key points. It is based on a detailed and well-planned organization which aims to achieve small goals constantly.

To do so, *Trello* application has been a very useful tool to post all information safe on Internet, communication between members of the project and task division.

Regarding organization, weekly reunions have been important to take a look in the small goals to achieve, evaluate the process with perspective and reconsider some aspects during the project performance. To work, time of reunion between members has increased from 3 days a week to every day reunion and working together. Moreover, once a month there have been some reunions with the director to ask doubts and control the path followed.

Working level should be equilibrated and both members must take part of all sections and decisions. Even though, there are some tasks from which one of the members is more specialized than the other and vice versa. From the one hand, Gerard has been more focused on topics like implementation, welding and PCB design with EAGLE; also in components selection and general knowledge of studied topic. From the other hand, Isabel has been more concentrated in simulation section with PSIM, calculus and programming; knowledge regarding boost converter is higher coming from her. It must be sad that teamwork has been fundamental and section classification has been minimal. That means each member has understood the whole project equally.

Finally, this deal in the report's method implies writing down everything we have done. All reports have been made following a self-made template, the tests and process (all included in annexes) are written and described in detail

1.5. Planning

The project carried out has been very planned. Before its beginning, a general planning was done for months, to give us an idea of how much time we could dedicate to each task. This planning would be constantly revised, but it would allow us to organize the time we had.

Once this general planning was designed, an organization of objectives per week began. This method attempted to increase efficiency, since small objectives had to be accomplished every day, which resulted in constant progress.

All this planning has been carried out using *Trello*, the tool already presented previously. Here is an example of our organization for a week:

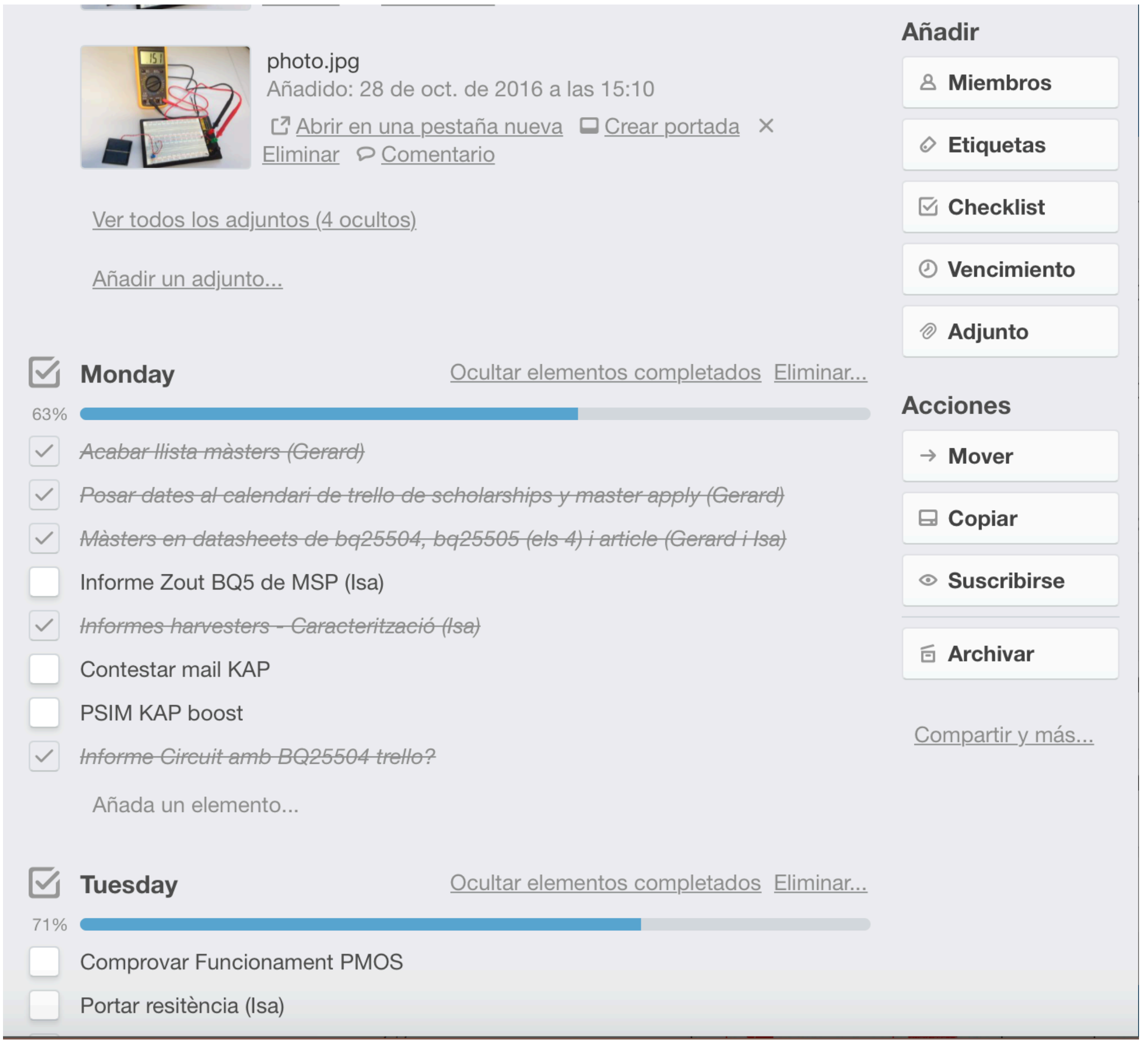


Figure 1.1. Example of an organization for a week using *Trello* [Self-made]

Finally, we can see the whole distribution of tasks and the times in which they have been carried out in a much more intuitive way in the Gantt Diagram that follows:

Task		Duration (weeks)	Start	Finish	Person	25-1	1-2	8-2	15-2	22-2	29-2	7-3	14-3	21-3	28-3	4-4	11-4	18-4	25-4	2-5	9-5	16-5	23-5	30-5	6-6	13-6	20-6	27-6	4-7	11-7	18-7	25-7
Theory	Energy Harvesting	2	25/1/16	7/2/16	Gerard																											
	Boost converter	2	25/1/16	7/2/16	Isabel																											
	Microcontroller	1	8/2/16	14/2/16	Gerard																											
	Batteries	1	8/2/16	14/2/16	Isabel																											
	State of the art	1	15/2/16	21/2/16	Both																											
Design	Idea	1	22/2/16	28/2/16	Both																											
	Module 1	1	29/2/16	6/3/16	Both																											
	Module 2	1	7/3/16	13/3/16	Both																											
	Module 3	1	14/3/16	20/3/16	Both																											
	Module 4	2	14/3/16	27/3/16	Both																											
	General	1	21/3/16	27/3/16	Both																											
Computations	Module 1	1	28/3/16	3/4/16	Both																											
	Module 2	1	28/3/16	3/4/16	Both																											
	Module 3	1	4/4/16	10/4/16	Gerard																											
	Module 4	2	4/4/16	17/4/16	Isabel																											
Simulations	Modules 1&2	1	4/4/16	10/4/16	Isabel																											
	Module 3	1	11/4/16	17/4/16	Gerard																											
	Module 4	2	18/4/16	1/5/16	Isabel																											
Components selection	Module 1&2	2	11/4/16	24/4/16	Gerard																											
	Module 4	2	18/4/16	1/5/16	Gerard																											
Implementation	Insertion	2	25/4/16	8/5/16	Isabel																											
	PCB design	3	25/4/16	15/5/16	Gerard																											
	PCB welding	1	6/6/16	12/6/16	Both																											
Programming	Complementary switching	1	16/5/16	22/5/16	Isabel																											
	Non-complementary switchin	2	23/5/16	5/6/16	Isabel																											
Experimental results	Module 1	2	9/5/16	12/6/16	Both																											
	Module 2	1	13/6/16	19/6/16	Both																											
	Module 3	1	20/6/16	26/6/16	Both																											
	Module 4	2	20/6/16	3/7/16	Both																											
	General	2	4/7/16	17/7/16	Both																											
	Others	2	4/7/16	17/7/16	Both																											
Writing	TI Contest	1	18/7/16	24/7/16	Both																											
Revising	TI Contest	1	25/7/16	31/7/16	Both																											

Figure 1.2. GANTT diagram, 1st part [Self-made]

						12-9	19-9	26-9	3-10	10-10	17-10	24-10	31-10	7-11	14-11	21-11	28-11	5-12	12-12	19-12	2-1
Design	Idea	1	12/9/16	18/9/16	Both	■															
	Module 1	1	12/9/16	18/9/16	Both	■															
	Module 2	1	12/9/16	18/9/16	Both	■															
	Module 3	1	12/9/16	18/9/16	Both	■															
	Module 4	1	12/9/16	18/9/16	Both	■															
	General	1	12/9/16	18/9/16	Both	■															
Computations	Module 1	1	19/9/16	25/9/16	Both		■														
	Module 2	1	19/9/16	25/9/16	Both		■														
	Module 3	1	26/9/16	2/10/16	Gerard			■													
	Module 4	2	26/9/16	9/10/16	Isabel			■	■												
Simulations	Modules 1&2	1	10/10/16	16/10/16	Isabel					■											
	Module 3	1	3/10/16	9/10/16	Gerard				■												
	Module 4	2	10/10/16	23/10/16	Isabel					■	■										
Components selection	Module 1&2	1	10/10/16	16/10/16	Gerard					■											
	Module 4	1	17/10/16	23/10/16	Gerard						■										
Implementation	PCB design	2	24/10/16	6/11/16	Gerard							■	■								
	PCB welding	1	21/11/16	27/11/16	Both											■					
Programming	Complementary switching	1	24/10/16	30/10/16	Isabel							■									
	Non-complementary switchin	2	24/10/16	6/11/16	Isabel							■	■								
Experimental results	Module 1	1	21/11/16	27/11/16	Both											■					
	Module 2	1	21/11/16	27/11/16	Both											■					
	Module 3	1	21/11/16	27/11/16	Both											■					
	Module 4	2	28/11/16	11/12/16	Both												■	■			
	General	1	12/12/16	18/12/16	Both														■		
	Others	1	14/11/16	20/11/16	Both										■						
Writing	TFG	6	7/11/16	23/12/16	Both									■	■	■	■	■		■	
Revising	TFG	1	2/1/16	5/1/16	Both																■

Figure 1.3. GANTT diagram, 2nd part [Self-made]

2. Theoretical Background

2.1. Power and Energy

‘Energy cannot be created or destroyed, it can only be changed from one form to another’ – Albert Einstein

Energy is often defined as the ability to perform work. It is a good definition, but it can lead to confusion. This is because it is not intuitive, for example, that the thermal energy we use to heat our room has the capacity to do a job.

Anyway, we know that energy is essential and we transform this energy to obtain certain results in each moment. The three main forms of energy we need in our life are kinetic energy, thermal energy and electrical energy, and many of our efforts are dedicated to obtaining them.

In addition, we increasingly need energy (more devices need power) and we have fewer resources to obtain it, at least some specific energy sources (known as non-renewable energies).

At this point it may be desirable to know the existing resources to generate energy; they are known as energy sources. An energy source is in charge of providing us with energy that we can transform to obtain what we want. In addition, once exploited, it regenerates itself. The problem is that sometimes it does not do it fast enough to make it meaningful to humans and the power source runs out. This group is known as non-renewable or finite energies. On the other hand, there is a group of energy sources that are regenerating themselves constantly and, therefore, they do not present the danger of being exhausted. They are renewable energy sources.

However, humans have ignored the problem of resource depletion and they have been using non-renewable energy sources unceremoniously. Now, we are in a situation in which we base the obtaining of energy in these sources and the whole system and the installations are prepared for them. This leads to a situation of collapse. That’s why renewable energy is acquiring importance, but any change requires a transition time and currently, renewable energy sources only produce approximately 10% of the total energy obtained. Let's take a closer look.

2.1.1. Non-renewable Energy

Energy and power coming from non-renewable sources have many things in common, and the majority of these things are considered as negative.

Fossil fuel and uranium are called the ‘dirty’ sources as they generate waste in their process of obtaining energy. This contamination could be in form of CO_2 directly to the atmosphere or due to U235 extraction process and final residues obtained. In any case, using this kind of energy means harming the nature and the place that we all share and live from: The Earth.

Other than that, the process of obtaining energy from fossil fuel as carbon, natural gas or petroleum is not so much worthwhile as the complexity in the process is high compared to the final amount of energy obtained. In the majority of cases, there are many energy losses in all different steps needed to obtain energy from that sources and the final percentage available to consume is very low. There are also cases which use more direct energy conversions as, for example, thermal energy production and combined cycle electricity generation from natural gas. Furthermore, fossil fuel and uranium are not accessible for all the population.

The clear advantage of this kind of ‘dirty’ sources is that they can be easily stored and quantified. On the contrary, the most important and alarming disadvantage is that they are finites. So humans will have to live without depending on non-renewable energy on a not-so-far future.

Main non-renewable energy sources are explained in detail below (For more detailed information see [12]).

<ins>Petroleum</ins>: is used as a primary source to obtain gasoline and diesel; both are used mainly to produce electrical and kinetic energy. A vast majority of electricity comes from this source, despite the efficiency of the process is 33% on average. On the other hand, ignition engines are the ones which convert the source to kinetic energy and their efficiency, regardless of consuming gasoline or diesel, is around 20%. Regarding thermal energy, gasoil is also used to burn and heat up. In this case, efficiency is around 77% which means this is the most profitable of the three energies obtained but, without forgetting that there is a huge amount of CO_2 thrown to the atmosphere while doing any of these processes.

<ins>Natural gas</ins>: is collected to produce mainly thermal and electrical energy, not for movement or transport purposes. The electrical efficiency goes between 32% and 45% depending on the process while the thermal one takes a generous 75% approximately. The emissions to the environment are lightly less than petroleum but the source itself I hard, destructive and expensive to extract.

<ins>Carbon</ins>: is a mineral from where usable carbon can be obtained and works in a similar way as petroleum does: the most common energy used is electrical energy with 27% of efficiency but it is

higher in thermal uses with 64%. Carbon is abundant and present in developed countries. It is also cheap to extract but it implies an extremely high CO_2 emissions; harmful for human live.

Uranium: is also used for electricity generation but the initial process is partially different. U235 isotope is obtained from mineral state of uranium and fission process takes place in a nuclear reactor. This reaction releases a considerable amount of energy that then is used to produce electric energy passing through a generator. The final percentage of electric energy obtained coming from uranium is around 23% and it implies residues that should be long-term treated a part from the CO_2 contamination. In addition, if the fission process is not well controlled, the consequences can be catastrophic.

2.1.2. Renewable Energy

On the premise that finite sources will run out at some point, renewable energies take advantage as they are unlimited. The sun, the wind and the water are accessible for almost everyone and are considered 'clean' sources. Getting energy from this kind of sources does not imply emitting CO_2 to the atmosphere and does not minimize the reserves of them. So the efficiency in renewable energies is only taking into account the economic factor.

When talking about costs, the only cost is the one regarding maintenance and installation, that is actually soon recovered. These sources are free and well distributed around the world in some way or another and the process to obtain kinetic, thermal or electrical energy from them is, in the majority of cases, direct conversion. So using renewable energies is the way that really pays off energetically speaking.

Next, main renewable energy sources are explained in deep (see more in [12]).

Solar energy: comes from the biggest source of light, hot and energy in human life: the Sun. This source is used to produce thermal energy with an 80% of efficiency and to produce electrical energy with a 15%-20% of efficiency. This last percentage is thanks to the photovoltaic effect, which converts directly the sunlight to electricity. Besides its low percentage of efficiency, solar energy is better compared with nuclear energy or fossil fuel as there is no losses between different steps and processes.

Wind energy: is also a direct electricity generation, coming from the wind, another inexhaustible source. Wind turbines turn with the wind force and an alternator attached transforms the kinetic energy to electrical energy. This process is 53% efficient and, despite its visual impact, these kinds of turbines are optimized and become one of the most used renewable sources.

Hydroelectric energy: works in a similar way but in this case the water is what makes the turbine turn. Power generator attached to the turbine makes a total efficiency of 81% when converting water movement to electricity. There are several ways to get that movement as river flow, dams and even ocean currents which is also called marine energy.

Geothermal energy: takes thermal flows under Earth's surface as a 'clean' heat power to produce both thermal and electrical energy depending on enthalpy given. The first one has a high efficiency of 60% while the second one has a 26%. This cheap heating method studies the release of energy given while changing the state of a fluid. So the impact to the environment is minimal.

Biomass: is also considered a renewable energy as it is obtained by the combustion of organic components. It becomes a regenerative process while the CO_2 emitted to the atmosphere is less than the one converted into oxygen that plants has taken before with the photosynthesis, so it is crucial to not abuse of this process. It is true that biomass is not unlimited, but is a way of transforming organic waste to clean thermal or electrical energy. Regarding heat power the efficiency is around 80%, referring to electric power the efficiency is between 30% and 40%. Biomass can also be used for kinetic energy, as a combustible for transport movement for instance, but the efficiency is only 11% and it is not really worthwhile.

2.2. Energy Harvesting

The importance of energy is undeniable. Energy is used for everything more and more. That is because the world is changing. We tend to a more connected world. The number of devices connected to the network is growing. *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, so a constant exchange of information is produced. It is done connecting the physical world and creating a great network that encompasses both the digital world and every small device. And each of those devices needs energy to be used. In addition, these devices are often sensors or small devices that are preferred to be autonomous and connecting them to the electrical network with a cable is a disadvantage.

Here is the importance of energy harvesting. Energy harvesting is a concept defined as the collection of energy from the environment to operate low consumption devices, such as wearables or sensors, or even mobiles or mp3's.

The importance of this concept is growing exponentially due to the appearance of numerous devices of low consumption and because this method of feeding devices offers a lot of advantages.

The energy is free (it is in our environment) and we also avoid cables, which can make the device transportable. The device will be autonomous and wireless. Furthermore, if you use the energy directly you can avoid installing batteries, which have a limited lifetime and are polluting.

You could even avoid charging your device forever if a good design of the collection of energy is done. That is because around us there is more energy than we imagine. So a big advantage of using this type of power is that you avoid charging devices and, more than that, these devices can be located in places of difficult access.

Basically, the energies used in energy harvesting are those that come from vibrations, light or temperature gradients. Sometimes, they are energies that cannot be used on a large scale and are only used for these small devices (since they never generate large amounts of energy).

2.2.1. Harvesters

There are many types of energy that can be harnessed from the environment. Some of them are also used on a large scale and many of them are not. The majority of them can be seen in the graph presented in the Figure 2.1.

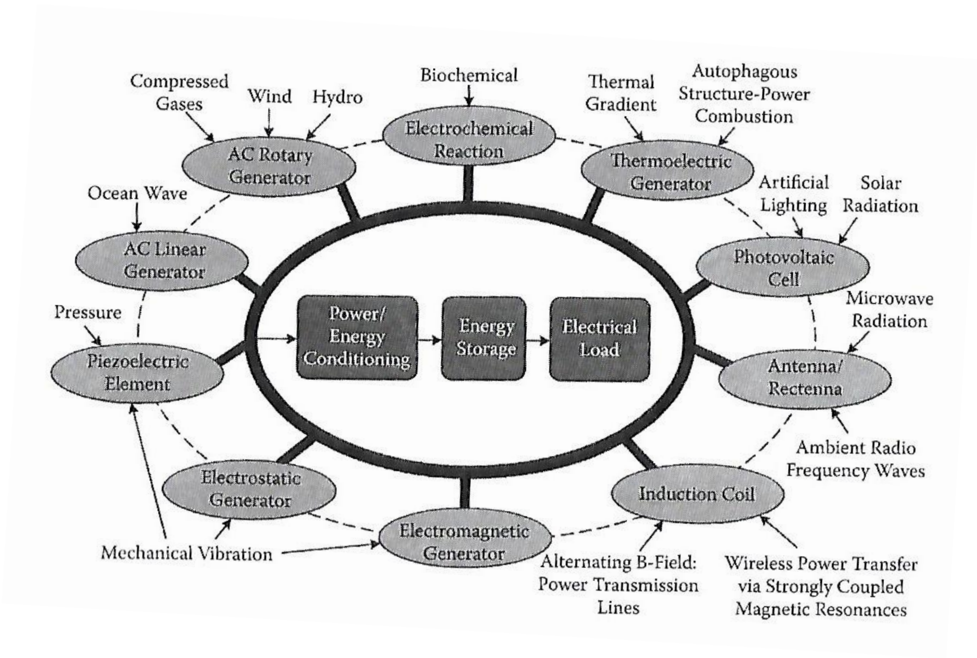


Figure 2.1. Energy harvesting sources available in the environment [6]

Converting the energy of the environment into electrical energy, which is what we always want to get to feed small devices, implies a device that does this task. The device that is in charge of doing so is called 'harvester'.

Therefore, at least there is one type of harvester for each energy that we want to transform into electrical energy. Actually, there are many types of each of the energies.

Some of the most important harvesters will be analysed, among which are the solar energy harvester (solar cells) and the thermal energy harvester, which takes advantage of the thermal gradients (TEGs), which are the two that will be used in our project.

Solar Cell: A solar cell can be defined as a photodiode with a big surface.

To dig deeper into this device, it is recommended to see [16]. There a lot of information and the formulas that characterize this harvester can be found. Here is presented the model that best represents a solar cell and that will allow to work with the harvester throughout the project, since its behaviour will be similar to that of the model. Ideally, a solar cell can be represented as a current source in parallel with a diode. However, there is not any device without losses, so the model should include a shunt and a series resistance. Finally, the model is the one represented by the following circuit:

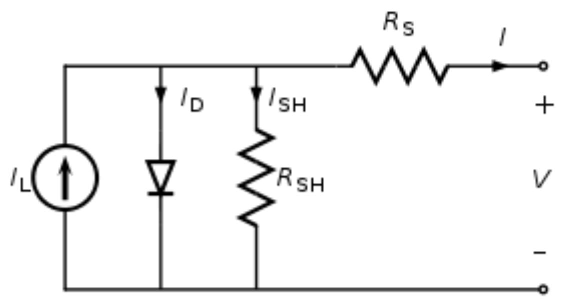


Figure 2.2. Solar cell model [17]

Another aspect that will interest us most about solar cells is the calculation of their equivalent series resistance, since knowing this value will allow us to make a maximum power transfer to the circuit to which it is connected. Subsequently in this project will be explained the procedure to follow to obtain this value. However, we can already advance that this value of resistance depends on the light that impinges on the solar cell and this behaviour is reflected in the following graph. Therefore, it will be essential to have this curve for each solar cell in particular.

TEG: Thermoelectric generators are able to produce a voltage increment with a gradient of temperature between two surfaces.

Thermoelectricity is based on a physical phenomenon called Seebeck effect, where some materials release or absorb free electrons when heating or cooling. Inverting the process, some materials can be heated or cooled due to an electric current; this is called Peltier effect.

This material used in current TEGs is bismuth-telluride semiconductor [26]. P or N doped, so it can act as electricity generator, cooler or heater. Thermoelectric materials must have low thermal conductivity to maintain the temperature gradient and high electrical conductivity to let the electrons flow easily. The more temperature gradient, that is more difference between hot part and cold port, the more voltage drop proportionally generated. Plates or surface in contact with heat or cold area must be electrically isolated [13].

Thermoelectric generators are made with the materials explained before connected electrically in series and placed thermally in parallel as it is shown in the Figure 2.3 as well as its symbol.

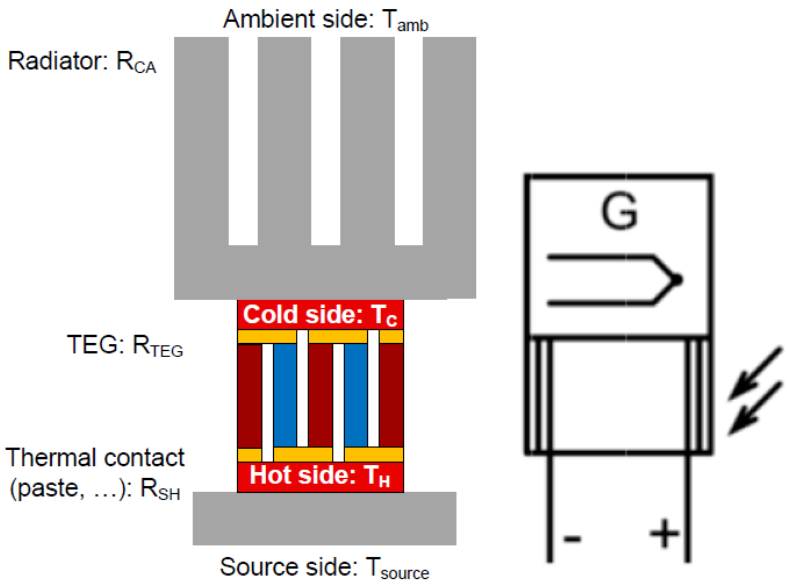


Figure 2.3. Thermoelectric generator representation and symbol [13]

These harvesters increase voltage while the n-type and p-type pairs are associated in series, if they are associated in parallel; the current increases [14].
Efficiency in TEGs is expressed as the following formula below:

$$\eta = \frac{SUPPLY\_ENERGY\_ON\_THE\_LOAD}{HEAT\_ABSORBED\_N-P\_JUNCTION} \quad \textbf{(Eq. 2.1)}$$

This term can also be expressed as a temperature function considered a merit factor (ZT):

$$ZT = \frac{\alpha^2 \sigma \Delta T}{\lambda} \qquad \textbf{(Eq. 2.2)}$$

Where:

- ΔT is the temperature difference between two TEG's surfaces
- α is the Seebek coefficient [V/K]
- σ is the electric conductivity [S/m]
- λ is the thermal conductivity [W/(m·K)]

In the next graph the relation between voltage and temperature in a TEG can be seen as example:

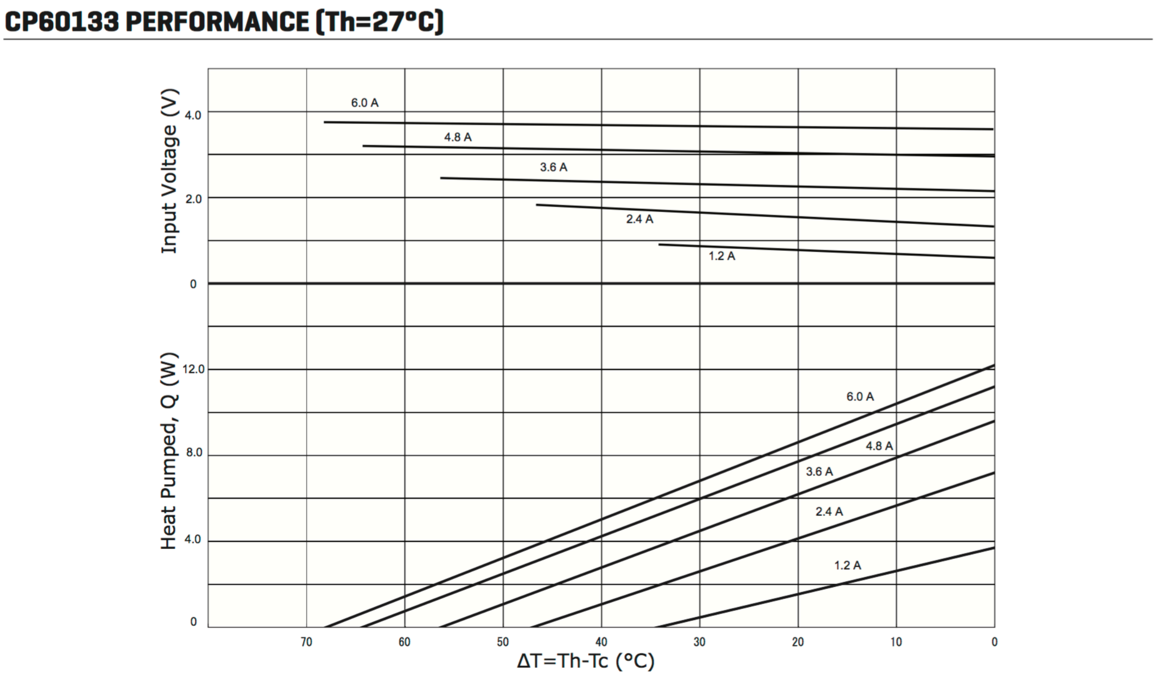


Figure 2.4. Voltage and heat vs temperature difference for CP60133 TEG [A.38]

<u>Piezoelectric</u>: is an effect which converts motion or pressure directly to a voltage increment. Piezoelectric materials are able to produce electric current due to a mechanical strain applied on it. It operates in AC (alternating current) as the pressure on it oscillates up and below 0 voltage. The same happens the other way around when some voltage is applied to a crystal and makes it oscillate. The majority of piezoelectric sources can give energy on the order of milliwatts, which means the efficiency and productivity is not high [5].

Others: there are also other devices considered as harvesters. First, AC generators can store kinetic energy coming from wind, water and ocean current in a low scale and using small turbines. Then, antennas are good collectors of microwave radiation and frequency waves. Finally, electromagnetism and induction can transform resonances and transmission fields into electricity.

In general, this other harvesting sources are not as worthwhile as the most used as harvesters, or they are not yet developed for doing so the same way as photovoltaic cells or thermoelectric generators (See representative graph in [6].

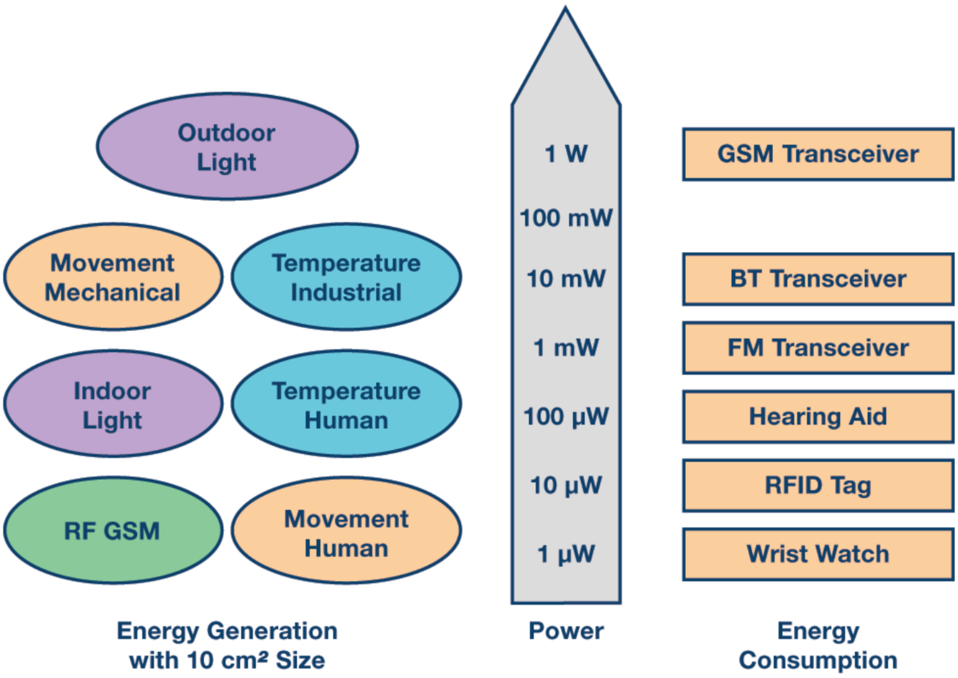


Figure 2.5. Power related to different energy sources [26]

Energy Source	Performance	Notes
Ambient light	100 mW/cm^2 (direct sunlight) 100 μW/cm^2 (illuminated office)	Common polycrystalline solar cells are 16% to 17% efficient, while standard monocrystalline cells approach 20%
Thermal	a. 60 μW/cm^2 at 5 K gradient b. 135 μW/cm^2 at 10 K gradient	Typical efficiency of thermoelectric generators are ≤ 1% for ΔT < 313 K a. Seiko Thermic wristwatch at 5 K body heat b. Quoted for a ThermoLife generator at ΔT = 10 K
Blood pressure	0.93 W at 100 mmHg	When coupled with piezoelectric generators, the power that can be generated is on the order of microwatts when loaded continuously and milliwatts when loaded intermittently
Vibration	4 μW/cm^3 (human motion-Hz) 800 μW/cm^3 (machines-kHz)	Predictions for 1-cm^3 generators; highly dependent on excitation (power tends to be proportional to ω, the driving frequency, and y_0, the input displacement)
Hand linear generator	2 mW/cm^3	Shake-driven flashlight of 3 Hz
Push button	50 μJ/N	Quoted at 3 V DC for the MIT Media Lab Device
Heel strike	118 J/cm^3	Per walking step on piezoelectric insole
Ambient wind	1 mW/cm^2	Typical average wind speed of 3 m/s in the ambient environment
Ambient radio frequency	<1 μW/cm^2	Unless near a RF transmitter
Wireless energy transfer	14 mW/cm^2	Separation distance of 2 m

Figure 2.6. Energy harvesting performance depending on the energy source [6]

2.2.2. Other Energy Harvesting Devices

A good energy harvesting implies having a harvester that transforms the energy of the environment that we want to take advantage of to electric energy, as we have seen in the previous section. The efficiency of this harvester is one of the main factors that will determine the amount of energy is obtained.

However, it is not enough to have a good harvester for this energy collection system to work well. All the components that are included in the circuit of transformation and use of this energy should favour a high efficiency. The main requirement of all of them is a low consumption. That's because the amount of energy obtained is very small and if the elements involved in the circuit consume more than adequate, the use of this type of energy does not show a good performance.

The components that can be part of the energy harvesting circuit are capacitors, diodes, transistors (MOSFET to promote low consumption), converters, etc.

In addition, it must be taken into account that the maximum power transfer is obtained when the resistance offered by the circuit is the same as that shown by the harvester. That is why it is convenient to know at all times the harvester resistance and adapt the resistance of the circuit to match the one of the harvester. There are chips that perform the MPPT (Maximum Power Point Tracking) function. These chips also have to be adapted so that their use does not harm instead of favouring a greater collection of energy. Therefore, all the devices involved in this type of circuits need a previous adaptation to be efficient.

One of the elements that play more roles in this type of applications is the boost converter. Its function is to increase the voltage it receives. Its importance lies in the fact that the voltages obtained from the sources of the environment are usually very small and need to be increased to power devices. This project will focus mainly on this element and the next section will introduce it.

2.3. Boost Converter

In the project this kind of circuit is used several times, so it is important to describe the boost converter in detail and understand how it works perfectly. Nevertheless, the concept of power electronics must be clarified.

Power electronics deal with electricity processing and it is based on switching to convert and control energy. This power conversion, regardless of the amount of Watts, aims to get the maximum efficiency and reduce the losses.

So power electronics is used to control power efficiency, this affects output voltage and current in a circuit. In energy harvesting this fact is crucial to obtain maximum power extraction from renewable energy. Power electronics used in energy harvesting applications is also called micro-power electronics as the order is in µW. This kind of application usually uses static converters, renewable energy sources and storage systems.

Boost converter is a static converter which transforms direct current on the input to different voltage on the output, also DC. These kinds of converters are also called DC/DC converters or *choppers* but power electronics also includes 3 other families of static converters, which also work with switches and optimize system's efficiency:

Rectifiers: which convert alternating current on the input in a DC voltage on the output.
Inverters: which convert a direct current into an oscillating AC voltage.
Cycloconverters: which modifies the frequency on an AC input signal to obtain a different AC voltage on the output.

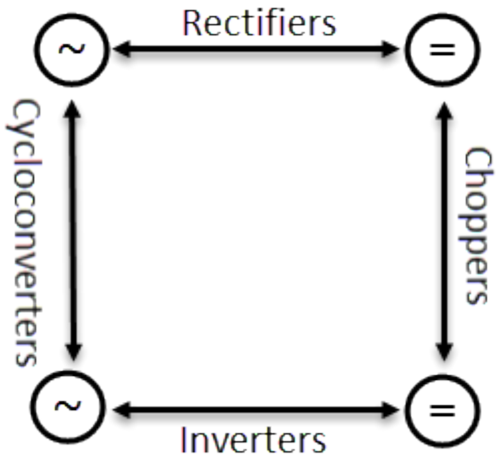


Figure 2.7. Power electronics AC DC converter types [10]

The main function of a boost converter, as it belongs to *choppers* family, is to convert an initial DC voltage given in the input to a higher C voltage on the output. That is boosting the voltage given to the circuit. The simplified circuit that makes a boost converter is shown below:

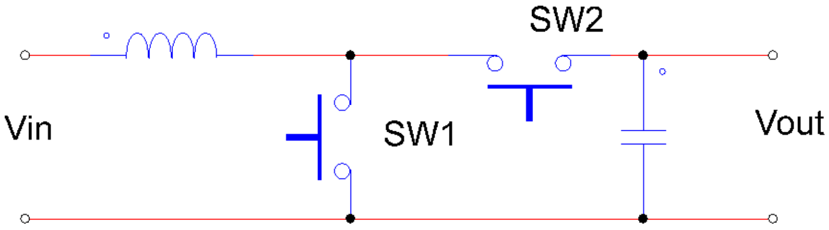


Figure 2.8. Boost converter basic structure [PSIM]

The circuit is made of two switches and one inductor. Input voltage is represented as a voltage source and output voltage is stored in a capacitor. To how a boost converter works step by step; an example with numerical values will be followed.

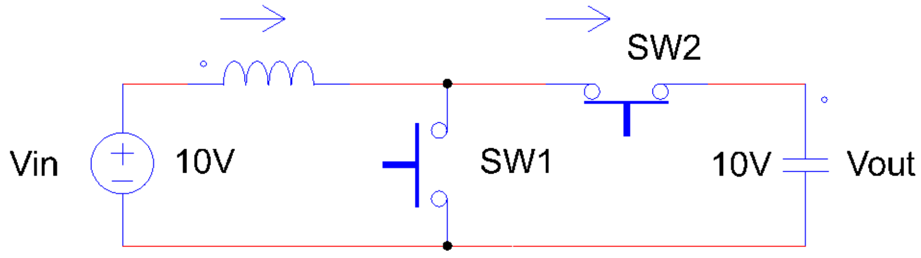


Figure 2.9. Boost converter example first step configuration [PSIM]

In start-up circuit it can be seen that SW1 is in OFF configuration (opened) and SW2 is in ON configuration (closed) so the voltage on the source is directly transferred to the output capacitor once this is completely charged.

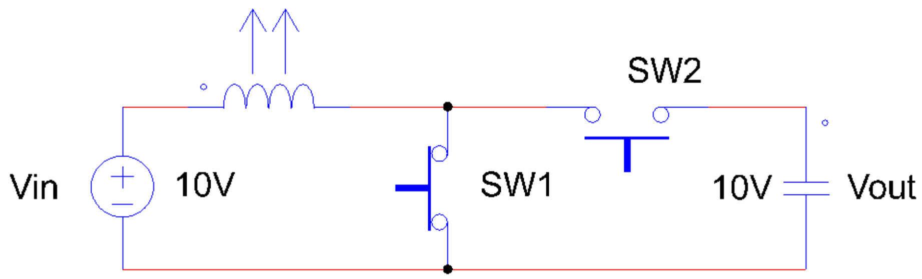


Figure 2.10. Boost converter example second step configuration [PSIM]

Then, the configurations of the complementary switches are inverted so SW1 is closed and SW2 is opened. This implies that C keeps the voltage because of the OFF state of SW2 and additionally, the source stores some energy on the inductor for a short period of time.

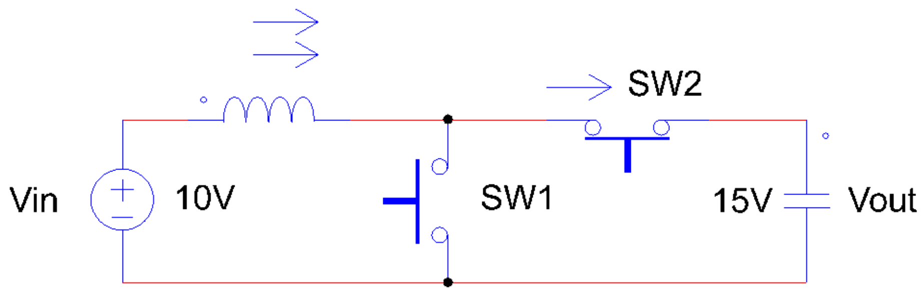


Figure 2.11. Boost converter example final step configuration [PSIM]

Finally, switches are inverted again and since current in inductors can't instantly change, current has to flow through the inductor to the capacitor because SW1 is OFF and SW2 is ON. This means adding more voltage potential to the output capacitor C.

This way, the voltage on C is higher than on the source and can be applied to a load. Moreover, complementary switching can be simplified with a controlled transistor, and a common diode which change its state automatically if current flows forwards through it or backwards to block it.

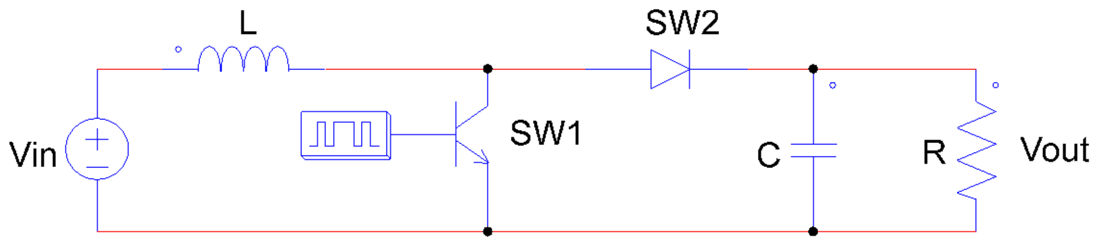


Figure 2.12. Boost converter configuration [PSIM]

Usually, the signal used to control the transistor is a pulse width modulated (PWM) binary signal where its frequency *f* is the inverse function of the total time T_s. This way, the time the signal is ON or high (T_{ON}) is represented in a percentage magnitude called duty cycle (*d*).

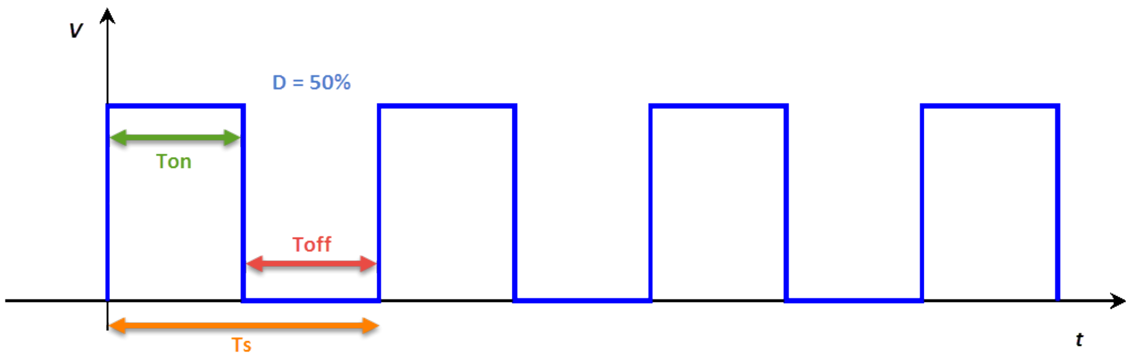


Figure 2.13. Duty cycle graphical representation [Self-made]

The duty cycle affect the input and output voltage as the time switches are closed or open implies more energy stored on the inductor.

A part from the boost converter, there are other typical circuits considered as DC/DC converters. Thus, buck converters turn an initial voltage into an output voltage with a lower value and buck-boost converter circuit can increase or decrease its input voltage depending on its duty cycle.

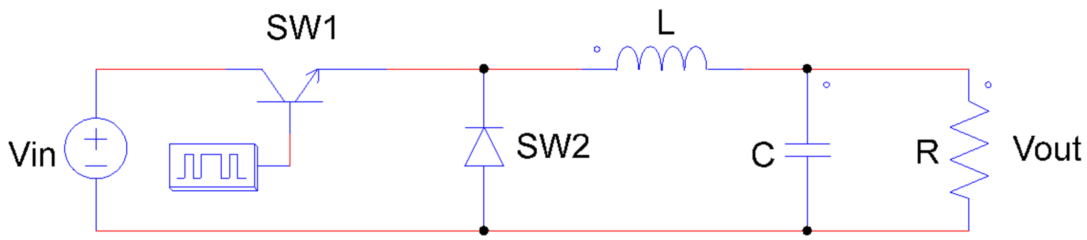


Figure 2.14. Buck converter configuration [PSIM]

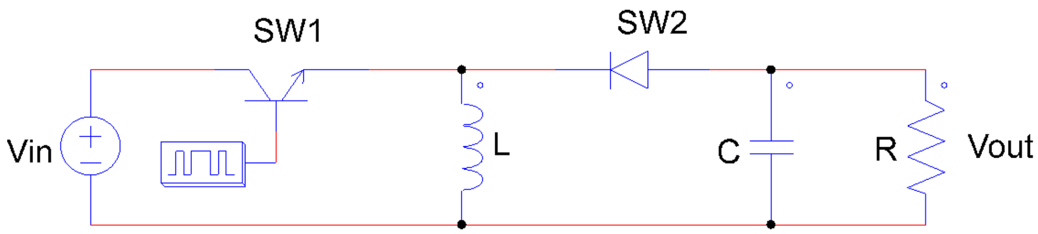


Figure 2.15. Buck-Boost converter configuration [PSIM]

The clue for this energy controlling is the precision on the switches used and their control. A switch is an element which theoretically does not affect the power circuit as it only becomes short-circuit when it is ON and becomes open-circuit when it is OFF. Real switches do affect circuits in terms of resistance, capacitance, etc. Anyway, there are different kinds of switches used for energy conversion and each of them has its own advantages and disadvantages. In the following table we can compare the most used switches with their characteristics:

Thyristor	GTO	BJT	MOSFET	IGBT
Very High Power	High Power	Medium Power	Low Power	Medium Power
Robust	Low Voltage Conducting	High Commutation Frequency	Very High Commutation Frequency	High Commutation Frequency
NO Block Control	Block Control	Block Control	Block Control	Block Control
Slow Operation	Slow Operation	High Energy Control	Low Energy Control	Low Energy Control
Unidirectional Current	Unidirectional Current	Unidirectional Current	Bidirectional Current	Unidirectional Current
	High Energy Block	Bad Response	Good Response	High Voltage Drop
	Complex Circuit	Fragile Circuit	Fragile Gate	No P-Channel

Table 1. Switch comparator table: advantages in green and disadvantages in red

In special, MOSFET transistors will have a considerable importance in the project; as it will be used in the Multiple-Input Multiple Output (MIMO) boost converter. It can be seen that MOSFET switch has plenty of advantages and it fits perfectly for low-power applications.

Diode: PN junction semiconductor which let the current flow only in one way.

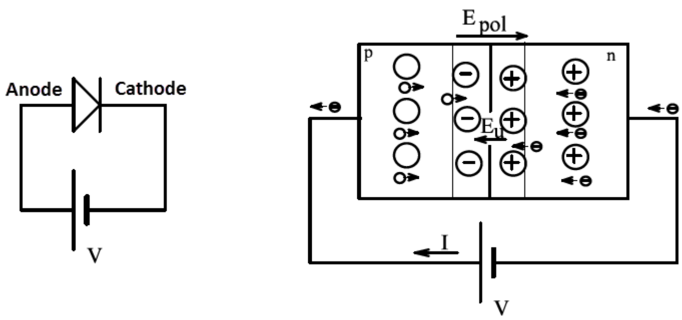


Figure 2.16. PN junction representation for a diode [18]

When a diode has a voltage potential across its terminals it can be forward (higher voltage in the anode) or reverse current (higher voltage in the cathode). The most used diode types are briefly described below:

Rectifier: conduction only in forward, 0.7V threshold voltage, AC wave rectifier applications.

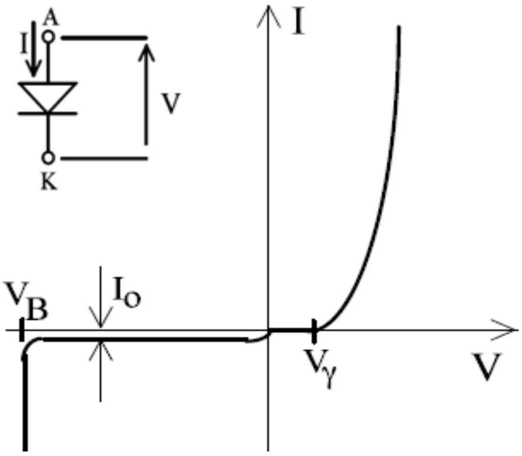


Figure 2.17. Voltage-Current graph and symbol for a rectifier diode: V_γ-threshold voltage, V_B-break voltage [18]

Zener: Voltage stabilizer, reverse conduction in –Vz threshold.

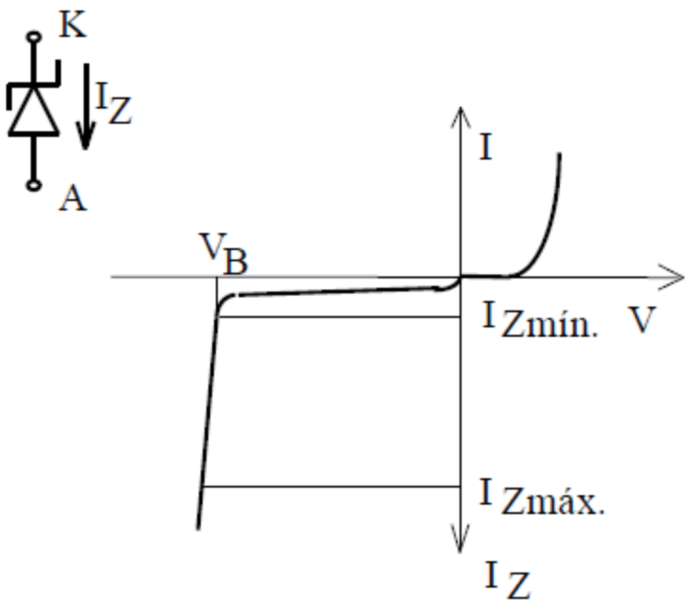


Figure 2.18. Voltage-Current graph and symbol for a zener diode: V_B-inverse voltage conduction [18]

Schottky: fast switch as it has 0.3V threshold, metal junction (aluminum).

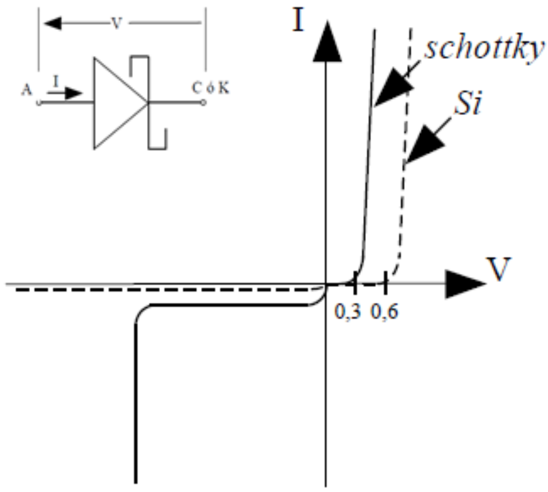


Figure 2.19. Voltage-Current graph and symbol for a schottky diode and comparison [18]

LED (Light emitting diodes): photon liberation during conduction, PN junction.

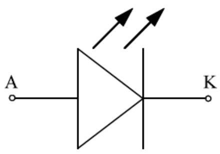


Figure 2.20. Light Emitting Diode (LED) symbol [18]

MOSFET Transistor: controlled switch using metal oxide semiconductor to be activated by an electric field. The most used are the ENRIQUECIMIENTO and there are two types; the N-Channel and the P-channel.

N-Channel is designed for forcing current to go from *drain* connection to *source* connection if the *gate* is activated with a logical '1' signal. P-Channel is designed for forcing current to go from *source* connection to *drain* connection if the *gate* is activated with a logical 'o' signal.

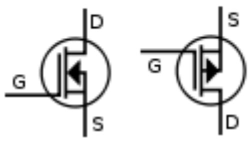


Figure 2.21. MOSFET N-Channel (left) and P-Channel (right) symbol [8]

Finally, there exists the Or-ing factor considered as a multiple input too. But it is important not confusing this phenomenon with the real adding of two inputs because is not the same as connecting two inputs and use the one that gives the higher voltage as the image is showing.

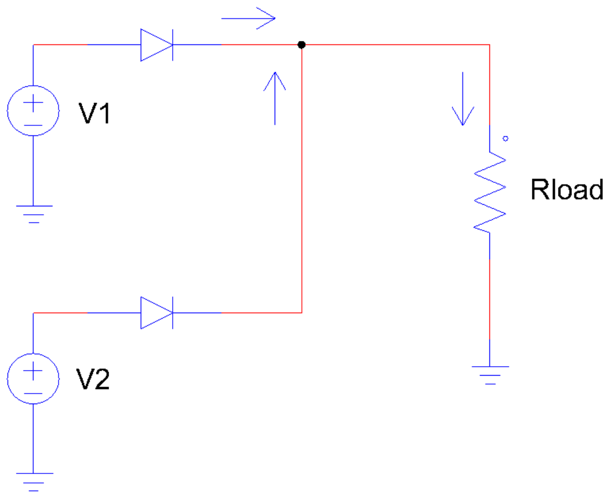


Figure 2.22. MOSFET N-Channel (left) and P-Channel (right) symbol [PSIM]

Diodes are used for not letting the higher voltage affect the other input. This effect cannot be used in this project as it will not be a real power adding. From the one hand, to sum voltages in this case, they both must be exactly the same and this is impossible in real life and the error increases when increasing the number of inputs. From the other hand, diodes placed need a minimum voltage threshold to operate so it affects on the consuming directly to the entrance. Or-ing is not the best option when adding energy for energy harvesting. In the case of two inputs, the one proportioning power will be the one which has more voltage on the output, the other inputs' energies would be lost.

Once the operation of the boost converter is known it is important to know that it has two basic modes of operation: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM).

The difference between them or the way of distinguishing them is that in MCC the current flowing through the coil is never zero, however in MCD there are instants in which the current through this inductor is zero.

Typically, when describing a boost converter a CCM is assumed and all the formulas presented are valid only for this mode. This mode of operation has been explained before. However, in this project we must know both behaviours (CCM and DCM) so they will be explained.

From [15] the main specifications for each conduction mode are obtained and presented here.

The graph that allows us to determine in which mode the circuit is working is the one that shows the relation between the current on the inductor and time. **Figure 2.23.** represents this relation in CCM, **Figure 2.24.** in the boundary between CCM and DCM and **Figure 2.25.** in DCM.

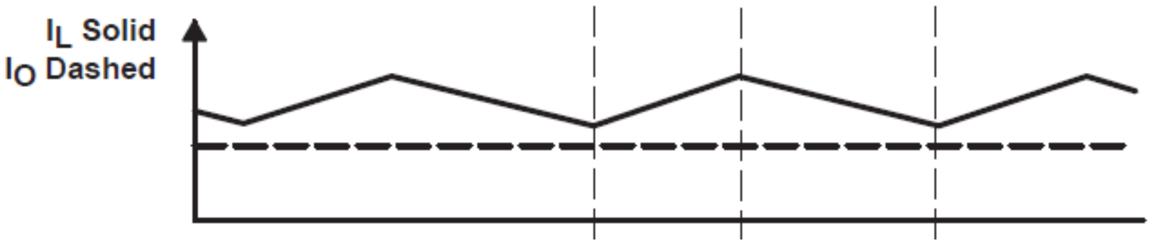


Figure 2.23. CCM: Inductor current related to time [15]

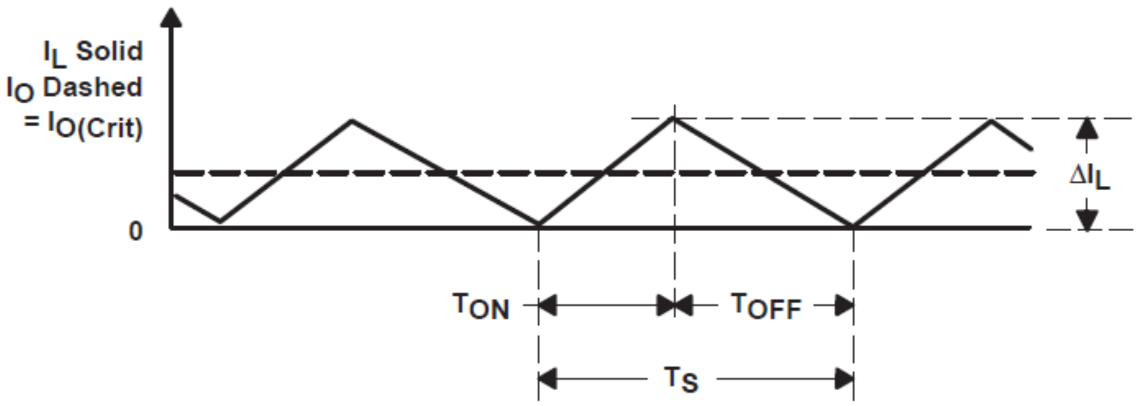


Figure 2.24. Boundary between CCM and DCM: Inductor current related to time [15]

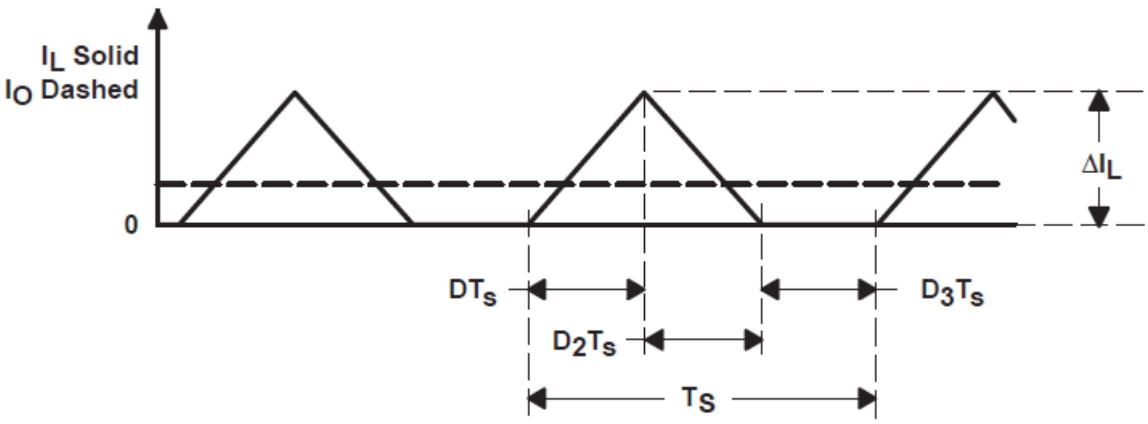


Figure 2.25. DCM: Inductor current related to time [15]

The following formulas define each conduction mode in general (from [15])

CCM:

Duration of ON state:

$$T_{ON} = D \times T_S \qquad \textbf{(Eq. 2.3)}$$

Where D is the duty cycle, T_{ON} is the time the switch is ON and T_S is the cycle time.

Duration of OFF state:

$$T_{OFF} = (1 - D) \times T_S \qquad \textbf{(Eq. 2.4)}$$

Where T_{OFF} is the switch is OFF.

Inductor current during ON state:

$$\Delta I_L(+) = \frac{V_I - (V_{DS} + I_L \times R_L)}{L} \times T_{ON} \qquad \textbf{(Eq. 2.5)}$$

Where ΔI_L (+) is the inductor ripple current, V_I is the input voltage, (V_{DS} + I_L x R_L) are losses and L the inductance value of the inductor.

Inductor current during OFF state:

$$\Delta I_L(-) = \frac{(V_O + V_d + I_L \times R_L) - V_I}{L} \times T_{OFF} \qquad \textbf{(Eq. 2.6)}$$

Where ΔI_L (-) is also the inductor ripple current, V_O is the output voltage, V_d is the diode forward voltage.

Ideal output voltage:

$$V_O = \frac{V_I}{1 - D} \qquad \textbf{(Eq. 2.7)}$$

DCM:

Duraction of ON state:

$$T_{ON} = D \times T_S \qquad \textbf{(Eq. 2.8)}$$

But in this case:

$$T_{OFF} \neq (1 - D) \times T_S \qquad \textbf{(Eq. 2.9)}$$

Inductor current during ON state:

$$\Delta I_L(+) = \frac{V_I}{L} \times T_{ON} = \frac{V_I}{L} \times D \times T_S = I_{PK} \qquad \textbf{(Eq. 2.10)}$$

Where I_{PK} is the peak inductor current.

Inductor current during OFF state:

$$\Delta I_L(-) = \frac{V_O - V_I}{L} \times T_{OFF} = \frac{V_O - V_I}{L} \times D2 \times T_S \qquad \textbf{(Eq. 2.11)}$$

Where D2 is the duty cycle for T_{OFF}.

Output voltage:

$$V_O = V_I \times \frac{1 + \sqrt{1 + \frac{4 \times D^2}{K}}}{2} \qquad \textbf{(Eq. 2.12)}$$

Where K is defined as:

$$K = \frac{2 \times L}{R \times T_S} \qquad \textbf{(Eq. 2.13)}$$

Where R is the output load.

2.4. Microcontroller

It is important to clearly understand what a microcontroller is and which roll does it take in the project. In general terms, in an electronic circuit there must be a device responsible for computations, processing, thinking and controlling. That is, what it could be called the 'brain' of the circuit, the microcontroller (μC).

The chip known as microcontroller is an integrated combination of memories ports and an electronic device from sequential digital electronics family. This peripheral components work together with the microprocessor and they are usually designed to work all together in an autonomous way. The microprocessor (μP) is used as a CPU and contains some important components internally: registers, program memory, RAM memory, decoder, control unit, ALU (arithmetical logic unit) and more, depending on the type processor [11].

There are several ways to program a microcontroller or, in other words, to communicate with it and give the correct instructions to make other parts of the circuit operate. The way of having a control with actuators on the circuit is having a closed loop with the controller. That is, knowing and understanding the results of the operations sensing them in a way or another and introducing again the information on the chip. This way, the microcontroller is able to correct and execute again with less error.

Other than that, it is important to know the difference between a MCU or microcontroller and a DSP or digital signal processing. The first one is a flexible device with much many features and program memory, whereas the second one is oriented to be an input/output device to work as a very fast calculating machine. MCUs are robust programmable small computer used for embedded applications and DSPs, on the contrary, are specialized in algorithms and mathematical operations, designed for signal improving or modifying.

The most well-known microcontroller is maybe the one used for Arduino platform, which is based on ATmega328P from Atmel. This electronic board is known worldwide as being simple to use and is a nice introduction to the microcontroller and electronics' world.

Arduino platform is considered open source, this means all schematics and layout is public so everyone can build one. The fact that everything is on internet has advantages and disadvantages. From the negative point of view, other enterprises can build the same circuit and sell it cheaper. This may decrease the sells but on the contrary, everyone has access to the platform so there are so many users and programs available on the network.

Arduino kits are programmed in a very simple way based in C programming. They usually use analogical and digital input outputs with 40mA of maximum current and a voltage range from 6V to 20V.

As another example of microcontroller is the 87C51 from Intel. This was one of the firs incorporations in electronics and it is commonly used to be programmed in assembler, C and other languages related. The μC includes CMOS technology compatible with TTL, 4K x 8bits of program EPROM memory, 128bytes x 8bits of random access memory (RAM), two 16 bits counters and *duplex* serial communication.

Another well-known and common used microcontroller is the PIC 16F887. This chip from Microchip is also programmed in C language and has the characteristics of operating up to 20MHz of frequency, 8K ROM memory, watch-dog timer and Analog/Digital converters incorporated.

In this project, MSP430 microcontroller family from Texas Instruments is chosen as it is the most recommended and suitable for energy harvesting applications. The other chips mentioned have high consumption compared with TI microcontrollers. Other competitor working also with energy harvesting applications could be Linear Technology.

2.5. Batteries

Batteries are also very important elements in energy harvesting applications.

The use of batteries has some disadvantages such as: the batteries have a certain useful life, and therefore, they will need to be replaced in a not too long time; they pollute; they usually occupy a relatively large space, etc.

But they also have a great advantage: they can store energy and provide it to the device when it needs it. This prevents the device from running out of power if the ambient energy is not constant and therefore corrects the irregularities in the amount of energy available. It is due to this great advantage that we contemplate them in this project, since its use will be very habitual in these applications. There are many types of batteries. Let's see below the main types of batteries, both primary and secondary.

Primary batteries are those that are single-use, and therefore cannot be recharged. The main types of these batteries are: Carbon-Zinc Batteries, Zinc-Chloride Batteries, Alkaline Batteries, Lithium Batteries, Lithium-Iron Disulfide Batteries, Mercury Cells, Silver Oxide Batteries and Zinc Air Batteries (See more in [9]). In the next figure a comparison of all these types of primary batteries can be seen.

TYPE (CHEMISTRY)	COMMON NAME(S)	NOMINAL CELL VOLTS	INTERNAL RESISTANCE	MAXIMUM DISCHARGE RATE	COST	PROS AND CONS	TYPICAL APPLICATIONS
Carbon-zinc	Standard-duty	1.5	Medium	Medium	Low	Low cost, various sizes, but terminal voltage drops steadily during cell life	Radios, toys, and general-purpose electrical equipment
Zinc-chloride	Heavy-duty	1.5	Low	Medium to high	Low to medium	Low cost at higher discharge rates and at lower temperature; terminal voltage still drops	Motor-driven portable devices, clocks, remote controls
Alkaline zinc-manganese dioxide	Alkaline	1.5	Very low	High	Medium to high	Better for high continuous or pulsed loads and at low temperatures, but terminal voltage drops	Photoflash units, battery shavers, digital cameras, handheld transceivers, portable CD players, etc.
Lithium-manganese dioxide	Lithium	3.0	Low	Medium to high	High	High energy density, very low self-discharge rate (excellent shelf-life), good temperature tolerance	Watches, calculators, cameras (digital and film), DMMs, and other test instruments
Zinc-mercuric oxide	Mercury cell	1.35	Low	Low	High	High energy density (compact), very flat discharge curve, good at higher temperatures	Calculators, pagers hearing aids, watches, test intruments
Zinc-silver oxide	Silver oxide cell	1.5	Low	Low	High	Very high energy density (very compact), very flat discharge curve, reasonable at lower temperatures	Calculators, pagers, hearing aids, watches test instruments
Zinc-oxygen	Zinc air cell	1.45	Medium	Low	Medium	High energy density, very lightweight, flat discharge curve, but must have access to air	Hearing aids and pagers

Figure 2.26. Primary battery comparison chart [9]

The discharge curve of these batteries is showed below:

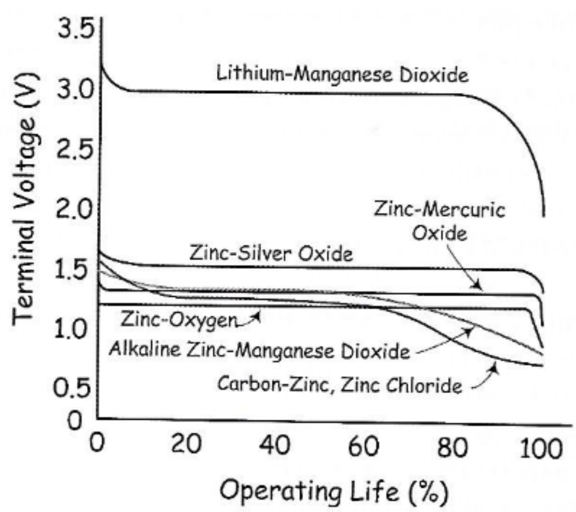


Figure 2.27. Primary battery discharge curves [9]

Secondary batteries are rechargeable and, therefore, of more than one use. The main types of these batteries are: Lead-Acid Batteries, Nickel-Cadmium (NiCad) Batteries, Nickel Metal Hydride (NiMH) Batteries, Li-Ion Batteries, Lithium Polymer (Li-Polymer) Batteries, Nickel-Zinc (NiZn) Batteries, Nickel-Iron (NiFe) Batteries and Rechargeable Alkaline-Manganese (RAM) Batteries. In the following table a comparison of all these types of secondary batteries can be seen.

TYPE (CHEMISTRY)	NOMINAL CELL VOLTS (APPROX.)	ENERGY DENSITY (Wh/Kg)	CYCLE LIFE	CHARGE TIME	MAX. DISCHARGE RATE	COST	PROS AND CONS	TYPICAL APPLICATIONS
Sealed lead-acid	2.0	Low (30)	Long (shallow cycles)	8–16 h	Medium (0.2 C)	Low	Low cost, low self-discharge, happy float charging, but prefers shallow charging	Emergency lighting, alarm systems solar power systems, wheelchairs, etc.
Rechargeable alkaline-manganese	1.5	High (75 initial)	Short to medium	2–6 h (pulsed)	Medium (0.3 C)	Low	Low cost, low self-discharge, prefer shallow cycling, no memory effect but short cycle life	Portable emergency lighting, toys, portable radios, CD players, test instruments, etc.
NiCad	1.2	Medium (40–60)	Long (deep cycles)	14–16 h (0.1 C) or <2 h with care (1 C)	High (>2 C)	Medium	Prefer deep cycling, good pulse capacity, but have memory effect, fairly high self-discharge rate, environmentally unfriendly	Portable tools and appliances, model cars and boats, data loggers, camcorders, portable transceivers, and test equipment
NiMH	1.2	High (60–80)	Medium	2–4 h	Medium (0.2–0.5 C)	Medium	Very compact energy source, but have some memory effect, high self-discharge rate	Remote control vehicles, cordless mobile phones, personal DVD and CD players, power tools
NiZn	1.65	High (>170)	Medium to high	1–2 h	—	Medium	Low cost, environmentally green, twice energy density of NiCad	Exceptional performance, no memory, long shelf-life
NiFe	1.4	High (>200)	Extremely long	Long	—	Low	High cycle life, incredibly long life up to 80 years, environmentally friendly	Forklifts and other, similar SLA-like applications, but where longevity is important
Li-ion/LiPo	3.6	Very high (>100)	Medium	3–4 h (1 C-0.03 C)	Med/high (<1 C)	High	Very compact, low maintenance, low self-discharge, but needs great care with charging	Compact cell phones and notebook PCs, digital cameras, and similar very small portable device

Figure 2.28. Rechargeable battery comparison chart [9]

The discharge curve of these batteries is showed in the next figure:

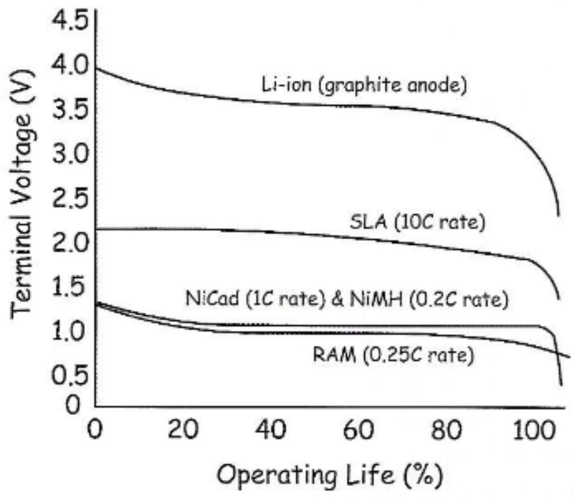


Figure 2.29. Rechargeable battery discharge curves [9]

3. State of the Art

3.1. Presently

3.1.1. Energy and Power Now

Energy is part of our society, humans are now energy dependents. It is inevitable to be part of energy transformation cycle as consumption is very high. Every daily quotidian action requires consuming some type of energy but the real clue is how this energy is distributed. At present, as it is explained before in section 2.1, fossil fuel and nuclear energy take the majority of power consumption while renewable energies are taking only the 16% in Europe. The following picture shows how energy consumption was distributed in 2010 comparing some countries from Europe.

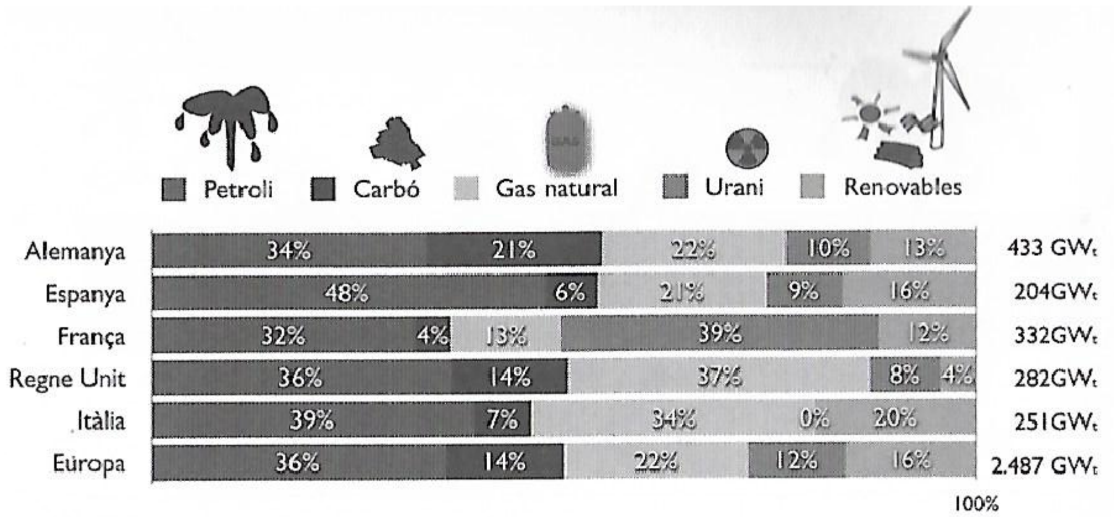


Figure 3.1. Energy consumption: Europe 2010 [12]

Analyzing the graphic, this countries has a highly dependence on some sources they do not produce. France has a high percentage in nuclear energy, Italy is highly dedicated to petroleum and United Kingdom divides its consumption in equal parts between natural gas and petroleum.

Despite the fact that it is dangerous and finite, society keeps taking profit of non-renewable energies, even the process is accelerating more and more. For sure, sooner or later there will be a necessary change.

Studies and previsions demonstrate that the world can be perfectly maintained with renewable energies. It is not only that, the thing is that humans have no choice.

Regarding non-renewable energies, it is predicted and calculated that in 30-40 years people will run out of ‘dirty’ sources. Petroleum is the most common non-renewable source used for kinetic energy presently; gasoline and diesel are the main combustibles for transport. The process to obtain that kinetic energy is a more complex process than the one used for obtaining thermal energy. Furthermore, losses in the process are huge when moving a person from one point to another using fuel, for example. Taking into account that in a car displacement, the vehicle is moving by using a low efficiency conversion in an injection engine and from all that mass, human driving represents a very low portion, efficiency is even lower. Natural gas is nowadays not easy to find and *fraquing* phenomena, which is expensive and affects the environment, is taking place. Carbon will have really harmful effects on human live if this source is ever runs out. Nuclear plants are generating disputes as the more plants existing and the more time they are working, the more dangerous become the zone where it is placed. So it is polemic in terms of security and danger. Moreover, Contamination taxes are elevated and there is still no way of transforming the residues generated in the process to any good. This means, the waste is just stored and becomes a problem of future generations.

From the other hand, renewable energies are logically growing. The percentage in countries shown in **Figure 3.1.** is not enough to afford the energetic change in the following years. Nevertheless, some sources are well treated and keep improving. Biomass is more and more used for thermal energy consumption only due to its high efficiency. An exception could be the biogas, which is considered a recycled waste and implies CO_2 emitting. Geothermal energy is common used in zones where Earth’s surface is still in movement. Heat produced by this planed can be still treated and explored to improve the method and extract more ‘clean’ energy. Power considered as low enthalpy, coming from geothermal energy, is used mainly for heating up, which is a very efficient conversion. Solar energy could be easy to obtain and easy to install as it can be seen before in 2.1.2 section. But solar stations must be placed in zones with high light; and the same happens with the wind turbines and windy zones. So the perfect combination is to design and implement stations which contain both energy collection and treating; this way sources can be complemented, time reduced and minimize losses. Frequently, the storage is the hard part when talking about solar and wind power collection. The conversions are direct but the photovoltaic effect is still improving and making efficiency higher. Wind turbines are improving as well, they can be placed on the floor or hill (*onshore*) and on the see (*offshore*). This last type has the advantage of producing electricity coming from windy zones in the ocean that are actually not utilised and without causing any visual impact, but the maintenance is harder. All this electric energy is going directly to the network, so the way to store is a real problem which must be solved and remaining energy can be combined also with hydroelectric power, which is the renewable energy most used nowadays. As disadvantages, some hydroelectric plants bring environmental impact and power obtained from ocean currents is not as much developed as it should be.

If society keeps going like this, in 2050 petroleum, uranium and natural gas will run out. Finishing carbon sources on Earth would imply harmful effects on human health so it is directly not considered. In conclusion, everything points to the development of renewable energies, specially starting with low consumption devices that can perfectly be supplied by this kind of energies.

3.1.2. Harvesters Now

The concept of energy harvesting is getting more importance in the present, both scientifically and at corporate level. When this happens, it is because we are facing a revolution. At the scientific level it is being investigated how to take advantage of all this energy in an efficient way, and therefore, not to arrive at a situation of collapse in which we depend on energies that are being exhausted. Furthermore, its use would avoid contamination and the rest of the disadvantages of non-renewable or finite energies.

At the business level, if this grows quickly, it is because energy harvesting will play a crucial role in the future. In a world that tends to interconnect, it will be necessary that the devices can be fed wirelessly and autonomously, and all companies that want to be in the world of the future want to be pioneers in this topic, as it will offer them a great competitive advantage. Visionary companies are not letting go of the opportunity and are investing in research and development of this technology. Some of the companies included in this group are: EnOcean, Pavegen, Powerfilm, Europavia, Ceramtec, Otego, Lairdtech…

3.1.3. Energy Harvesting Devices

As it is a recent relatively recent discovery, devices are developed but there is still a lot to do and explore… Talking about power supplies in general terms, for many devices it is possible to make tem wok with energy harvesting devices to store some 'clean' energy.

Regarding harvesters, there are many enterprises that work with them, do research and development and are well distributed and commercialized. In present, solar panels are becoming more and more efficient and usual in houses' roofs or even in some electronic devices to give them some clean charge. The efficiency keeps going between 10% and 20% in the most domestic examples. An actual view of the leaders companies regarding solar panels could be the following [18].

Manufacturer	Model	Type	Module Efficiency
SunPower	X21-345	Monocrystalline	21.5%
Ja Solar	JAC M6PA-4	Monocrystalline	20.9%
Sanyo	HIT Double 195	Monocrystalline	20.5%
SunPower	327-320	Monocrystalline	20.4%
AUO	SunForte PM318B00	Monocrystalline	19.5%

Figure 3.2. Leading brands in efficient solar panels [19]

There are some well-known enterprises in energy harvesting world as EnOcean which has many interesting applications with solar energy. Even solar cells are going further with manufacturing becoming thin and flexible as Power Film enterprise does.

TEGs will be used to collect wasted heat from engines and pipes and convert to electricity. Thermoelectric generators have evolved lately [13]: first generation of TEGs was assembled automatically and was based on bulk; multiple elements of 1mm of size, second generation (2010) was similar but based on thin-films; sized on µm, and third generation (2014) combines new structures and materials sized in nanostructures.

TEGs are used for oil and gas process control, wireless nodes working autonomously, instrumentation supplying for portable cases and automation. TEGs they have been growing but it is not that extended and well-known due to their low efficiency, between 5% and 10% [14]. Power generated is ordered in µW or mW.

Some available products are analyzed in order to have a general view of power achieved in this devices and its price. As it is logical, price increases when output power coming from the TEG and surface is bigger. Higher module can reach 30W of power, but this amount of energy can only be achieved with a 200º temperature gradient or with a combination of many TEGs. Compared with solar cells, thermoelectric generators are considered more expensive regarding the power obtained.
Some enterprises that work with thermoelectric devices and are specialized in energy harvesting applications are: *Marlow*, *Thermal Electronics Corporation*, *OTEGO*, *European Thermodynamics*…

Piezoelectric systems are used to store energy coming from human movement as footsteps for instance. They are also related with vibration and can be combined with some human behaviors. In terms of energy harvesting, piezoelectric effect is used for wireless supply buttons, which get the power to work from this harvesters.

In general, harvester devices is not much explored and developed; there is still a lot of work to do to obtain the energy from all sources explained before and to maximize their efficiency.

Boost converters are used to power up an input voltage, commonly for heating applications. In energy harvesting world are usually implemented in optimized circuits with low consume elements and parameters.

A common circuit like that contains electrolytic capacitors to store the input and output voltage. It also includes ceramic capacitors to protect them from non-desired high frequency signals and interferences. Also, switches are considered to be as much efficient as possible and to consume the less allowed so the following considerations must be taken into account when designing a boost converter circuit for micro-power electronics applications. From the one hand, non-controlled diode switch must have a fast response and a very low threshold voltage so a Schottky diode is the best option. From the other hand, controlled switch can't be a simple BJT transistor as its consumption is relatively high; MOSFET transistors are better considered as they are controlled by voltage and consumption is lower. Furthermore, integrated boost converter circuits are thought to automatically regulate small changes in the load in the output so that switching can be compensated.

Microcontrollers are also becoming more and more self-sufficient in terms of energy. Its consumption is reduced when talking about energy harvesting and switches that have to deal with them are typically voltage-controlled as MOSFETs for example.

3.1.4. Energy Harvesting Now

Talking about how energy harvesting is currently being used implies distinguishing between two branches: the scientific one and the real one. The scientist is the one who investigates all the possibilities. The real branch, which often coincides with the business branch, is the one that chooses from all the investigated options which of them are worthwhile (are efficient and can give good results when used).

The scientific world is following many lines of investigation that study different harvesters which can be used and different ways to profit the energy obtained.

Most of the options that currently exist that combine different types of energy, choose at each instant the harvester that brings more energy and only that input is used **Figure 3.3.** However, there are also other researches that want to use the energy of all inputs and propose a way to add them. A very interesting article that will be taken as reference is [1]. But there are other options as: [20], [21], [22], [23], [24] and [25].

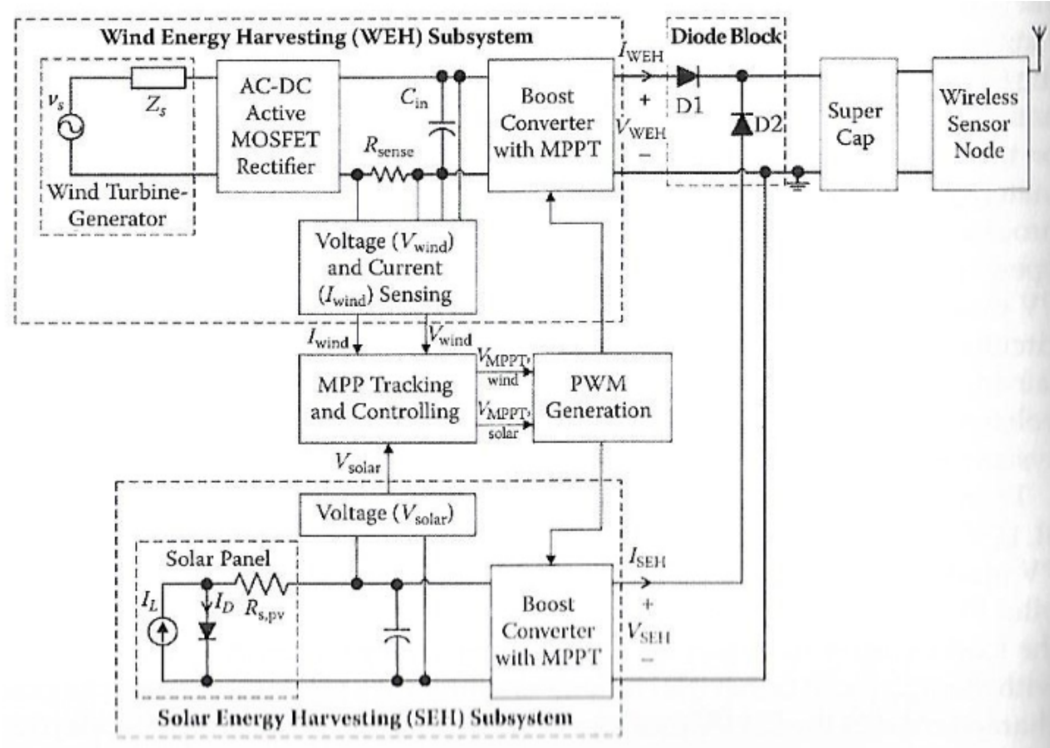


Figure 3.3. Block diagram of an hybrid OR-ing system: wind and solar [7]

In the business world, those currently in use are basically solar and thermal (solar cells and TEGs), in addition to piezoelectric in many cases (vibrations). These types of energy are used because they are currently the most efficient.

3.2. Alternative Options

The idea of this project is to design a boost converter that adds the energies obtained from the surroundings. Therefore, the chosen option is the use of renewable energies and the sum of them through an innovative circuit. However, there are other options that will be analysed in this section and can also offer good results.

3.2.1. Use of other Energy Sources

Of course there are many applications in which energy harvesting is not an option. The direct competitor of low power supplying is the high power or current one. That is, using electricity network and being energy dependent. Going further and taking into account that energy in the network can also be supplied by renewable sources, is not that bad compared to energy harvesting, which is exactly the same but in a lower scale.

The real problem comes when the electricity on the network comes from uranium, petroleum and all non-renewable sources explained before with all problems that they have as a consequence.

Energy harvesting is about collecting the energy that can be collected to supply devices that can be working with that enough amount of power. Because the energy is going to be there anyway, the clue is how to take advantage of that specifically.

Moreover, in Spain for example, being partially connected to the electricity network and producing your own energy using free renewable energy could be a problem, sometimes this option can deal with fees and government. Being totally out of the network is not easy but possible, so there is no sense on being dependent when there is the possibility to get some portability, and living outside of the monopoly and infrastructure.

Finally, up in energy terms, a good option for the transition from finite sources to renewable ones is the combination of both; hybrid cars for example.

3.2.2. Energy Harvesting as Usual

All the information in section 3.1.4 could be included here. But there will be detailed the closest alternatives to our application and it will be explained why these alternatives have not been chosen.

The first great alternative is to take in each moment the energy of the source that generates more. This has the advantage that you do not need a control to make a switching (necessary in the case of adding energies) and depending on the case this can save energy (in case you consume more in the control than what you save).

Another great alternative is to charge a different battery for each type of power source. In this case it takes advantage of all the energy, but the drawback is the space they occupy.

Our option has been chosen because of the belief that a circuit efficient enough to save more energy than wasted in its control can be implemented, and because it is believed that the use of space is very important, since the devices fed with this type of energy are usually very small.

4. System Architecture

In this chapter the structure of the circuit is explained in detail. Each section describes a different part of the circuit and its features to be more understandable.

4.1. General View

As it has been previously mentioned, the device designed, studied, calculated and implemented in this project has the following goal: obtaining the energy from the environment or renewable sources. As it is explained in chapter 3, nowadays there are many ways to use this kind of energy, all of them gathered in the concept of energy harvesting.

The proposed circuit is thought as an innovation because not only expects to use the energy collected to store the energy in batteries or to supply it to low-power devices, the real discovery is the possibility to sum up power coming from difference sources.

As in the state of the art (chapter 3) is commented, energy harvesting devices, when having more than one input, they use only the one that has more power, following the *Or-ing* concept. This means that the energy coming from the other secondary sources is lost in many cases. The present circuit is able to sum power coming from multiple sources and store all this energy in a battery or directly applied to a load.

To be able to do so, the circuit must fulfil the following requirements:

- Energy collecting using harvesters.
- Reconditioning of that energy obtained.
- Circuit optimization to maximize power transmission (MPT)
- Power reunion coming from different input sources.
- Correct load feeding or battery storage.

In the present project, the circuit is taking only two inputs to show how the circuit works and to easy demonstrate how the power from both sources is used and collected. The implementation and testing is also done with two inputs, however in future work (chapter 13) more than two inputs are considered and explained.

Once it is known that the MIMO Boost converter will have the parameters written before, the whole circuit will be divided in 4 modules. Each module will have a different function in the circuit clearly distinct and a part from that, as a matter of energy source coming first; there are also the harvesters. And at the end of the circuit, as an output, there is the battery, to store the energy collected or the load, as a possible circuit device to be powered.

Continuing with this, here comes a brief explanation of all elements on the circuit. The order will follow a little bit the path energy follows though it. 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 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. Module 2 will do the same thing with the energy coming from the solar cell. Both modules will boost voltage and will adjust the impedance according to harvester's features and power giving. 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.

The following bloc diagram illustrates the circuit studied in this project represented as modules:

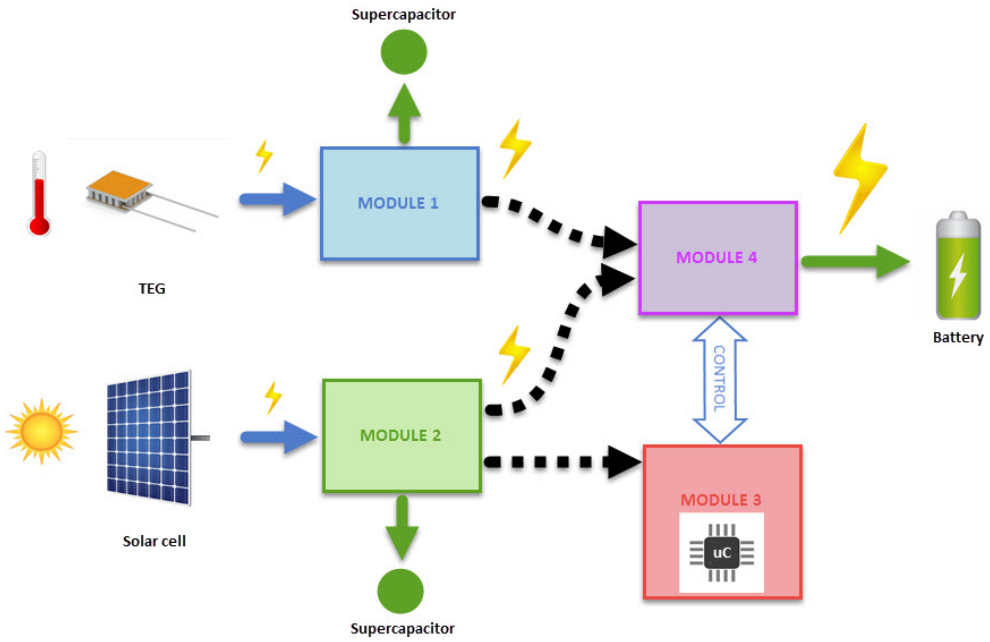


Figure 4.1. General block diagram [Self-made]

4.2. Module 1

This module is adapted to the harvester that gives the energy, the thermoelectric generator. These elements are described and explained in theoretical background (chapter 2), but now it is crucial to represent the electrical model to make the corresponding study for the module 1 and to obtain the maximum efficiency and voltage amplification. The best model that represents a TEG is a voltage source with a fixed value resistor in series.

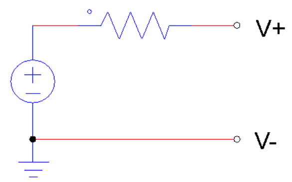


Figure 4.2. Thermoelectric generator electrical model [PSIM]

Following the Maximum Power Transfer (MPT) theorem, the maximum efficiency takes place when the load some source is feeding has the same ohm value as the inner resistance of that source. In this case, R_{TEG} should have same value as the load this harvesting is giving the power to. This is the main goal of this module. Then, to design the module circuit, it is necessary to know first the internal resistance associated to the TEG used. Also , taking into account that each thermoelectric generator has its own inner series resistor and that this resistance value is not depending on temperature or other factors, but fix.

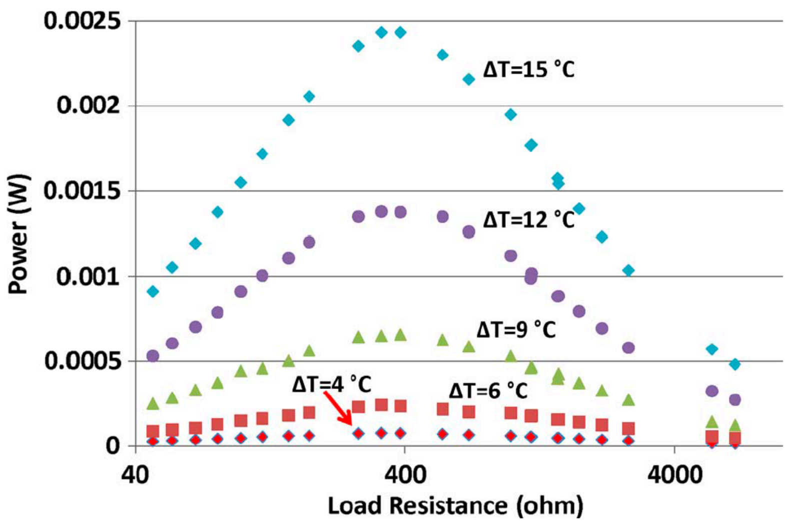


Figure 4.3. Power versus resistance for various temperature differences from MPG-D751 [1]

To know the exact real value of this resistor it is recommended to do a test which is briefly described below.

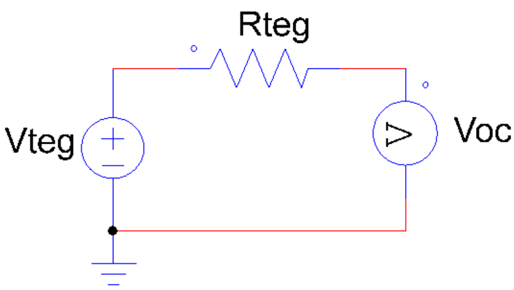


Figure 4.4. TEG model measured in open circuit [Self-made]

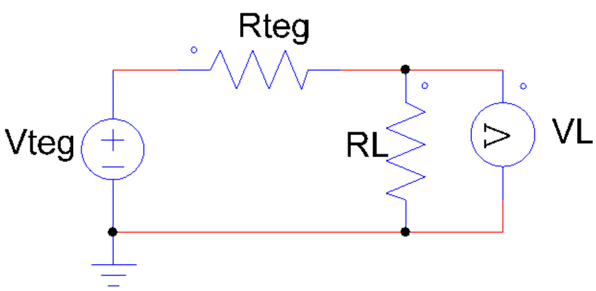


Figure 4.5. TEG model measured with a load [Self-made]

The steps are:

1. Measure the voltage in open circuit directly to the harvester (V_{OC}). **Figure 4.4.**
2. Measure the voltage in the load coming from a known resistor (V_L, R_L) **Figure 4.5.**
3. Calculate the desired taking into account the resulting circuit as a voltage divider (R_{TEG}).

$$R_{teg} = R_L \times \frac{V_{OC} - V_L}{V_L} \qquad \textbf{(Eq. 4.1)}$$

This way, R_{TEG} can be obtained and applied to the final conclusion regarding the circuit, which aims to have same ohm value following $R_{EQ} = R_{TEG}$ to have the maximum power transmission. Module 1 will try all time to change the circuit's equivalent resistor to be the same as the one TEG harvester has in series as well as adjusting boosted voltage.

All this features can be done by a boost converter from Texas Instruments brand called BQ25505 [3]. Moreover, this chip has very low consumption and it is designed precisely for energy harvesting applications. An important aspect in this project is to understand how this integrated boost converter works and to know some of its basic features that are explained below. However, it is highly recommended to check the datasheet to expand the information [3] especially when working with the chip.

Basic specifications, inputs and outputs:

- V_{IN}: voltage on the input, coming directly from the harvester.
- V_{STOR}: voltage output designed to connect a load on it.
- V_{BAT_SEC}: voltage output designed to connect a storage element as a supercapacitor or a secondary battery.

Despite there are two outputs, each dedicated for a different type of element to feed, V_{STOR} has preference. That means module 1 tries all time to give the energy to the load in V_{STOR}, and only when there is enough power to supply the load, V_{BAT} starts giving the same voltage value as V_{STOR} to store the remaining power to some secondary battery or supercapacitor.

The same happens the other way around, when battery is charged and V_{STOR} gives not enough power, as both outputs are connected, load in V_{STOR} is taking power from the battery in V_{BAT_SEC} until it reaches a value set by the user which protects the battery of being in danger of damaging by under voltage.

To sum up:

$V_{BAT\_SEC} = V_{STOR}$ if $V_{BAT\_SEC} > V_{UV}$

where V_{UV} is a voltage threshold chosen by the user.

In the next section other outputs from BQ25505 will be known, but those are not necessary for TEG optimisation and boosting. This chip is not all integrated; some values must be calculated, chosen and installed outside of the chip. With this elements, maximum power transfer (MPT) can be set; and in the case of thermoelectric generator, 50% is the optimal one as it can be seen before with R_{TEG}=R_{EQ}. The selection and changes available in the outer components of the chip will be explained later in components selection (chapter 7).

The following scheme shows the basic circuit given in module 1.

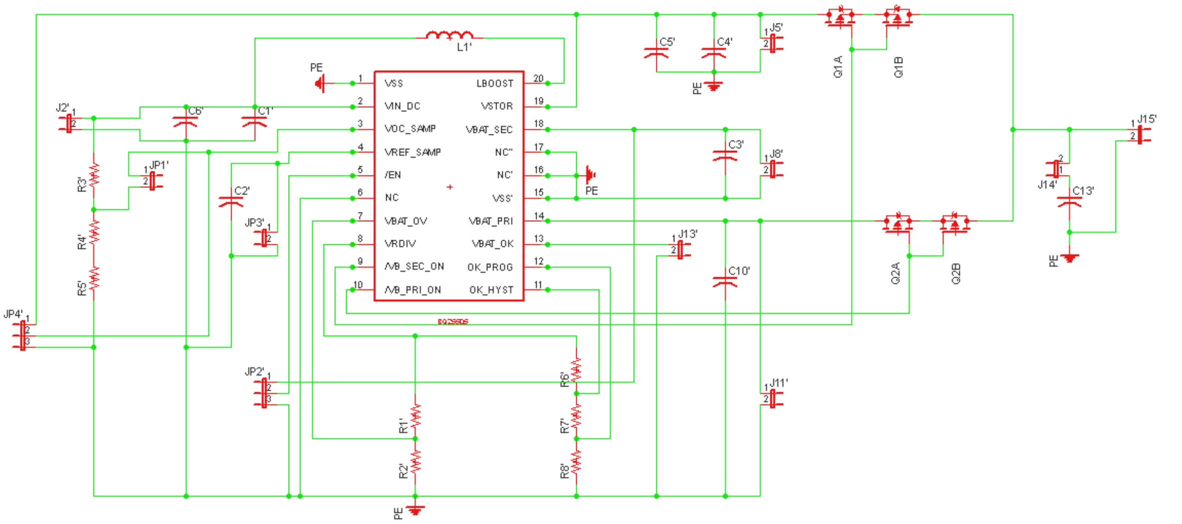


Figure 4.6. Schematic diagram from module 1 [EAGLE]

4.3. Module 2

This part of the circuit works similar to module 1 and it is using the same chip BQ25505, but this time the boost converter is adapted to a solar cell input. That is arranging itself to solar energy behaviour. Again the main goal is to maximize the power transfer and boost the voltage given by the solar cell.

Regarding electrical model, photovoltaic cell is considered as a current source with a series resistor R_S and another resistor in parallel R_{SH} as it can be seen in the next figure.

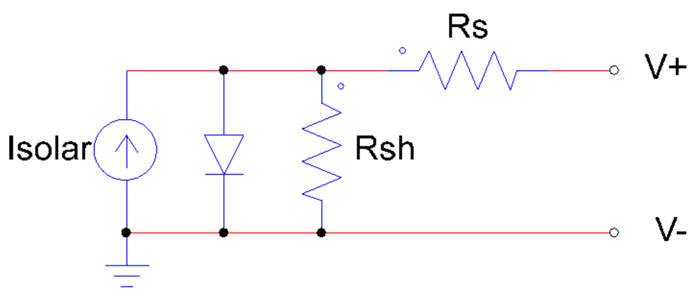


Figure 4.7. Solar cell electrical model [PSIM]

Representing this module will make the user understand how the solar cell behaves and how to get the maximum power from it. The MPT theorem works in a different way for this harvester as it is not a constant value, so here it is necessary to apply the Maximum Power Point Tracking.

A good example of a curve representing the resistance difference depending on the light received on the cell is shown in the following figure.

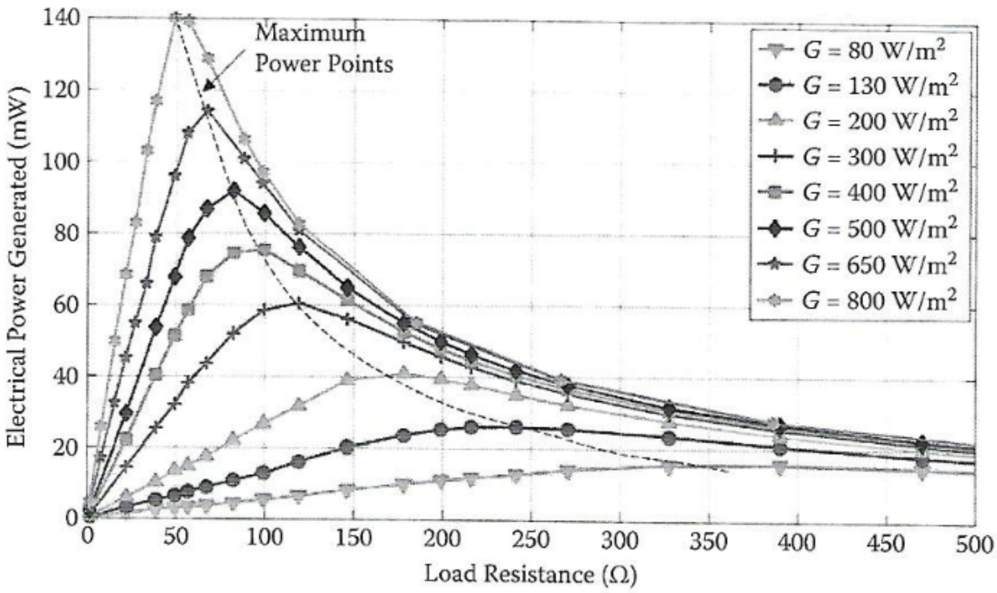


Figure 4.8. Power curves of a solar panel over load resistances' range [7]

In the curve, the more incidental light means lower value of optimal R_{EQ}, and this graphic must be followed in order to obtain the maximum power transfer from the solar cell. The equivalent resistor in module 2 will be adjusted depending on the light on the photovoltaic cell. Notice that this curve is so different from the one in TEG in the previous chapter.

The steps to get the optimal equivalent resistance follow firstly the MPPT curve to know which resistance value corresponds to each value of electrical power generated in mW. Also considering that each solar cell model has its own MPPT curve associated. To get this real path a test must be done, as with the TEG before, but this time the results will be used to draw the curve mentioned before.

This test consists, in general terms, in obtaining power transferred data in different incident light situations where these two values are changing. So finally a kind of sweep can finally represent a curve.

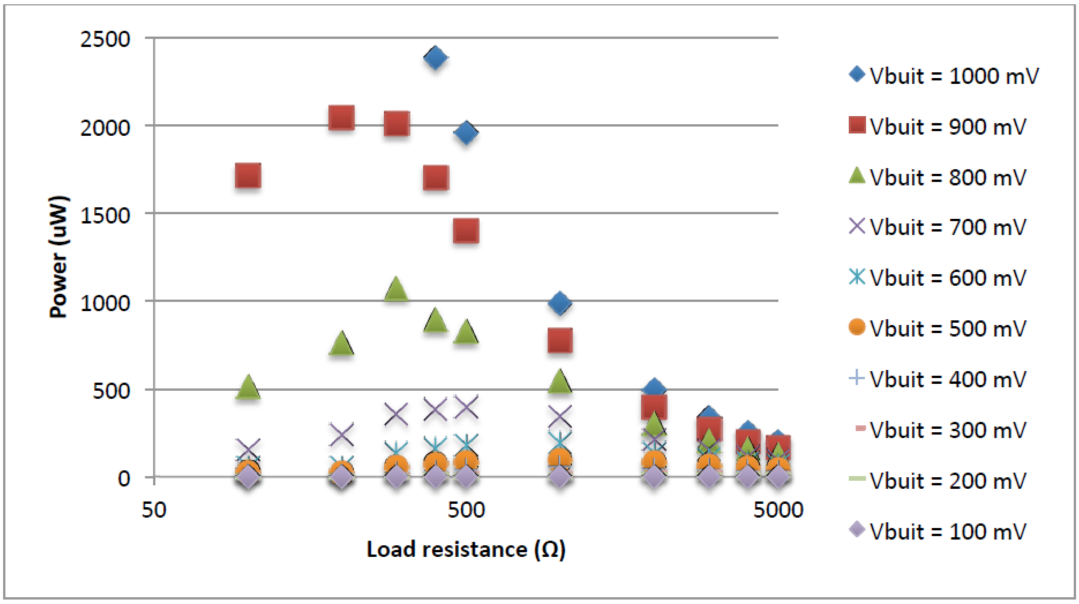


Figure 4.9. Generated power related to load resistance in the solar cell depending on incident light [A.10]

This test can be followed step by step in detail in annex [A.10].

Once features from the harvester are clear, module 2 will try to get the optimal results from solar input. For that, BQ25505 is fair and appropriate again. Basic specifications, which have been explained in the previous chapter, are also used in this module. But there are also other functions the chip is able to do which are useful for module 2.

As it can be seen in chapter 2.2.1, a thermo electric generator is not giving as much power as a photovoltaic cell does. So between module 1 and module 2, the second one is better to distribute and divide the energy. Then, module 2, taking energy from solar cell, will be feeding module 3 as well as giving power to be added in module 4. So V_{IN} introduces power coming by the harvester, V_{STOR} gives the power to be added in module 4 and V_{BAT_SEC} stores the power the load in V_{STOR} does not need in any storage element as in module 1.

But, there is advanced output called V_{OR}, which ensures the supply of the device connected between the terminals; in this case will ensure that module 3, which controls the whole circuit, is always powered on. This output is designed to feed the parts of the circuit that can't turn off, the microprocessor for example.

To give always power through V_{OR}, the voltage supplied through this output will be always V_{STOR}. And in the case the source in module 2 gives not enough energy to feed V_{STOR}, V_{OR} will get the voltage from another source called V_{BAT_PRI}.

To sum up:

$V_{OR} = V_{STOR}$ if $V_{STOR} > V_{NEEDED}$

$V_{OR} = V_{BAT\_PRI}$ if $V_{STOR} < V_{NEEDED}$

The advanced input used in module 2 that makes a difference compared with module 1 is V_{BAT_PRI} input. This includes a primary battery, which can be used in the extreme case of V_{IN} not being enough for the load in V_{OR}. With all this, V_{OR} will always have somewhere to take power from and to be the supply for the module 3.

Concluding with module 2, the main functions it does are the following:

- Boosting the voltage coming from the solar cell.
- Doing MPPT
- Giving non-stop energy to the microcontroller in module 3, which have to be working all time to make the whole circuit stable, taking power from the module itself (V_{STOR}) or from an external primary battery attached (V_{BAT_PRI}).

It is important to take into account that the external components around BQ25505 must be set to adjust the maximum power transfer from the solar cell. The general percentage of this MPT for solar cells is 80% and all computations will be explained in detail in main computations (section 5).

The schematic diagram from this module is the same as in module 1. (**Figure 4.6.**)

4.4. Module 3

The 'brain' of the whole circuit stays in this module. It contains the microcontroller that decides everything in the system, following instructions the used programs in the chip. This module 3 organisation implies being prepared for signal receiving and processing coming from modules 1 and 2, and signals executing to the module 4 to guarantee the optimal circuit working.

All this operations are possible thanks to the presence of a microcontroller (µC) in the module. This component must be chosen to have ultra low consumption because, if the power consumed to make this control and processing is higher than the result of generating energy, the system will not work and the chip will be useless. So before using the microcontroller, the fact it is worthwhile must be studied. This factor will also determine if the system will use a microcontroller or not.

For the present project, the ultra-low power microcontroller MSP430 has been the best option to the energy harvesting application. The detailed description will go further in the controller in the chapter Components Selection (chapter 7) but the main function of this controller will be controlling the switching of module 4. That is, the signals turning ON and OFF the switches in the last module.

Mainly, it will be three signals to control by modifying the duty cycle: the signal controlling the switch that determines the main operation of the boost, the signal controlling the switch that let voltage coming from module 1 in and the signal controlling the switch that let the voltage coming from module 2 in. This switching operation will be seen in deep in Main Computations (chapter 5).

In addition, module 3 will have a supercapacitor on it entrance to store the voltage coming to power the microcontroller. This will also help to keep the chip functioning all time.

The following picture shows the configuration of module 3.

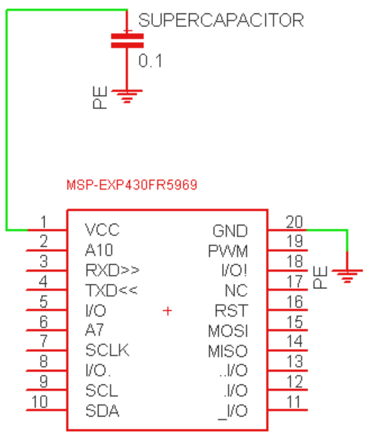


Figure 4.10. Schematic diagram from module 3 [EAGLE]

4.5. Module 4

This is the harder part of the whole system because it has all innovation features and thoughts. The power adding fact can really be a revolution in energy harvesting state of the art and future applications.

Module 4 is a multiple input boost converter that is the responsible of giving the proper voltage to the output by adding all inputs in the circuit. The way this module works is the same as a normal boost, already explained in section 2.3 but with some modifications to make it multiple-input. As it is explained in detail in the theoretical background, boost configuration stores energy in the output capacitor and rises up this power with energy produced by the inductor. In the multiple input case, some complementary switches change the input sequentially without modifying the boost structure. These switches; which allow each input to be the input in the boost and therefore give the energy to the circuit, are controlled by module 3 as well as the switch responsible for boosting energy by duty cycle.

Every time an input is connected, this power coming to the boost converter is rising as a normal boost. Other inputs that are not connected would be losing its energy if it weren't for a parallel capacitor attached in the input; this way this voltage that is not yet connected to the circuit is stored in the capacitor. See the following figure.

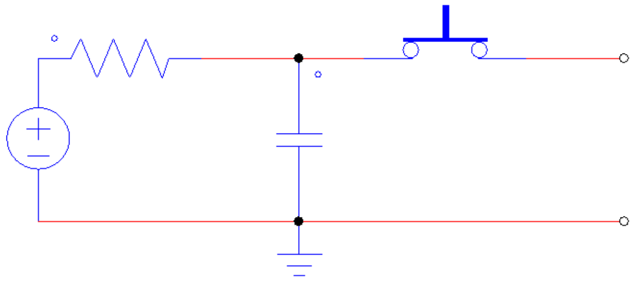


Figure 4.11. Capacitor in parallel in a boost converter input [PSIM]

This clue element must have enough capacitance to store voltage coming from the non-connected input and, at the same time, it should not reach the full storage for not loosing energy. If this capacitor would not be connected, the circuit would not add energy as the non-connected inputs would have nowhere to store its energy and that power would be lost. So every input has a capacitor to store its power when the input is not connected, it can be seen in the next picture:

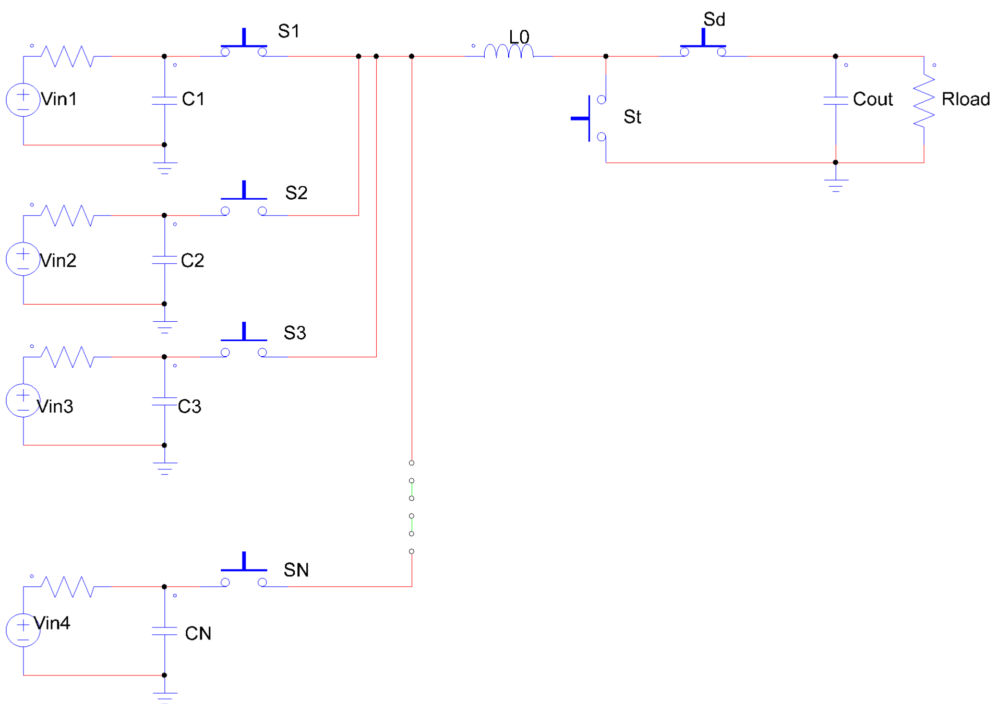


Figure 4.12. Multiple input boost converter with N inputs [PSIM]

To add powers coming from different sources it is better to have similar voltage values on all inputs. This job is done by BQ25505 in modules 1 and 2, they boost voltage to give approximately 4V on the input of module 4. The elements in that boost must consume the less as possible and they are following same features than a normal boost. As the present project uses only two inputs, the configuration of module 4 will be the following:

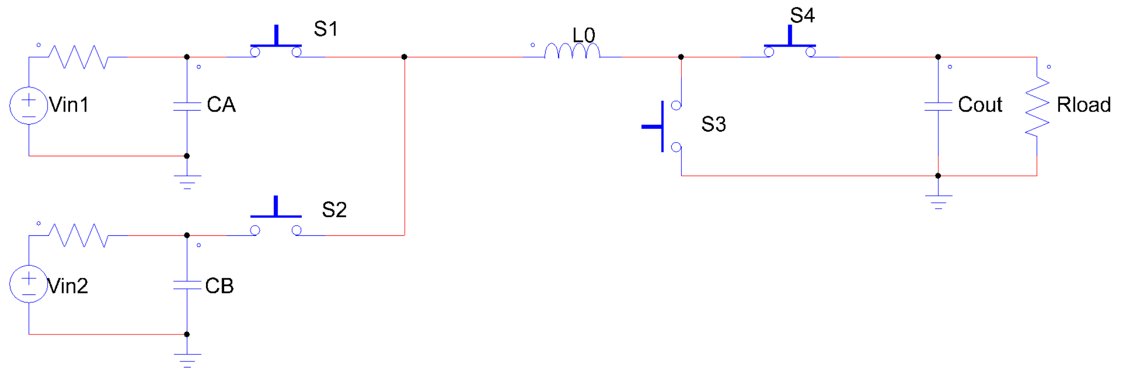


Figure 4.13. Double input boost converter [EAGLE]

Regarding switches and following the previous figure:

- S4 will be a diode to let the current flow only in one way and block to make the output capacitor discharge over the load only. This switching is automatic in the diode as depends on the voltage potential between anode and cathode.

- S3 will be implemented as a N-Channel MOSFET Transistor because it has the source directly connected to ground and this implies the switch to be activated with a logic '1' referenced to the same ground signal (short circuit), and deactivated by a logic '0' on the gate (open circuit). Furthermore, MOSFET Transistors are easy to turn ON and work with electric-field so the consume is very low. As the diode works automatically, module 3 affects on both S3 and S4 switches only by controlling the transistor; as it happens also with the normal boost configuration.

- S1 and S2 will be implemented as P-Channel MOSFET Transistors and they connect each input to the circuit in a complementary way. Again, they are a very low consumption operation switches. This kind of transistors are activated with a logic '0' signal on the gate (short circuit) and deactivated with a logic '1' signal (open circuit). They are P-Channel as in the drain it cannot be any fix voltage ensured, on the contrary, the input voltage is known so a voltage difference between gate and source can be easily forced. This will be specially taken into account when programming the switching considering that S1 and S2 activation signals are GND signals and S3 activation signal is Vcc, generally speaking.

Once the switching functioning is known, it must be clarified that switching in module 4 will be controlled be module 3 in the following way:

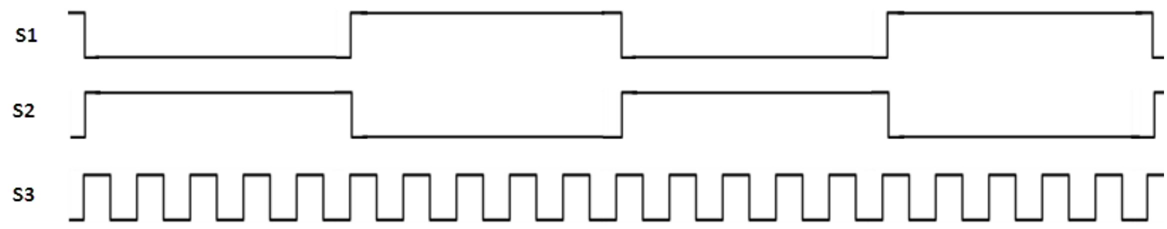


Figure 4.14. Complementary switching in module 4 [Self-made]

For instance, considering a duty cycle of D=50% in S3; the one responsible of the boost itself, S1 and S2 must ensure that there will be always one input connected. That is D_1=50% and D_2=50%, and f_1= f_2 is 10 times lower than f_3. All this parameters will be studied in Main Computations (chapter 5).

From the one hand, multiple inputs are the two used in the project (solar and thermoelectric), but it can be as much as user can implement in the circuit following same computations and structure. From the other hand, as an output there is the one in module 4, which is the most probably a rechargeable battery, and also there are two more storage elements placed in module 1 and 2 considered as outputs as well. The supercapacitors or secondary batteries placed in the input modules, which store energy not used by the module 4 and either module 3, are also elements that can give later on energy for other applications and uses. This factor is what makes the system in the present project called MIMO (multiple input multiple output) boost converter.

Finally, in the following scheme the module 4 circuit configuration can be seen:

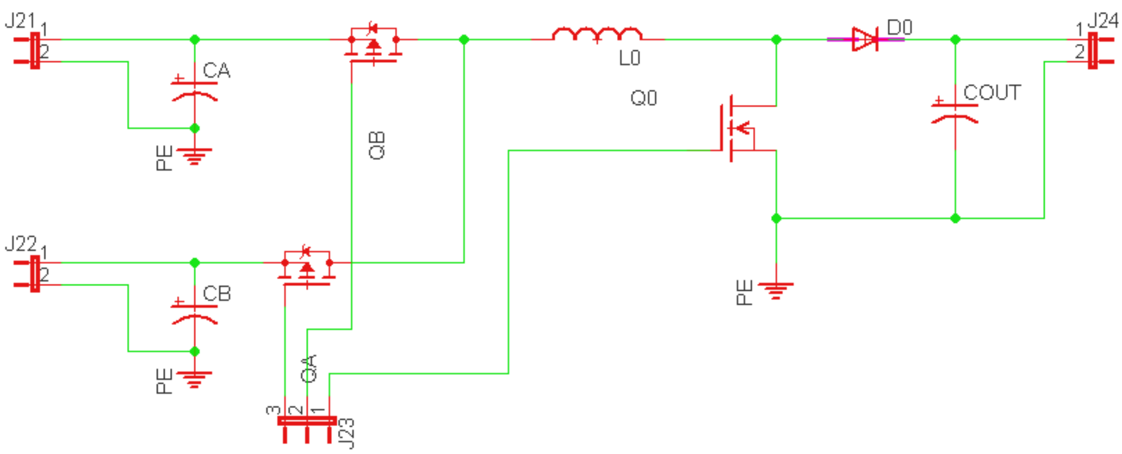


Figure 4.15. Schematic diagram from module 4 [EAGLE]

4.6. Circuit Start-up

In this chapter the circuit functioning will be explained. 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.

4.6.1. Transient Operation

a) All modules and devices are turned off and harvesters start collecting energy.

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

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

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

e) Module 4 controlled by module 3 sums the two voltage inputs from 1 and 2.

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

4.6.2. Stable Operation

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.

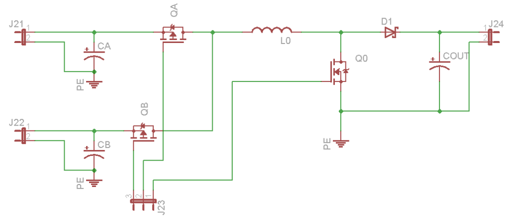
During stable operation, all modules are working continuously and together: module 3 gives the three PWM signals to the switches in module 4, modules 1 and 2 gives the energy to the supercapacitors in the outputs and through the module 4 to the final load or battery if the harvesters are giving enough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

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'.

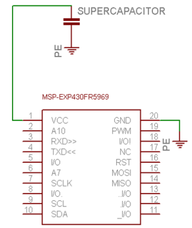
4.7. Schematics

Next page is showing the complete electronic circuit with all modules connected together and corresponding names. The schematic design has been built with EAGLE PCB design software; Easily Applicable Graphical Layout Editor.

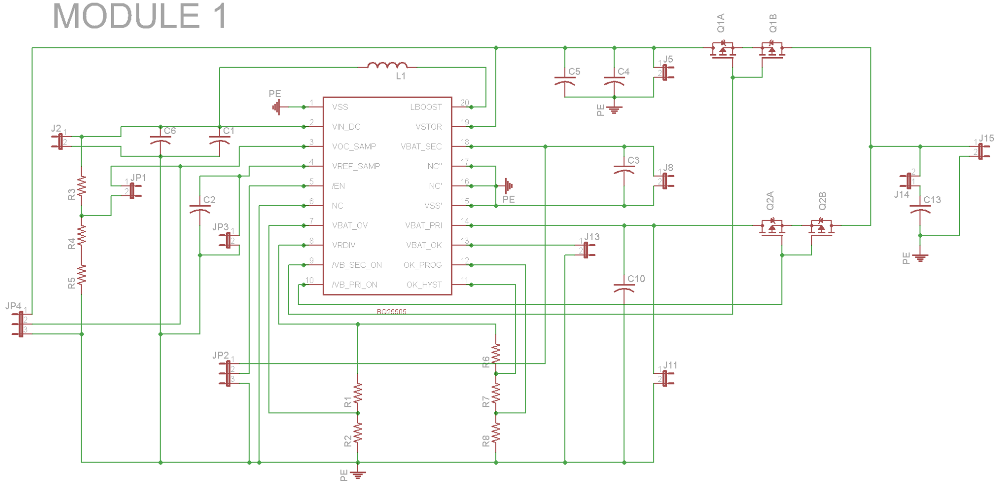
MODULE 4



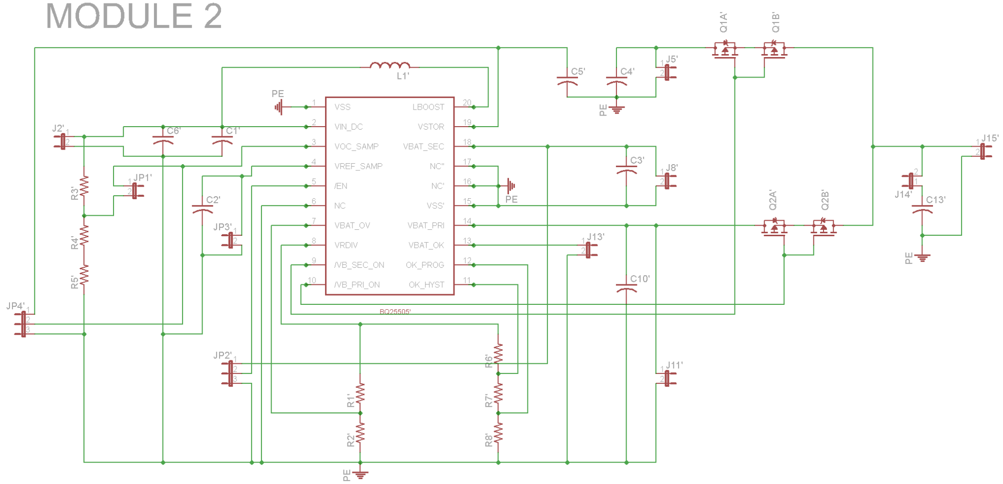
MODULE 3



MODULE 1



MODULE 2



5. Main Computations

In this chapter all calculus regarding parameters that take part of the circuit are executed. Standard values of the components will be taken from computations to get these values too. This section intents to be brief and clear so formulas and calculus done here are the important ones. If the user wants to go more in deep, annexes show this information in deep.

5.1. Module 1

The aim here is to get most appropriate standard values of the components used in the first module. For module 1 there are two circuit possibilities using different chips. From the one hand, the optimal option due to its advanced design and flexibility is a circuit based on BQ25505. System architecture chapter (CHAPTER) shows the schematics and specifications of the circuit but here, the component's values will be calculated. From the other hand, there is another circuit based on BQ25504 chip that can also be used. Section 5.1.2 is indicates the detailed specifications.

5.1.1. Best Option

Texas Instruments recommends this device for energy harvesting applications as it has battery control features that must be considered. Before going further in calculations, there must be a previous study that can be focused on the datasheet (DATASHEET). For TEG application, as module 1 is prepared for, calculus and specifications are followed from BQ25505 datasheet (DATASHEET) in deep, or can be followed from this chapter with the basic equations. Once the values are got for each component, its selection can take place.

The general scheme proposed by [3] is showed in the following figure:

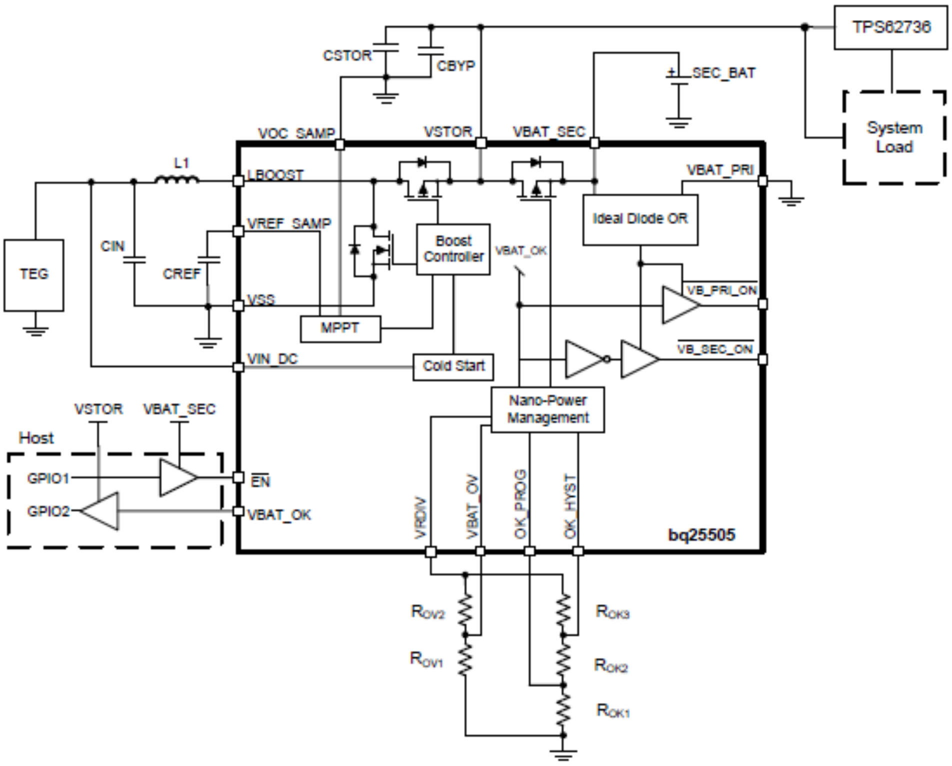


Figure 5.1. Typical TEG application circuit using BQ25505 [3]

So the parameters that must be calculated are: R_{OV1}, R_{OV2}, R_{OK1}, R_{OK2} and R_{OK3}.

Here are presented some of the formulas and a brief explanation about them, but it is recommended to read [3] to follow these computations easily. Furthermore, Texas Instruments has designed a tool which computes these values automatically (and can be found in [28]).

To calculate R_{OV1} and R_{OV2}, $RSUM_{OV}$ = 13 MΩ is chosen and VBIAS and VBAT_OV are specified in [3].

$$R_{OV1} = \frac{3}{2} \times \frac{RSUM_{OV} \times VBIAS}{VBAT\_OV} \times \frac{3}{2} \times \frac{13M\Omega \times 1{,}21V}{4{,}2V} = 4{,}75M\Omega \qquad \textbf{(Eq. 5.1)}$$

$$R_{OV2} = RSUM_{OV} - R_{OV1} = 13M\Omega - 4{,}75M\Omega = 8{,}25M\Omega \qquad \textbf{(Eq. 5.2)}$$

Where the standard values are the same: R_{OV1} = 4,75 MΩ and R_{OV2} = 8,25 MΩ.

To calculate R_{OK1}, R_{OK2} and R_{OK3}, $RSUM_{OK}$ = 13 MΩ is chosen and VBIAS and VBAT_OK_HYST are specified in [3].

$$R_{OK1} = \frac{VBIAS \times RSUM_{OK}}{VBAT\_OK\_HYST} = 4,22M\Omega$$ **(Eq. 5.3)**

$$R_{OK2} = \left(\frac{VBAT\_OK}{VBIAS} - 1\right) \times R_{OK1} = 8,06M\Omega$$ **(Eq. 5.4)**

$$R_{OK3} = RSUM_{OK} - R_{OK1} - R_{OK2} = 13M\Omega - 4,22M\Omega - 8,06M\Omega = 0,72M\Omega$$ **(Eq. 5.5)**

Where the standard values (rounding to the nearest 1% resistor) are: R_{OK1} = 4,22 MΩ, R_{OK2} = 8,06 MΩ and R_{OK3} = 0,698 MΩ.

5.1.2. Alternative Options

To better know BQ25504 there is a brief description below. To have more information about the chip, it is recommended to read its datasheet [1].

BQ25504 is a similar device as BQ25505, a low-power boost converter designed for applications in energy harvesting. Even though, the design and architecture is simpler and is not including some of the inputs and outputs in BQ25505. This is one of the fundamental reasons that makes this device an alternative option and not the best one. Some specifications regarding the boost converter are the following:

- Low consume
- MPPT calculation
- QFN-16 packages
- INOUT from USER MANUAL

Then, as BQ25505 is already known, BQ25504's functioning is easy to understand. Regarding basic specifications, it is time to focus on its functionality. Module 1 is designed for getting power from TEG so the computations in this section are taken from this point of view. The general scheme proposed by [1] is showed in the following figure:

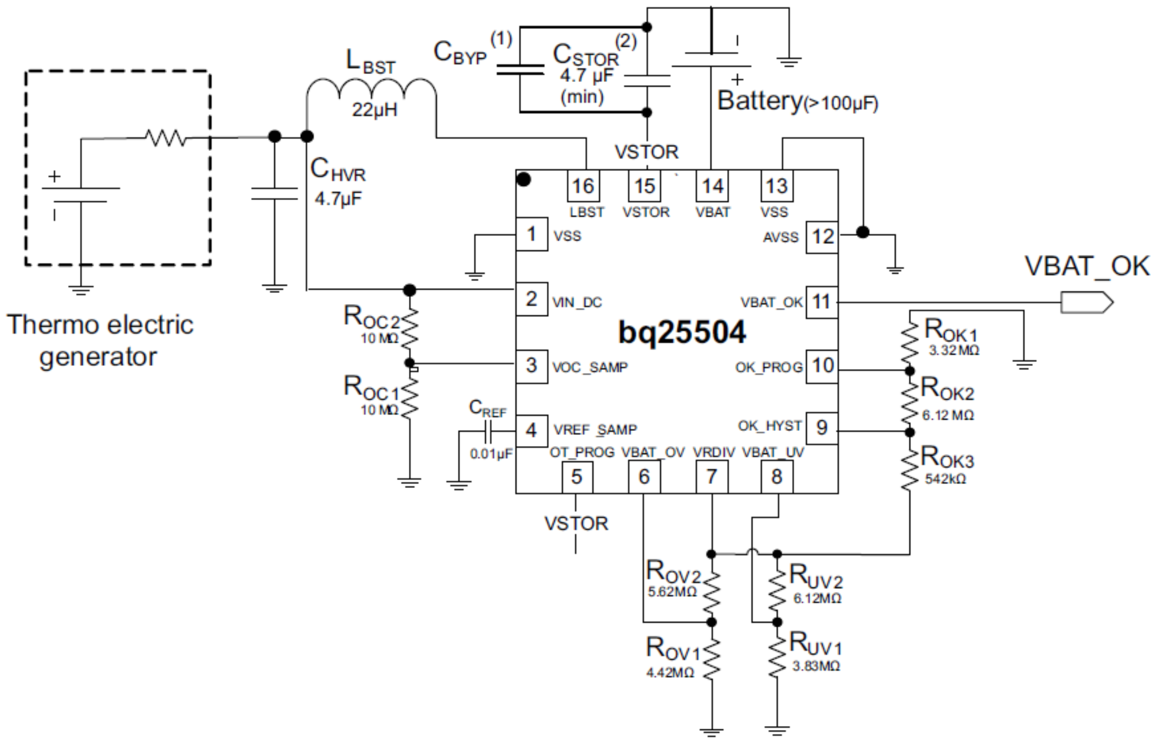


Figure 5.2. Typical TEG application circuit using BQ25504 [2]

So the parameters that must be calculated are: R_{OV1}, R_{OV2}, R_{UV1}, R_{UV2}, R_{OK1}, R_{OK2}, R_{OK3}, R_{OC1} and R_{OC2}.

Here are presented some of the formulas and a brief explanation about them, but it is recommended to read [1] to follow these computations easily. Furthermore, Texas Instruments has designed a tool which computes these values automatically (and can be found in [27]).

To calculate R_{OV1} and R_{OV2}, $RSUM_{OV}$ = 10 MΩ is chosen and VBIAS and VBAT_OV are specified in [1].

$$R_{OV1} = \frac{3}{2} \times \frac{RSUM_{OV} \times VBIAS}{VBAT\_OV} \times \frac{3}{2} \times \frac{10M\Omega \times 1{,}25V}{3{,}15V} = 4{,}42M\Omega \quad \textbf{(Eq. 5.6)}$$

$$R_{OV2} = RSUM_{OV} - R_{OV1} = 10M\Omega - 4{,}42M\Omega = 5{,}58M\Omega \quad \textbf{(Eq. 5.7)}$$

Where the standard values (rounding to the nearest 1% resistor) are: R_{OV1} = 4,42 MΩ and R_{OV2} = 5,49 MΩ.

To calculate R_{UV1} and R_{UV2}, $RSUM_{UV}$ = 10 MΩ is chosen and VBIAS and $VBAT_{UV}$ are specified in [1].

$$R_{UV1} = \frac{RSUM_{UV} \times VBIAS}{VBAT_{UV}} = \frac{10M\Omega \times 1,25V}{2,2V} = 3,83M\Omega \quad \text{(Eq. 5.8)}$$

$$R_{UV2} = RSUM_{UV} - R_{UV1} = 10M\Omega - 3,83M\Omega = 6,17M\Omega \quad \text{(Eq. 5.9)}$$

Where the standard values (rounding to the nearest 1% resistor) are: R_{UV1} = 3,83 MΩ and R_{UV2} = 6,04 MΩ.

To calculate R_{OK1}, R_{OK2} and R_{OK3}, $RSUM_{OK}$ = 10 MΩ is chosen and VBIAS and VBAT_OK_HYST are specified in [1].

$$R_{OK1} = \frac{VBIAS \times RSUM_{OK}}{VBAT\_OK\_HYS} = 3,32M\Omega \quad \text{(Eq. 5.10)}$$

$$R_{OK2} = \left(\frac{VBAT\_OK\_PROG}{VBIAS} - 1\right) \times R_{OK1} = 6,04M\Omega \quad \text{(Eq. 5.11)}$$

$$R_{OK3} = RSUM_{OK} - R_{OK1} - R_{OK2} = 0,64M\Omega \quad \text{(Eq. 5.12)}$$

Where the standard values (rounding to the nearest 1% resistor) are: R_{OK1} = 3,32 MΩ, R_{OK2} = 6,04 MΩ and R_{OK3} = 0,536 MΩ.

To calculate R_{OC1} and R_{OC2}, $RSUM_{OC}$ = 20 MΩ is chosen and VREF_SAMP and VIN_DC(OC) are specified in [1].

$$R_{OC1} = \left(\frac{VREF\_SAMP}{VIN\_DC(OC)}\right) \times RSUM_{OC} = 10M\Omega \quad \text{(Eq. 5.13)}$$

$$R_{OC2} = RSUM_{OC} \times \left(1 - \frac{VREF\_SAMP}{VIN\_DC(OC)}\right) = 10M\Omega \quad \text{(Eq. 5.14)}$$

Where the standard values are the same: R_{OC1} = 10 MΩ and R_{OC2} = 10 MΩ.

5.2. Module 2

Module 2 is using a solar cell as a harvester and, at the same time, ensures the permanent supply of module 3. This can be possible as BQ25505 boost converter offers the possibility of incorporating a primary battery input, which acts in the rare case if solar cell is not being able to give power to both module 4 and module 3. There is no alternative option for this module as this chip is the only one with this unusual feature.

The general scheme proposed by [3] is showed in the next figure:

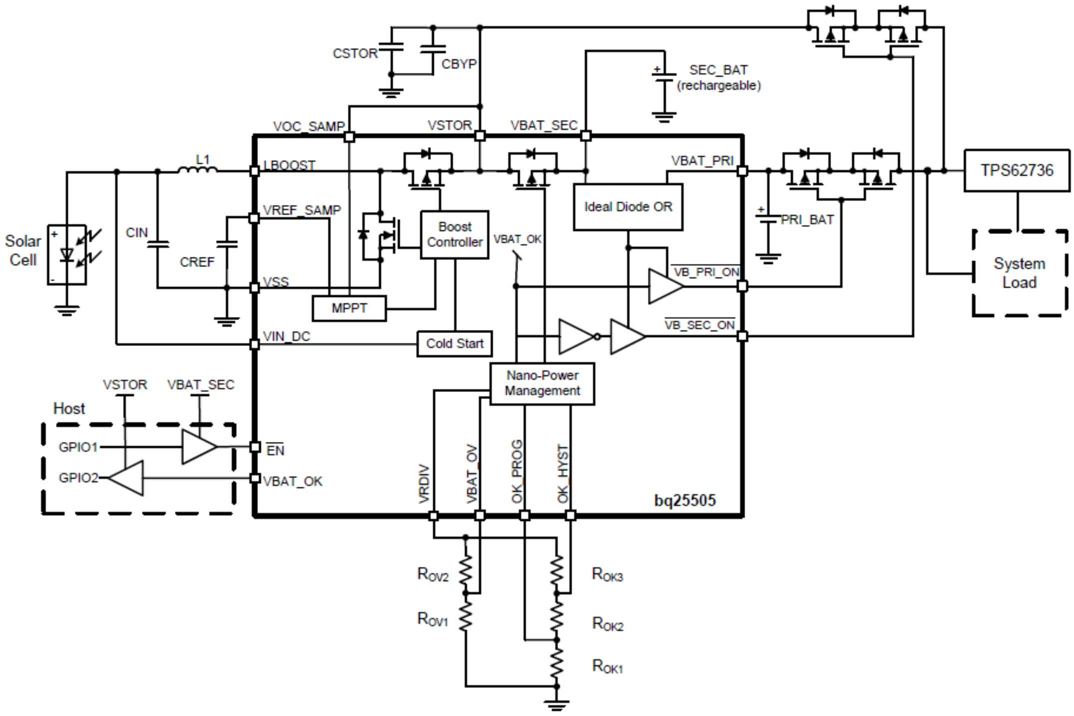


Figure 5.3. Typical solar application circuit using BQ25505 [3]

So the parameters that must be calculated are: R_{OV1}, R_{OV2}, R_{OK1}, R_{OK2} and R_{OK3}.

Here are presented some of the formulas and a brief explanation about them, but it is recommended to read [3] to follow these computations easily. Furthermore, Texas Instruments has designed a tool which computes these values automatically (and can be found in [28].

To calculate R_{OV1} and R_{OV2}, $RSUM_{OV}$ = 13 MΩ is chosen and VBIAS and VBAT_OV are specified in [3].

$$R_{OV1} = \frac{3}{2} \times \frac{RSUM_{OV} \times VBIAS}{VBAT\_OV} \times \frac{3}{2} \times \frac{13M\Omega \times 1,21V}{4,2V} = 5,61M\Omega \quad \textbf{(Eq. 5.15)}$$

$$R_{OV2} = RSUM_{OV} - R_{OV1} = 13M\Omega - 5,62M\Omega = 7,38M\Omega \quad \text{(Eq. 5.16)}$$

Where the standard values (rounding to the nearest 1% resistor) are: R_{OV1} = 5,62 MΩ and R_{OV2} = 7,32 MΩ.

To calculate R_{OK1}, R_{OK2} and R_{OK3}, $RSUM_{OK}$ = 13 MΩ is chosen and VBIAS and VBAT_OK_HYST are specified in [3].

$$R_{OK1} = \frac{VBIAS \times RSUM_{OK}}{VBAT\_OK\_HYST} = \left(\frac{1,21V}{2,8V}\right) \times 13M\Omega = 5,62M\Omega \quad \text{(Eq. 5.17)}$$

$$R_{OK2} = \left(\frac{VBAT\_OK}{VBIAS} - 1\right) \times R_{OK1} = \left(\frac{2,39V}{1,21V} - 1\right) \times 5,62M\Omega = 5,479M\Omega \quad \text{(Eq. 5.18)}$$

$$R_{OK3} = RSUM_{OK} - R_{OK1} - R_{OK2} = 13M\Omega - 5,62M\Omega - 5,479M\Omega = 1,904M\Omega \quad \text{(Eq. 5.19)}$$

Where the standard values (rounding to the nearest 1% resistor) are: R_{OK1} = 5,62 MΩ, R_{OK2} = 5,49 MΩ and R_{OK3} = 1,87 MΩ.

5.3. Modules 1&2 Design

As seen before, the best option for module 1 is the one using BQ25505 chip, which is the only possibility in module 2. Nevertheless, values and computations in each module vary as harvesters are not the same.

As an objection, there is an existing evaluation module from Texas Instruments called EVM-BQ25505 that is designed to optimize circuits using either solar panels or thermoelectric generators. Modules use jumpers to change component settings combination depending on harvester's application. This offers a huge flexibility as the same circuit is including solar and TEG configuration.

Despite the fact that the modules exist, in this project they are redesigned and implemented in a different way due to the reasons below.

- Improving some features.
- Size reducing
- Complete circuit integration
- Save money, cheap manufacturing
- Learning

Anyway, specifications in both built and TI models are almost the same so all information reported from now on in this section is extracted from [4].

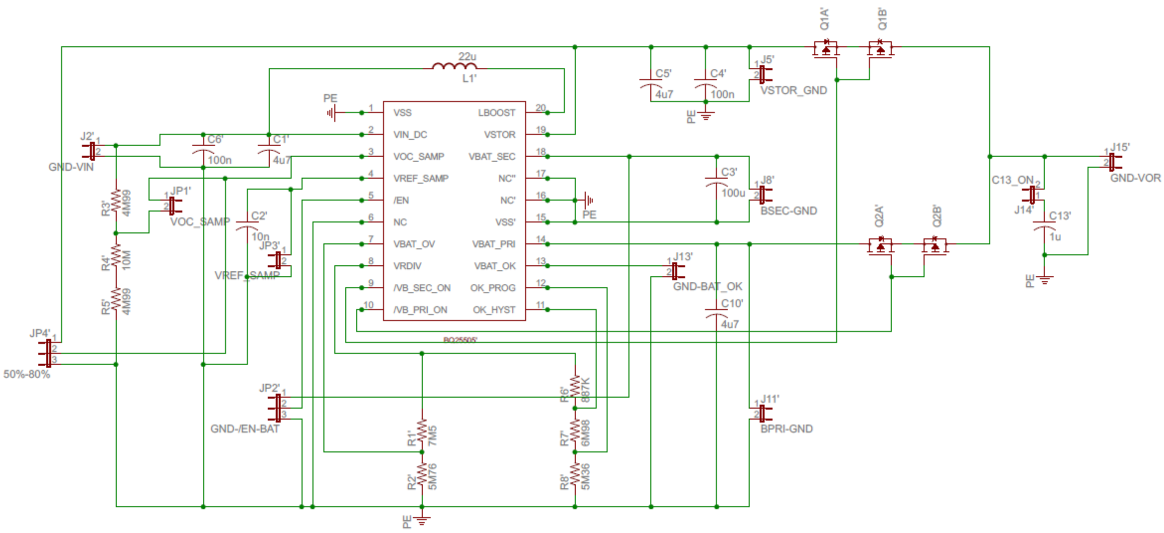


Figure 5.4. Schematic diagram from module 1 and 2 with values calculated [EAGLE]

5.4. Module 3

Module already designed and implemented by Texas Instruments is used for switching controlling application in the project, so all numerical specifications can be found in the schematics and user guide ([A.26] and [A.27]).

Nevertheless, there is the possibility to implement only the part of the circuit used for the present application. This portion includes the microcontroller and only the components needed to make it work.

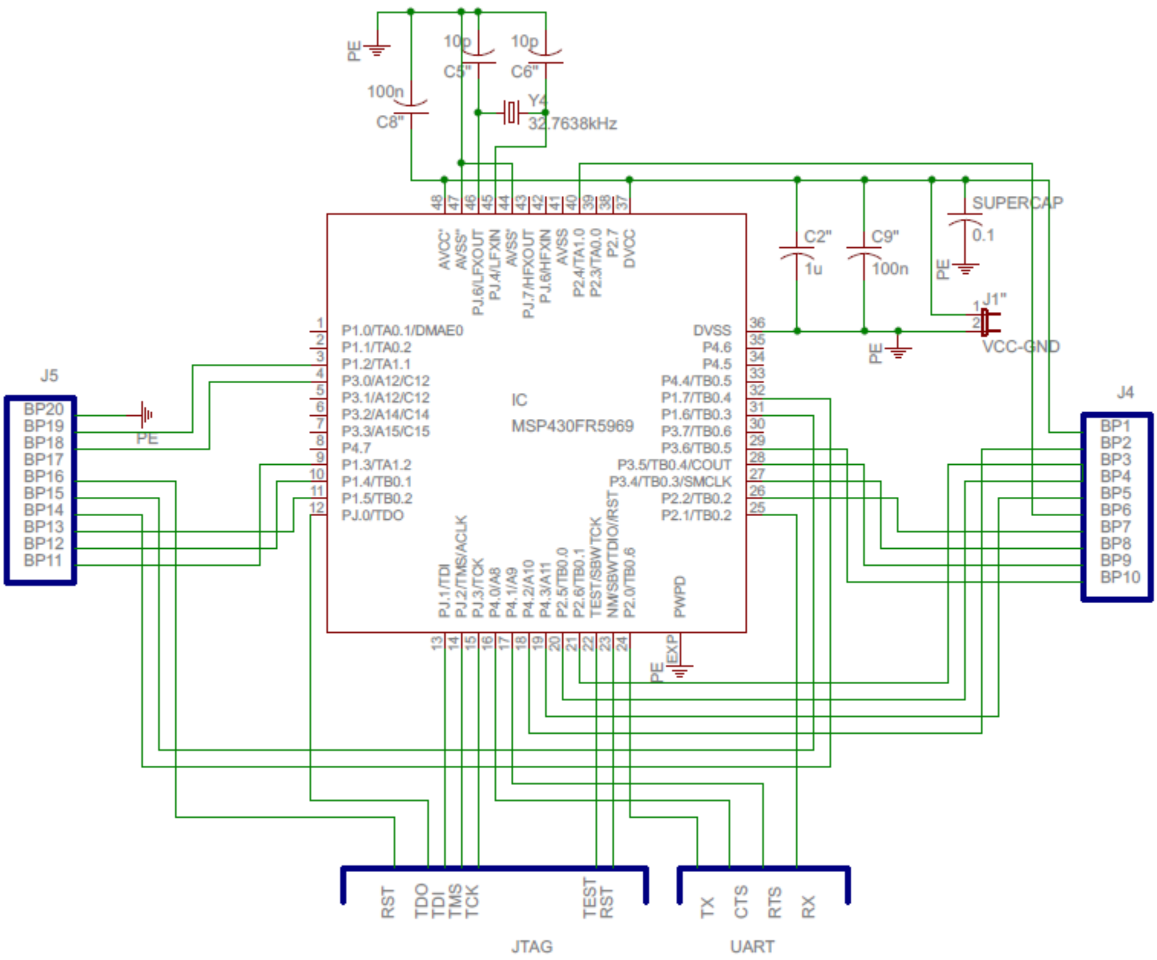


Figure 5.5. Schematic diagram from module 3 with numerical values [EAGLE]

Moreover, something to be calculated is the switching that the module should offer. To do this, the scientific paper [1] is used as reference.

This switching is as follows:

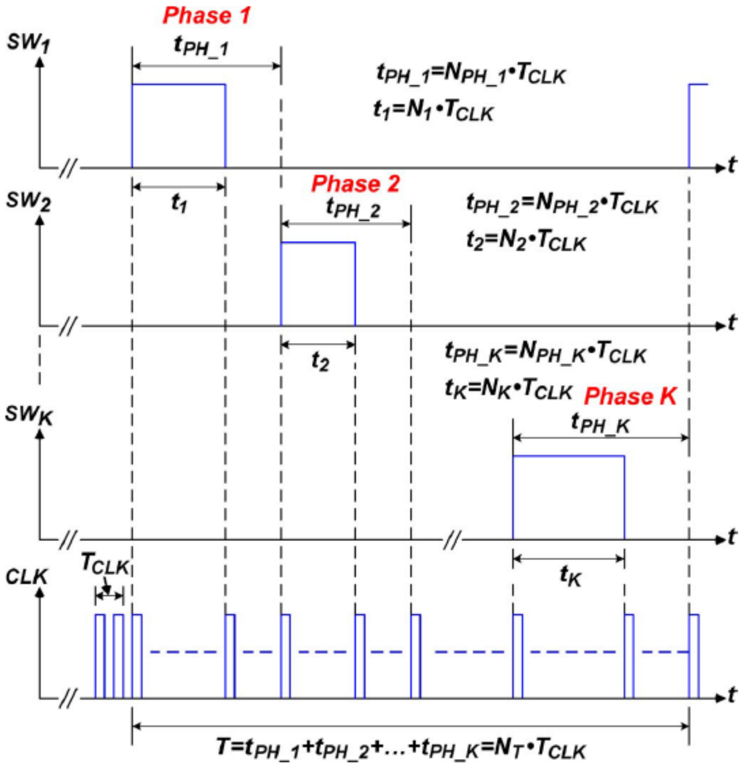


Figure 5.6. Switching proposed by the article [1]

As shown in [1] this switching uses 10 clock cycles for each input and in these 10 cycles the input is ON as many cycles as necessary to achieve the desired duty cycle. For example, if a 60% duty cycle is desired, the input must be connected six cycles of those 10 cycles. In those cycles reserved for other inputs, this entry will input be disconnected. This is a logical and intuitive switching, and is one of the options to be tested in our circuit.

However, the prototype is intended to be of two inputs and another logical configuration could be a switching with two complementary inputs, i.e., that one is connected when the other is disconnected. See **Figure 4.14.**

Both options are simulated and tested in our circuit to obtain conclusions.

5.5. Module 4

In this section the most appropriate components for our innovative module are found. Therefore, the parameters that define a normal boost with the desired characteristics must be determined and then the optimal input capacitors value should be studied.

This procedure has been done using as a reference the article [1]. Thus, the basic procedure was as follows.

It is desirable that the emulated resistance of the circuit (R_{em}) and the harvester resistance have the same value in order to obtain the Maximum Power Transfer (MPT).

So first, the formula to compute R_{em} should be presented (obtained from [1]):

$$R_{em} = \frac{8LN_T}{T_{CLK}N_1} \qquad \textbf{(Eq. 5.20)}$$

Where L is the inductance value of the inductor used, N_T is an integer that indicates the number of clock pulses in a full cycle (where all the inputs are connected once to the circuit), N_1 is the number of clock pulses in the cycle of the input connected and T_{CLK} the clock period.

Then, the maximum emulated resistance is:

$$R_{em,\max} = \frac{8LN_T}{T_{CLK}} \qquad \textbf{(Eq. 5.21)}$$

And the minimum emulated resistance is:

$$R_{em,\min} = \frac{8LK}{T_{CLK}} \qquad \textbf{(Eq. 5.22)}$$

Where K is the number of inputs.

The different harvesters that has been studied present an equivalent series resistance in the range 100 Ω – 500 Ω approximately. The module 3 is able to work properly in a frequency of 100 KHz. Higher values can present errors and lower values can be so slow. Furthermore, the prototype will have two inputs and each of them will use 10 clock cycles, so N_T = 20 and K = 2. Taking in account these values and knowing that:

$$f_{CLK} = \frac{1}{T_{CLK}} \qquad \textbf{(Eq. 5.23)}$$

L can be computed for the two extreme cases from equations [ref-eq Rem,max] and [ref-eq Rem,min].

For $R_{em,max}$:

$$L = \frac{R_{em,\max}}{8N_T f_{CLK}} = \frac{500}{8 \times 20 \times 100000} = 31,25\mu H \qquad \textbf{(Eq. 5.24)}$$

And for $R_{em,min}$:

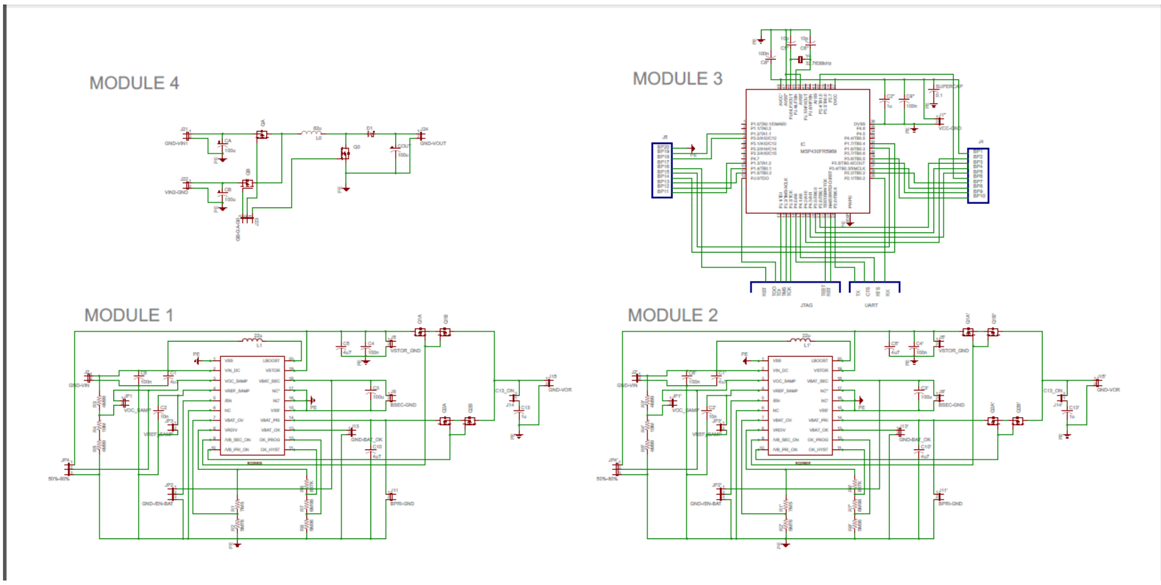
$$L = \frac{R_{em,\min}}{8Kf_{CLK}} = \frac{100}{8 \times 2 \times 100000} = 62,5\mu H \qquad \textbf{(Eq. 5.25)}$$

So, the inductor selected must have a value near these results. The four nearest values are tested to see which of them work better. These values are: L_1 = 22 µH, L_2 = 56 µH, L_3 = 82 µH and L_4 = 120 µH. Furthermore, 100 µF capacitors are selected because it is the recommended value for the output capacitor of the modules 1 and 2. This capacity is big enough to store the energy from the disconnected harvester and small enough to avoid a pronounced delay.

Later module 4 will be simulated with these components to see if the circuit is working properly and finally determine which values of these components are more convenient.

5.6. General Schematic Diagram

Next page is showing the schematic diagram with all values calculated in this section.


MODULE 4
MODULE 3
MODULE 1
MODULE 2

6. Simulations

This chapter includes all simulations regarding the circuits used for the MIMO boost converter design. This previous circuit verification through computer software is essential in the project, especially for module 4.

6.1. Modules 1&2

Both options in module 1 (BQ25504 and BQ25505) and module 2 are designed following specifications in EVM-BQ25504 and EVM-BQ25505 from Texas Instruments; so simulations are not crucial in this aspect. Even though, Tina software is used to know better the functioning and behaviour. The examples listed below show simulation profiles done with PSIM software. A great disadvantage of using this program is its limited utility and slowness when processing and obtaining results.

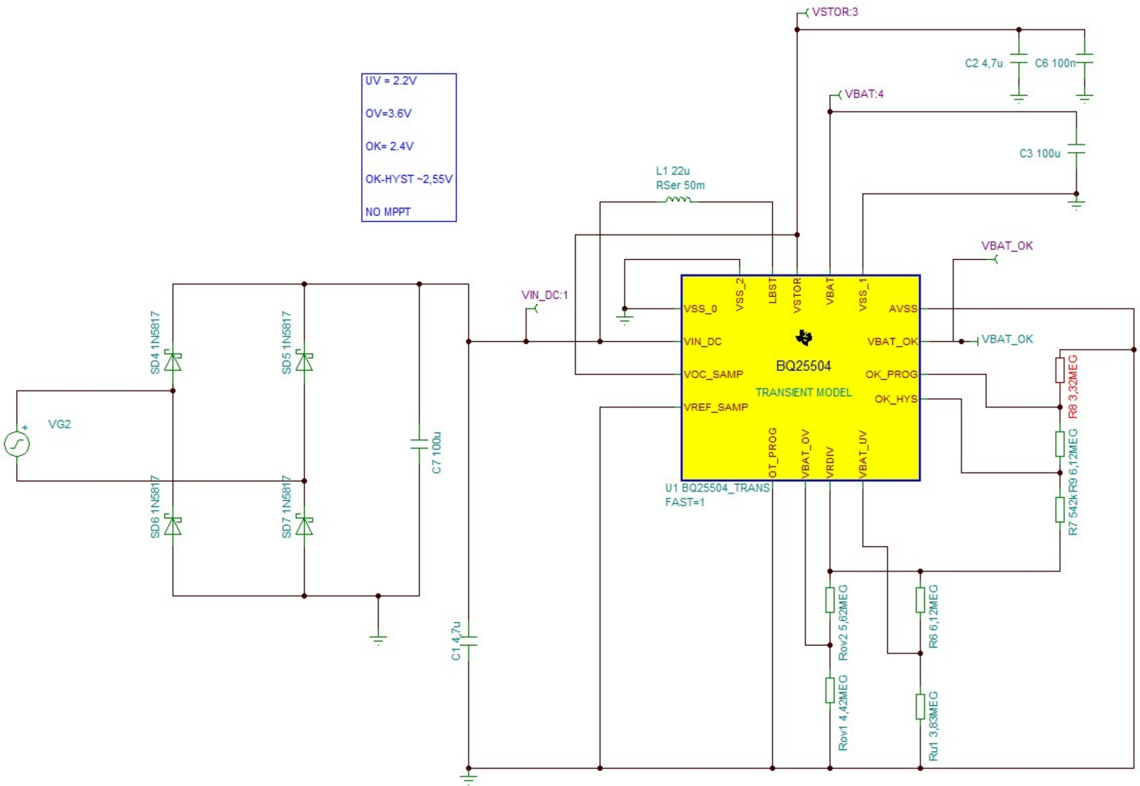


Figure 6.1. BQ25504 transient model for TEG application [TINA]

Previous results are used to understand circuit's working and they are coherent with datasheet information.

6.2. Module 3

Module 3 needs to be connected to MOSFET transistor's gates in module 4; this way it can control the switching. This three input signals are simulated in PSIM software following the two switching options and forms coincide correctly with the theory. First switching option is simulated below:

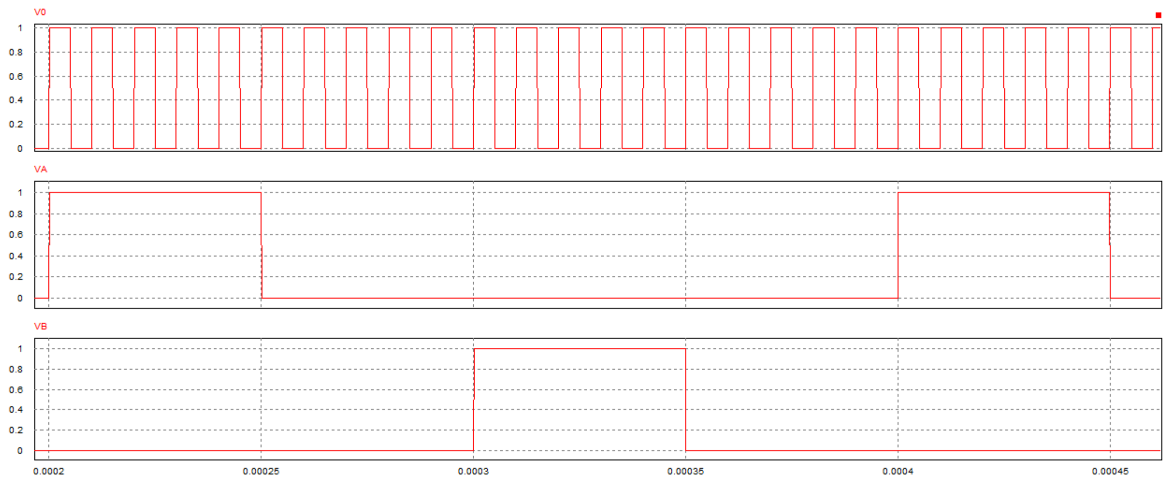


Figure 6.2. Non-complementary switching in module 3: V0, VA and VB from top to bottom [PSIM]

Second switching option simulation is shown below:

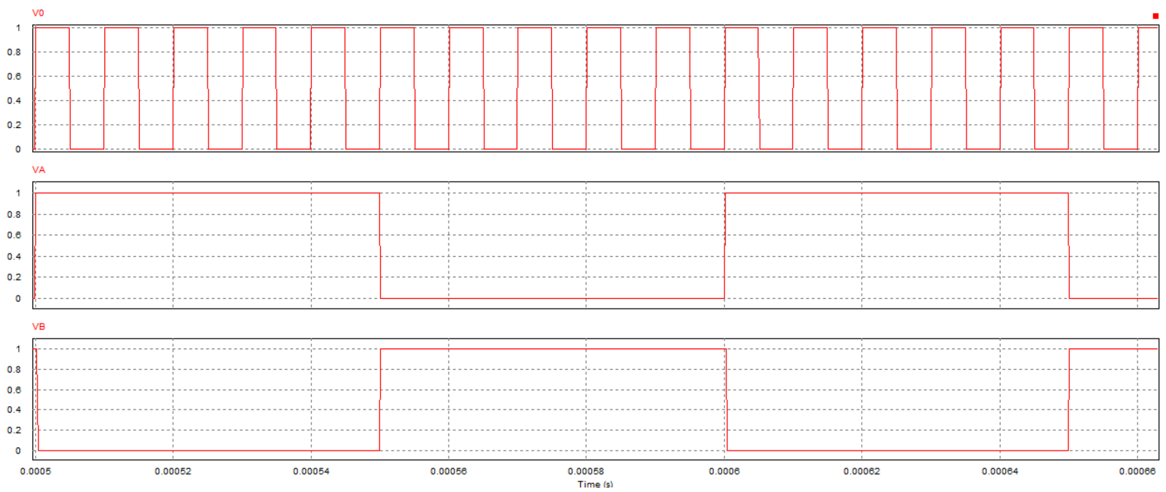


Figure 6.3. Complementary switching in module 3: V0, VA and VB from top to bottom [PSIM]

6.3. Module 4

This innovative module requires indispensable simulations to understand this module behaviour. Power SIM software is used as it can simulate small periods of time and components are well characterized. This makes PSIM better than PSpice for example, as it can represent more than 3 high frequency signals at the same time with no restrictions and this makes it a suitable program for this project's application. Tests corresponding to both switching options will take place in this section.

Before that, the fact that the circuit is adding powers needs to be demonstrated. So it is mandatory to follow the next simple procedure:

1. Use the circuit with component values as a normal boost and note the results.

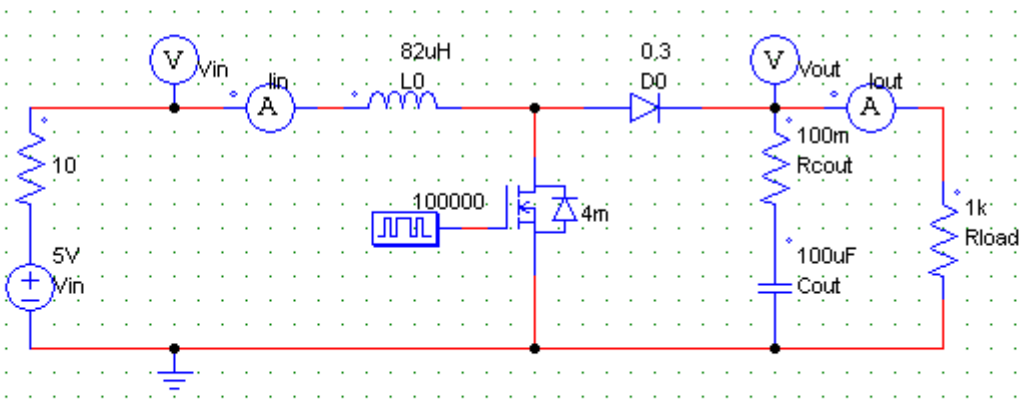


Figure 6.4. Normal boost circuit schematics and measurements: D=50% [PSIM]

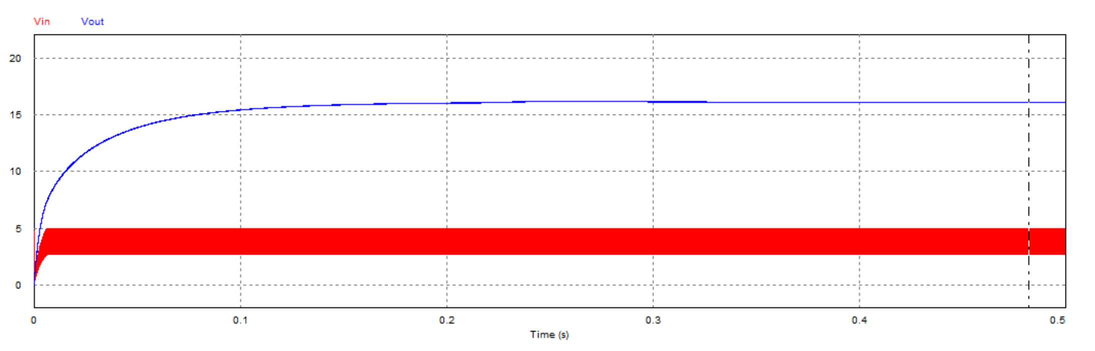


Figure 6.5. Normal boost graphical result: Vin in red, Vout in blue [PSIM]

Time	4.7213930e-001
Vin	5.0000061e+000
Vout	1.6099015e+001

Figure 6.6. Normal boost numerical result: Vin in red, Vout in blue [PSIM]

2. Use the same circuit values but this time with two inputs switching at any duty cycle, note the results.

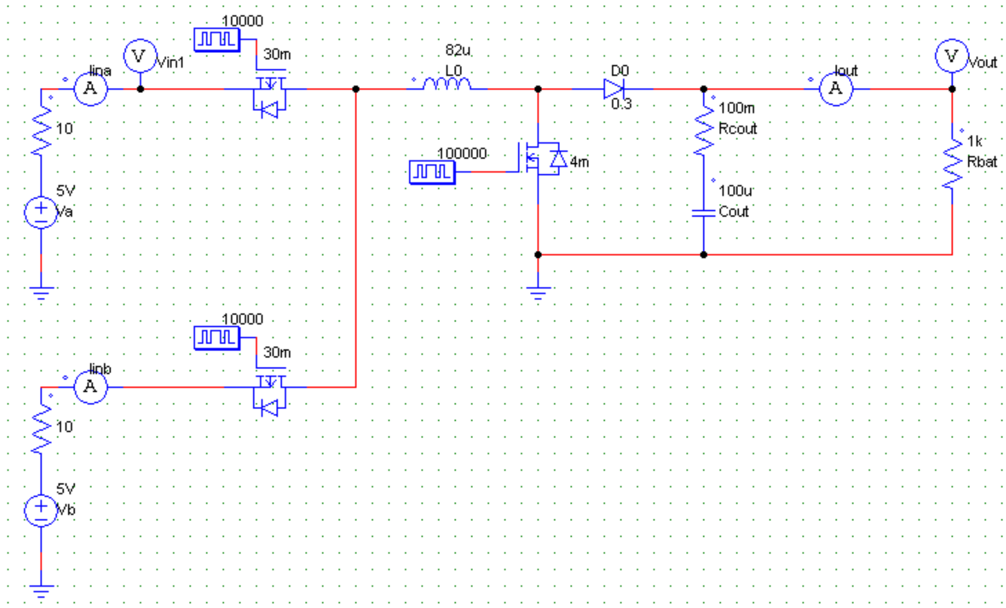


Figure 6.7. Normal boost with multiple input schematics and measurements: D=50% [PSIM]

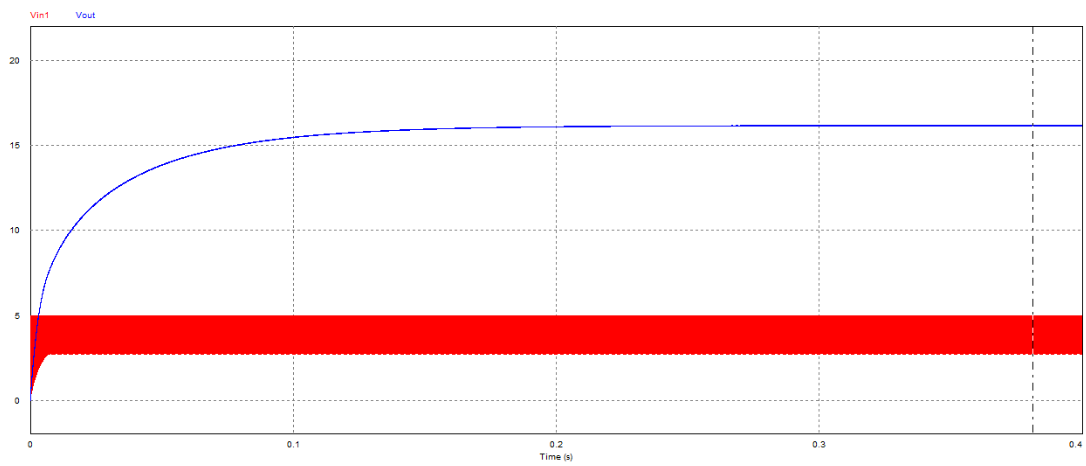


Figure 6.8. Normal boost with multiple input graphical results: Vin in red, Vout in blue [PSIM]

Time	3.8107884e-001
Vin1	5.0000031e+000
Vout	1.6172682e+001

Figure 6.9. Normal boost with multiple input numerical results: Vin in red, Vout in blue [PSIM]

It can be observed that, for an ideal simulated circuit, results for single input and double input are exactly the same. This can be possible as MOSFET switching only changes the input and the circuit acts as it has always same source value. While one of the inputs is disconnected, all power coming from that disconnected source is not stored anywhere; so it is not giving power to the circuit.

3. Use the same circuit values with two inputs and parallel capacitor connected, note the results.

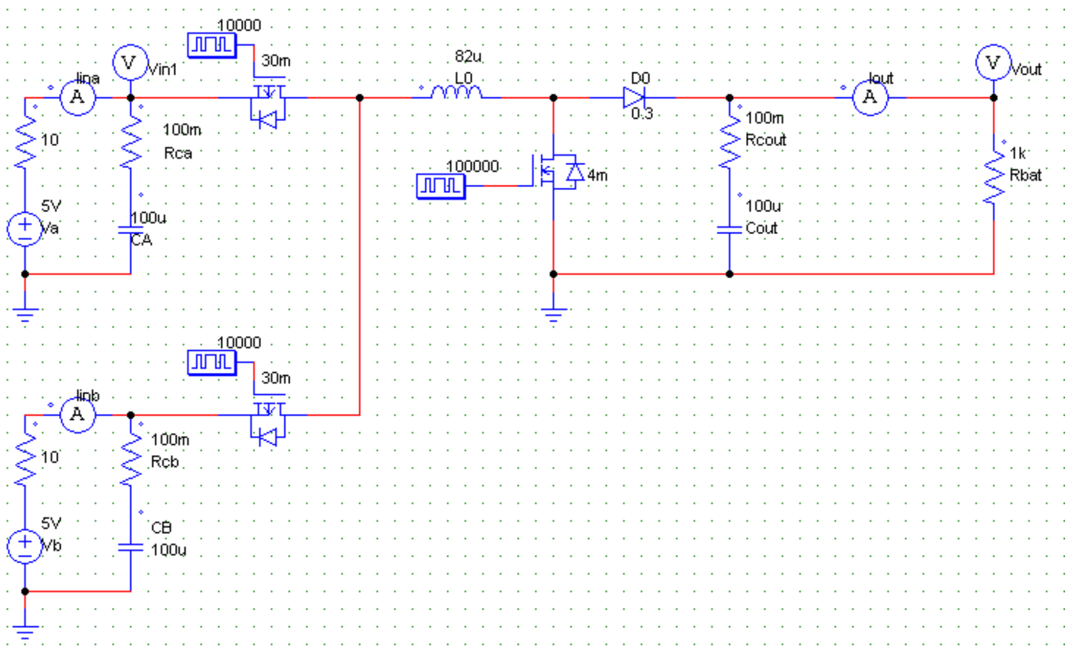


Figure 6.10. Double input schematics and measurements: D=50% [PSIM]

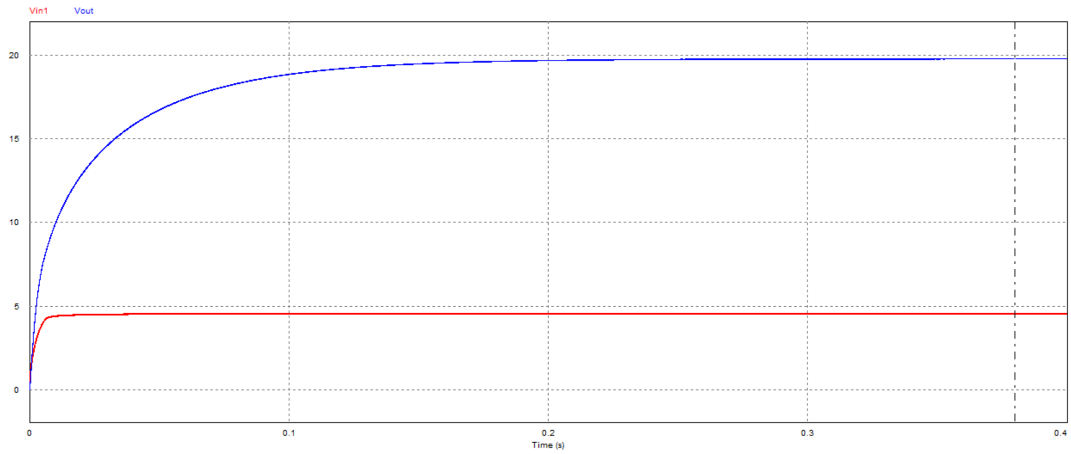


Figure 6.11. Double input graphical results: Vin in red, Vout in blue [PSIM]

Time	3.7975104e-001
Vin1	4.5618538e+000
Vout	1.9788186e+001

Figure 6.12. Double input numerical results: Vin in red, Vout in blue [PSIM]

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 V_{IN}.

Once the previous fact is demonstrated, it is necessary to optimize the circuit and make it as efficient as possible. To do so, different circuits are simulated following calculated values to verify the functioning and behavior. Circuits are simulated with the configuration below, only changing the value of the inductor.

Notice that circuits on the inputs corresponding to module 1 and module 2 are represented as a Thevenin equivalent circuit using a voltage source and a series resistor.

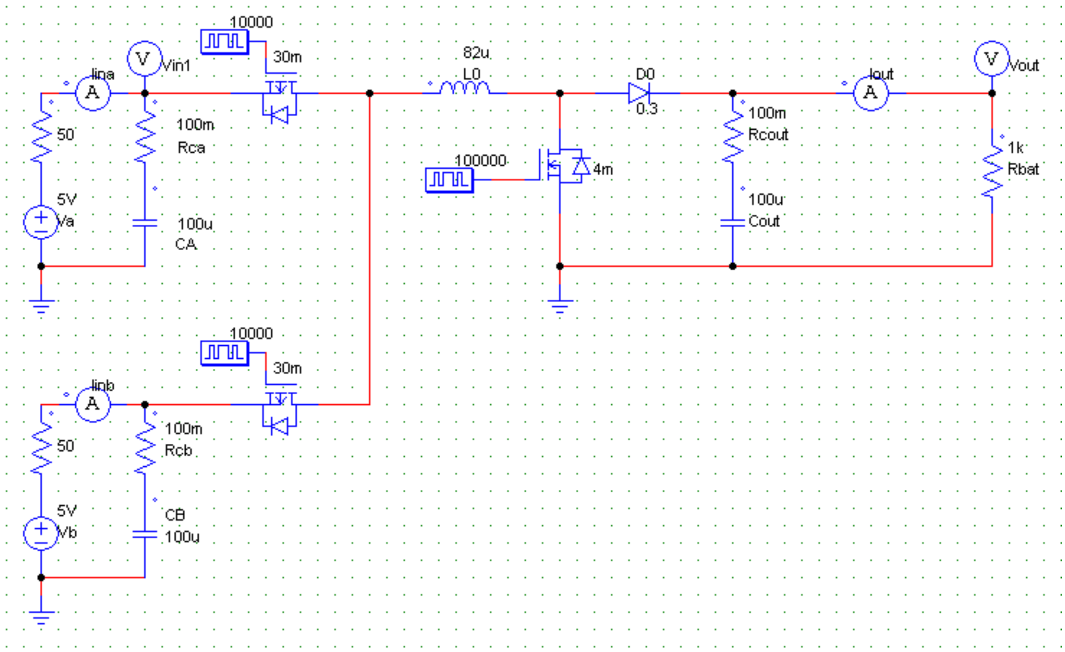


Figure 6.13. Simulation circuit configuration template [PSIM]

Inductor	Magnitude	D=10%	D=30%	D=50%	D=70%	D=90%
22µH	V_{IN}(V)	4.5	3	1.94	1.27	0.87
	I_{IN}(mA)	9	38.5	61.5	75	83
	V_{OUT}(V)/I_{OUT}(mA)	9	14.8	14.9	12.3	11.3
56µH	V_{IN}(V)	4.7	3.9	3	2.21	1.46
	I_{IN}(mA)	5.6	22	40	56	70
	V_{OUT}(V)/I_{OUT}(mA)	7	12.8	15.2	15.3	14
82µH	V_{IN}(V)	4.76	4.1	3.35	2.63	1.56
	I_{IN}(mA)	4.6	17	32.5	47.3	69
	V_{OUT}(V)/I_{OUT}(mA)	6.48	11.68	14.6	15.5	14.1

	V_{IN}(V)	4.8	4.34	3.7	3	1.6
120µH	I_{IN}(mA)	4	13.3	26	39	67.5
	V_{OUT}(V)/I_{OUT}(mA)	6	10.5	13.6	15.1	14

Table 2. Circuit simulation results

Circuits can also be simulated in PSIM with solar cells included in the program instead of the model.

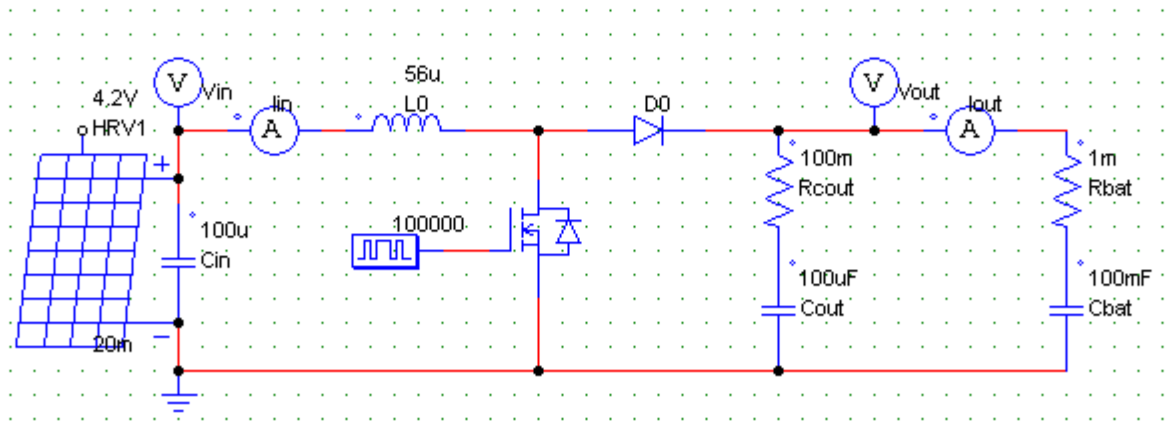


Figure 6.14. Simulated solar cell model example [PSIM]

From the results obtained in **Table 2.** and also from all simulations done in the project, some conclusions can be extracted:

- CIN only affects on retarding the signal to reach its maximum point, RC delay. It does not affect voltage values.
- COUT only affects the ripple in the output. It does not affect voltage values.
- The lower the inductor (L0), the greater the output voltage (VOUT) is.

- The higher is the duty cycle in NMOS transistor, V_{IN} 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: D → 100%; NMOS = ON; Rcircuit → 0.
  D → 0%; NMOS = OFF; Rcircuit → 1K.

Now, all circuit and simulations are exposed and described with respective conclusions. Value tables are also included below to characterize each circuit and find the optimal one; graphics are also extracted to see the involved parameters and forms. Later on, these results will be compared with the ones in implementated circuits to see how accurate the simulations are.

7. Components Selection

7.1. Modules 1&2

The selection of the components in modules 1 and 2 is based in BQ25505 TEG and solar application respectively. All components can be found in EVM-BQ25505 evaluation kit datasheet [A.25] as the resistors, capacitors, inductors and the chip itself. Even though, it is true that the PCB configuration is following the same schematic design but totally different distribution because:

- BQ25505 is welded on a QFN-DIP20 socket to reduce error possibility when soldering, to be able to change the chip if it is burned or damaged and to be easy to deal with and connection checking.
- Reducing of board size, cheaper and practical model.
- Different components regarding PMOS transistors.
- Standard pin input output configuration, to easy connect and disconnect cables.
- Avoid unnecessary repeated inputs and outputs.
- Jumpers and test points creating to modify the circuit.

Anyway, the description will appear in the next chapter Implementation and Prototyping (chapter 8).

7.2. Module 3

To evaluate, use and test the prototype with MSP430FR5969 microcontroller (MCU), the LaunchPad from Texas Instrument has been chosen. The reason for this is mainly the low consume of the chip as it must operate with energy coming from the harvesters; so the more power used for the microcontroller, the less power available on the output.

MSP-EXP430FR5969 LaunchPad has many advantages compared with others that are useful for the applications in the present project: it has an easy-to-use development for the chip including the emulation on-board for programming, battery-free applications using the MCU standalone, ultra-low power consumption and flexibility regarding other devices' connection.

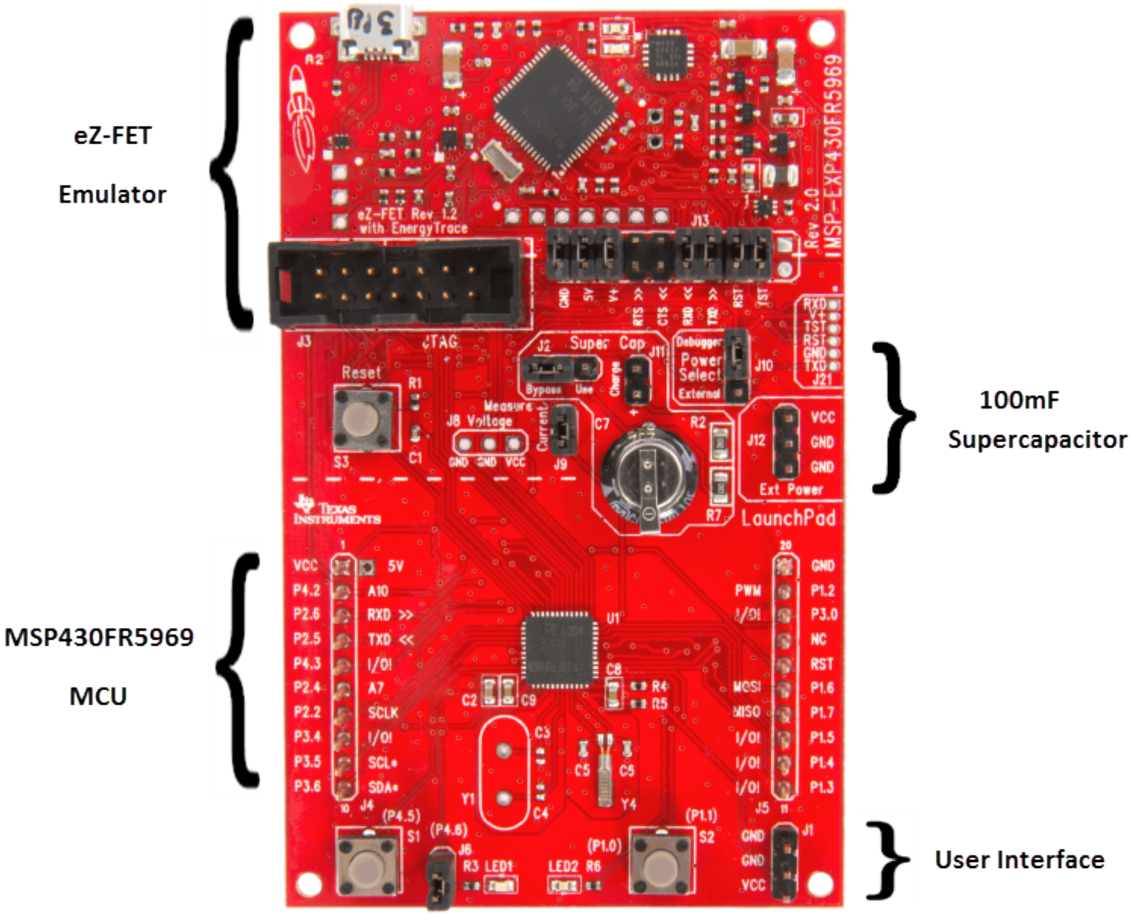


Figure 7.1. MSP-EXP430FR5969 LaunchPad [A.26]

The board can be divided in 4 sections:

a) eZ-FET Emulator

On the same board there is a debugger MCU to program the target microcontroller controlling the whole circuit, in module 3. This emulator is used in almost all MSP430 family of microcontrollers and is known as MSP430F5528. The chip is a low-cost debugger and there is no need of any expensive external programmer to interact with MSP430FR5969.

This MCU can be programmed with a personal computer using the Micro-B USB port. Other than the PC interface, there are two LEDs, red and green, which are used to visually communicate with the user.

Power LED	Mode LED	Function
○	○	MSP-FET430UIF not connected to PC, or MSP-FET430UIF not ready; for example, after a major firmware update. Connect or reconnect MSP-FET430UIF to PC.
●	○	MSP-FET430UIF connected and ready
●	●	MSP-FET430UIF waiting for data transfer
●	✸	Ongoing data transfer – during active debug session
○	●	An error has occurred; for example, target V_{CC} over current. Unplug MSP-FET430UIF from target, and cycle the power off and on. Check target connection, and reconnect MSP-FET430UIF.
✸	✸	Firmware update in progress. Do not disconnect MSP-FET430UIF while both LEDs are blinking.

Figure 7.2. LED colour code communication in MSP-EXP430FR5969 [A.26]

The debugger works with a 4MHz crystal and can use several communication methods as for example Spy-by-wire (SBW) emulation; with two cable protocol for communication with MSP430 MCU. eZ-FET also uses Backchannel UART for communication with other devices than the one on the board , despite it can also be used with the target chip. This last protocol is commonly used for hardware flow control between the MCU and eZ emulator, is a way of retaining and triggering data to update. Moreover, this devices support EnergyTrace™ Technology, which is a useful tool for monitoring energy profiles based in analysis and optimization of power consumption. In the emulator section there is also an electrostatic device protection (ESD) as well as a low-dropout regulator, which converts 5V coming from the USB connection to 3.3V coing to feed the MCU. Finally, there is a jumper block (J13) with double functionality: isolation with MSP430FR5969 to avoid power consuming and possibility of communication with external MCUs outside the board through it. Jumpers connects from left to right in the picture: three power signals as ground (GND), 5V and 3.3V (V+) signals; four signal corresponding to UART communication as RTS, CTS, RXD and TXD; and the two signals from the SBW emulation which are RST and TST. To a better understanding of the signals, it is recommended to follow the table below.

Jumper	Description
GND	Ground
V+	3.3-V rail, derived from VBUS by an LDO in the eZ-FET domain
RTS >>	Backchannel UART: Ready-To-Send, for hardware flow control. The target can use this to indicate whether 'it is ready to receive data from the host PC. The arrows indicate the direction of the signal.
CTS <<	Backchannel UART: Clear-To-Send, for hardware flow control. The host PC (through the emulator) uses this to indicate whether or not it is ready to receive data. The arrows indicate the direction of the signal.
RXD <<	Backchannel UART: the target FR5969 receives data through this signal. The arrows indicate the direction of the signal.
TXD >>	Backchannel UART: the target FR5969 sends data through this signal. The arrows indicate the direction of the signal.
RST	Spy-Bi-Wire emulation: SBWTDIO data signal. This pin also functions as the RST signal (active low)
TST	Spy-Bi-Wire emulation: SBWTCK clock signal. This pin also functions as the TST signal

Figure 7.3. LED colour code communication in MSP-EXP430FR5969 [A.26]

b) 100mF Supercapacitor

The next section allows the standalone working of the MSP430 thanks to the storage capacity of a 0.1F Supercapacitor attached on the board. This component can be used as needed and there are some jumpers to change the configuration and connection with the MCUs in the development kit.

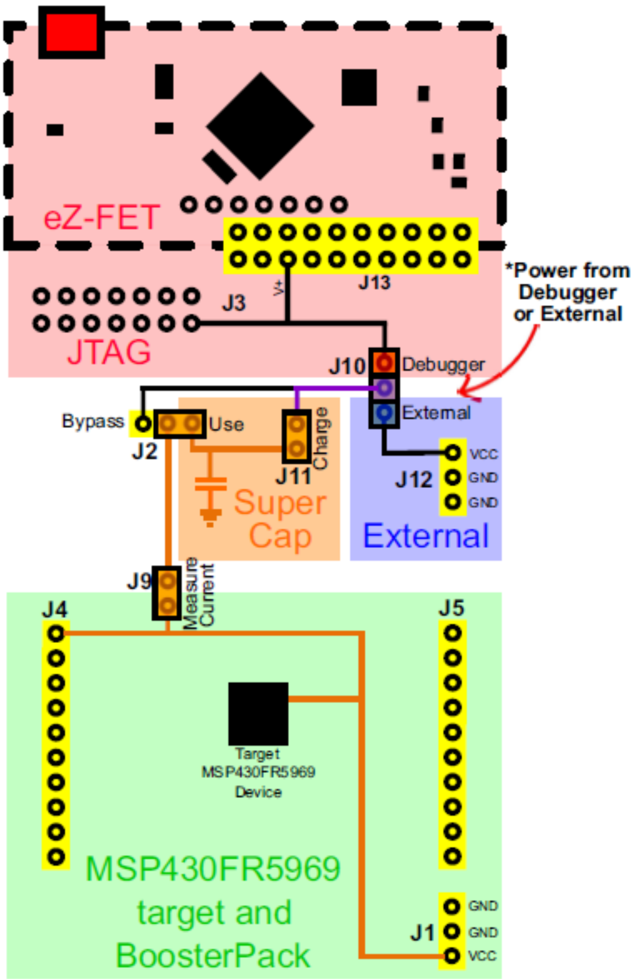


Figure 7.4. Supercapacitor charging configuration in Module 3 [A.26]

- Jumper J9 connects the Supercapacitor to the MSP430FR5969 controller and it can also be used to measure the current flow through it.
- Jumper J10 is used to choose the supply which can come from the debugger or from an external source connected in an extra header J12.
- Jumper J11 is used to charge the capacitor from the mentioned source, if connected.
- Jumper J2 is used as a bypass to avoid Supercapacitor voltage or to use it as the MCU's supply.

The typical steps, taken from the User Guide [A.26], to operate with supercapacitor connections are the following:

Charging the Super Cap

J11 connected to any supply giving power, J1 or a BoosterPack will not charge the super cap through J11. Placing a jumper across J11 will charge the super cap when there is 3.3V present, regardless of the state of the Bypass/Use J2 jumper, however if J2 is in the ‘Bypass’ state, changing it over to the ‘Use’ state will remove power from the target MSP430FR5969 and it will be reset.

Using the Super Cap

To use the super cap to power the LaunchPad, first change the J2 jumper to select ‘Use’ and then set a jumper on J11 to charge the super cap. After waiting for it to charge, any external power can be removed from the system, and it will be powered completely by the super cap.

To remove any additional power drain from the super cap, remove any jumper to disconnect power to any external source. This can be J11, J10, or J13 depending on the power configuration. This prevents the super cap from back-powering the debug circuitry or any external power circuitry connected.

The most effective method for charging the capacitor is outlined in the following steps. These steps assume the LaunchPad is powered by USB cable through the eZ-FET debugger.

1. Set "Power Selector" jumper (J10) to "Debugger" position.
2. Set jumper J2 to "Use" super cap position.
3. Set jumper J11 to "Charge" super cap position.
4. Set "V+" jumper J13.
5. Connect board to PC with USB cable.
6. Allow two to three minutes for the super cap to charge (time may vary depending on initial charge of the super cap) to full VCC.
7. Remove the "V+" jumper J13.

Disabling the Super Cap

To disable the super cap, change J2 to ‘Bypass’, and remove jumper J11 to prevent additional current for charging the super cap. With these two jumper selections, the super cap is completely disconnected from the system.

The configuration that will be used for this project will be the one connecting external supply, which will be coming from module 2, directly to the supercapacitor and, at the same time, this supercapacitor will store and give the energy to the MCU to generate PWM switching to module 4. So Jumpers must be placed like this:

- J10 set to 'External' mode.
- J9 and J11 connected.
- J2 set to 'Use' option.

To end with the section, there is also a 14-pin JTAG header related with the target microcontroller. The connector can be used for power supplying or also for communication with another external debug tool as desired.

c) MSP430FR5969 MCU

This ultra-low power microcontroller designed for energy harvesting applications includes 20 easy connection pins compatibility on the board, which can be extended with standard modules. Pins placed in the pas as headers and female connectors are very useful when communicating with other devices as module 4 in this project case. The pin headers (J4 and J5) distribution in MSP-EXP430FR5969 is the following:

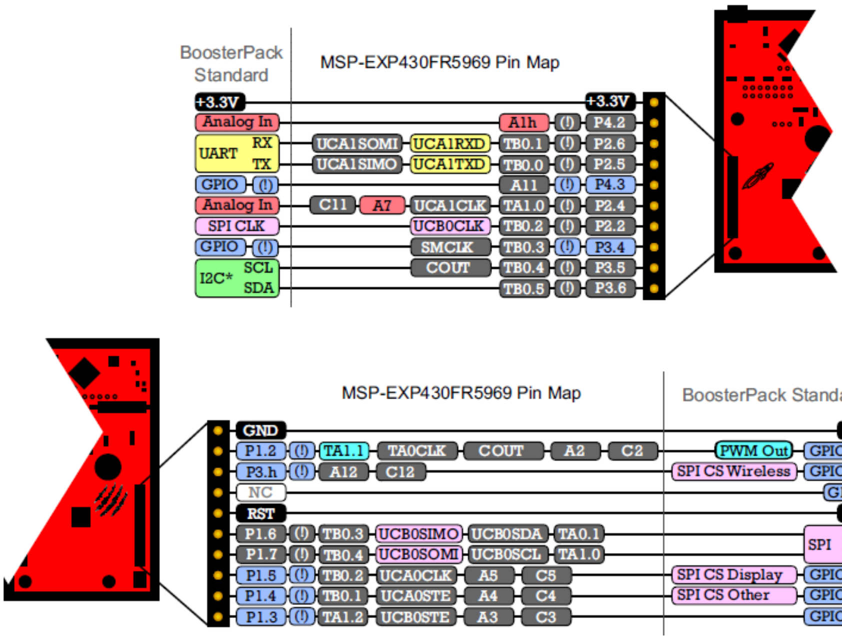


Figure 7.5. Module 3 pin out in J4 and J5 respectively [A.26]

Where the whole pin out connection on the chip is the one below:

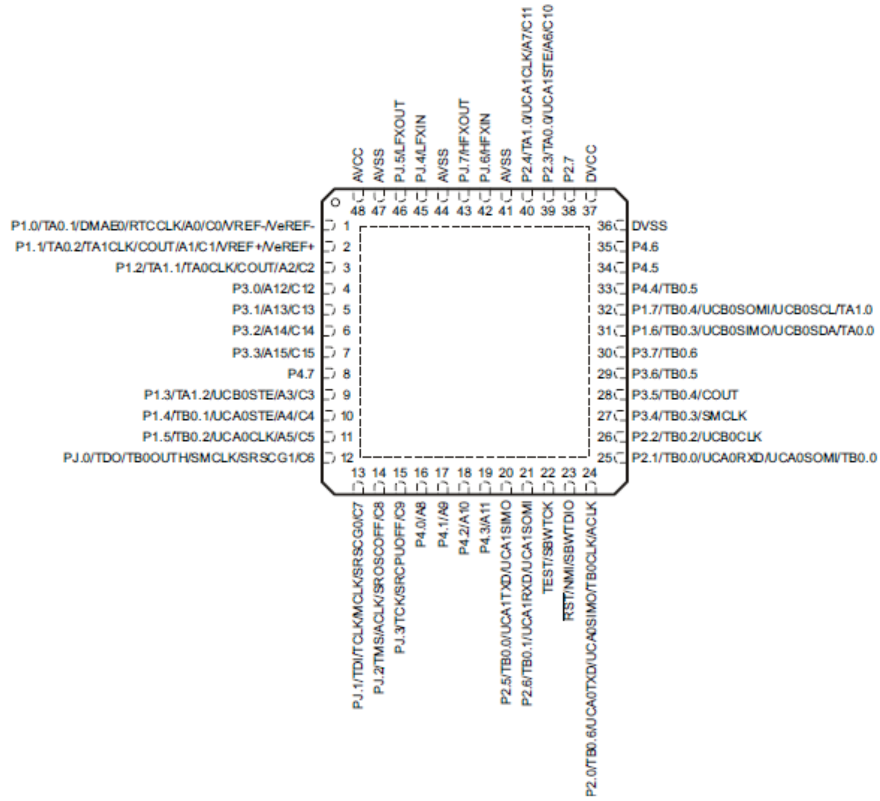


Figure 7.6. MSP430FR5969 complete pinout [A.26]

It can be seen that 20 pin configuration will be the most useful and commonly used to interact with other modules.

MSP430FR5969 features can be summarized and listed as:

- Voltage: 1.8V to 3.6V operation.
- Consumption: low power with 7µs wake-up, 450nA real-time clock mode and 100µA activation.
- Analog: 16-channel 12-bit differential ADC and 16-channel comparator.
- Digital: AES256, CRC, DMA, and hardware MPY32.
- Timmers: 5 blocks and up to three serial interfaces (SPI, UART, or I2C).
- Memory: Embedded 64KB FRAM and 2KB SRAM.
- Clock: Low frequency 32kHz crystal internal clock and up to 16-MHz system clock and 8-MHz FRAM access. Furthermore, an unpopulated region that supports HF crystal or resonator (4 to 24 MHz).

d) User Interface

On the bottom of the launchpad there are two buttons and two LEDs at the disposal of the user. They are to be used as needed; hardware which is already mounted on board to play with. Switches called S1 and S2 are connected to some digital inputs the MSP430FR5969 and they connect the in to GND when pressed. Light emitting diodes (LEDs) are configured as digital outputs on the chip.

Reset button under JTAG header is also considered as an interface button or switch. The difference is that reset is already configured for being so and other buttons are free programmable. Reset button is used start-up again the program in MCU.

For more information about the MSP-EXP430FR5969 LaunchPad, there is a User's Guide [A.26] in annexes section. Regarding programming part, there will be a dedicated chapter for explaining it in detail. See chapter 9.

In general, ultra-low power microcontrollers have applications as for instance: industrial sensing and communications, renewable energy, control and security, measurements and personal electronics.

7.3. Module 4

For the multiple-input boost converter all components will be deeply analyzed and studied. Each of them is crucial as if one of them consumes or dissipates power, it will unavoidably affect on the output as we are talking about energy harvesting, so microwatts of power. Any loss of power is significant.

All components combination must ensure a suitable input and output parameters. Moreover, all of them must be surface-mounted (SMD) to be placed on a printed circuit board (PCB). This way, energy losses are minimized and connections are optimized. The components have also high accuracy compared to insertion ones.

7.3.1. Transistor Q0

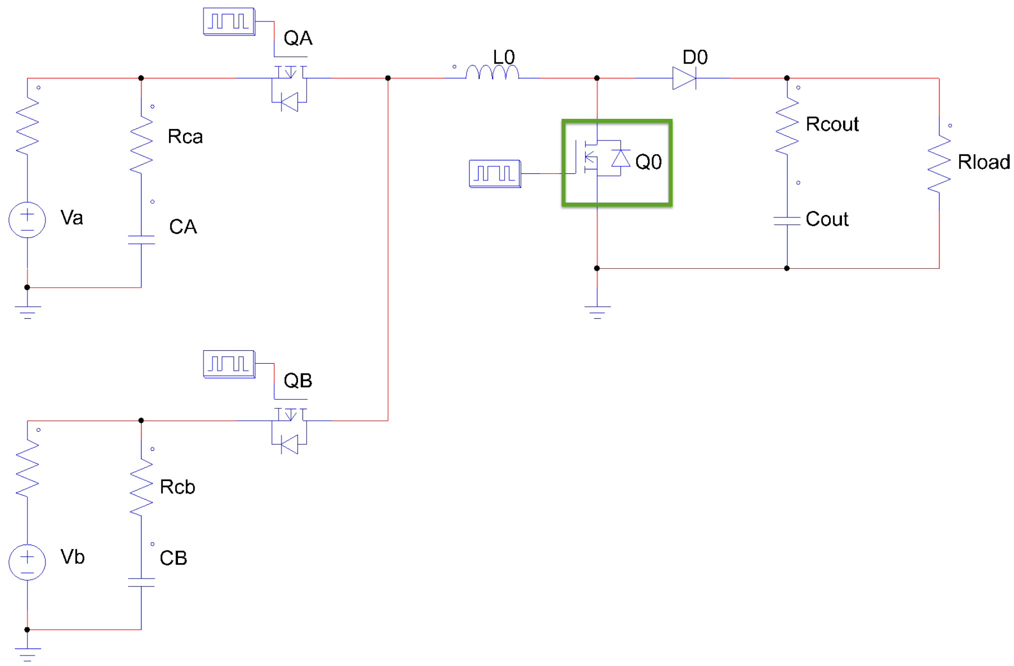


Figure 7.7. Schematic diagram module 4 with Q_0 highlighted [PSIM]

Transistor to control the boost functioning must be a N-Channel MOSFET as the source is directly connected to GND so the switch must be activated by a '1' logic signal. Furthermore, as the transistor is controlled by voltage apply, the consumption is almost zero, this is already explained in Theoretical Background (chapter 2). Another important factor in order to choose the optimal NMOS is having very low resistance to avoid consuming on the circuit.

The component chosen is **CSD18542KTT** from Texas Instruments [A.28].

- Type: Enhancement N-Channel MOSFET Transistor
- Package: TO-263
- V_{DS} resistance: 4 mΩ
- $V_{GS(th)}$ Threshold voltage: 1,8 V

This is the lowest resistance found in this kind of transistors.

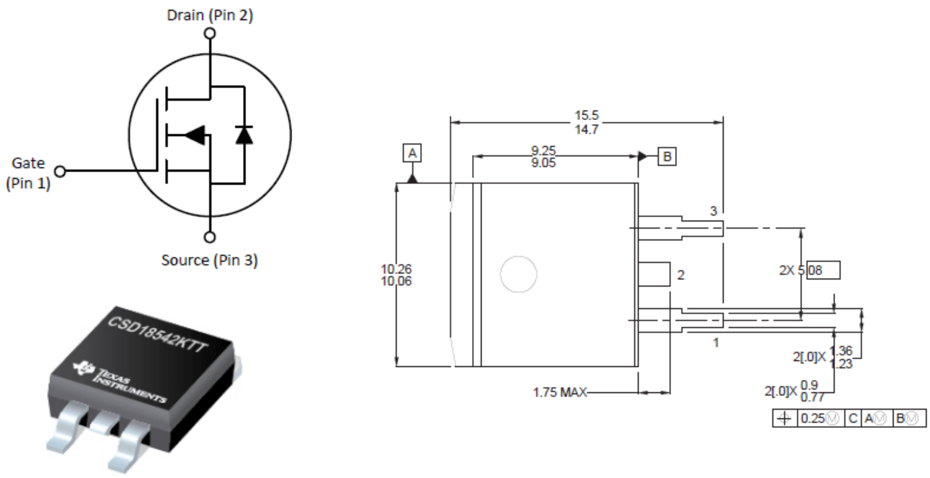


Figure 7.8. Image and connections from CSD18542KTT NMOS transistor [A.28]

7.3.2. Transistors Q_A and Q_B

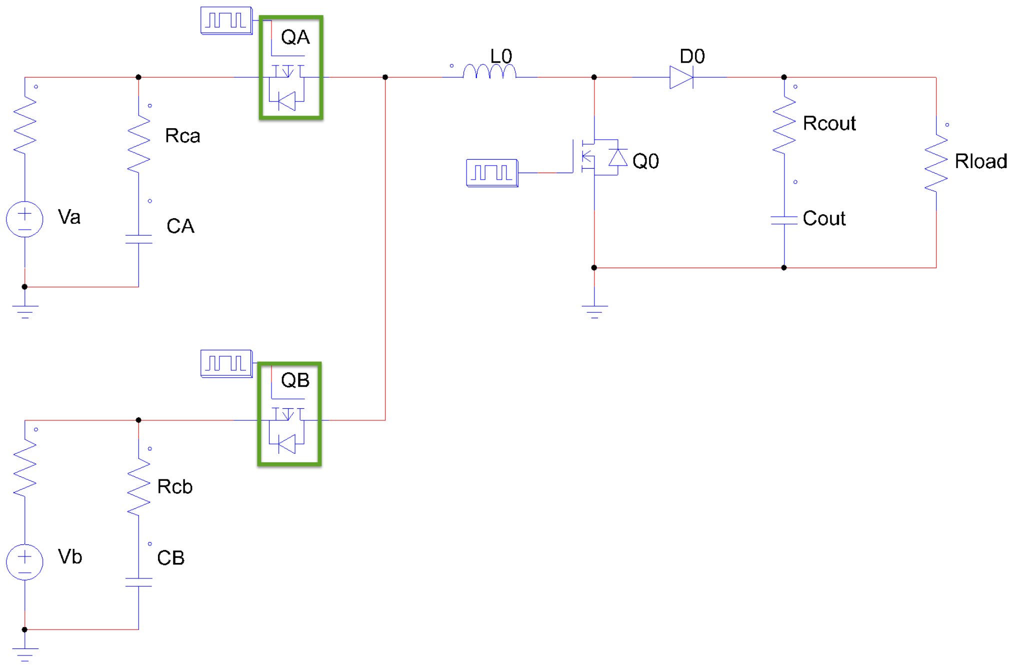


Figure 7.9. Schematic diagram module 4 with Q_A and Q_B highlighted [PSIM]

Transistors to control inputs in boost converter in module 4 are P-Channel MOSFET as the known voltage is the one on the input (source) and gate can be connected to GND to activate the switch with a '0' logic signal. This transistor is also working with voltage switching so it has low consumption. This can also be seen in the chapter mentioned before.

The components chosen are both **Si4943BDY** from Vishay [A.29].

- Type: Enhancement P-Channel MOSFET DUAL Transistor
- Package: SO-8
- V_{DS} resistance: 30mΩ

Dual configuration has been cheaper and perfect to reduce space on module 4 and modules 1 and 2 for V_{OR} switching.

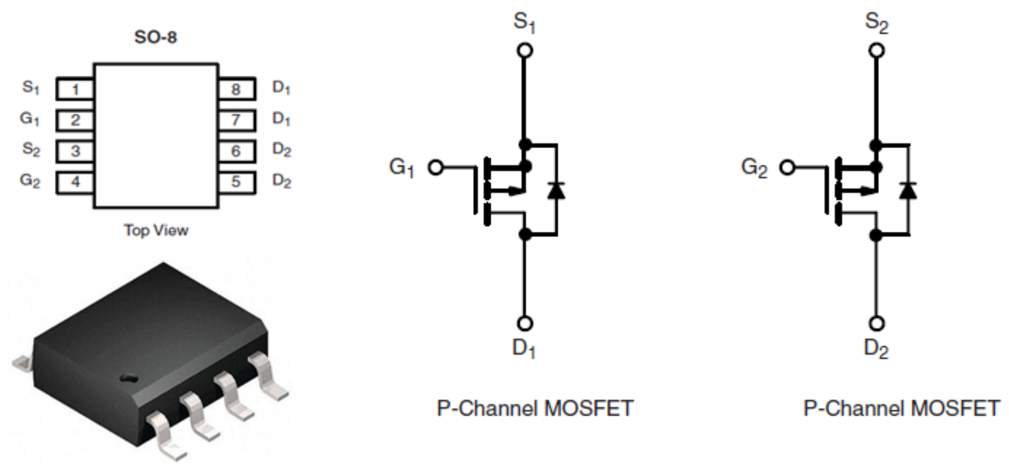


Figure 7.10. Image and connections from Si4943BDY PMOS transistor [A.29]

7.3.3. Diode D_0

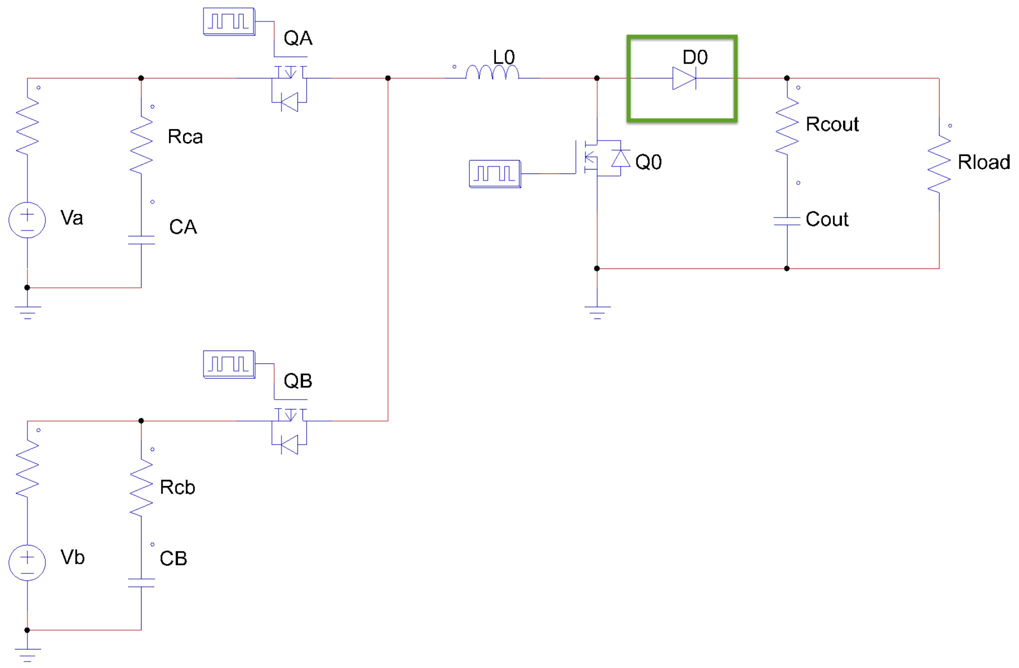


Figure 7.11. Schematic diagram module 4 with D_0 highlighted [PSIM]

For the diode, as it has been mentioned in the same chapter commented before, Schottky type has to be chosen as all voltage used in this switch is lost referring to the output battery or load. It must be fast in responding and selected according to the maximum I_F in previous calculation. Schottky diodes are characterized to have low V_F and low serial equivalent resistor, from many searched, the best one is the following one.

The component chosen in **MBRS130L** from Fairchild Semiconductor [A.30].

- Type: Diode rectifier Schottky
- Package SMB/DO214AA
- I_F= 1A
- V_F= 0.3V

This Schottky diode is SMD type.

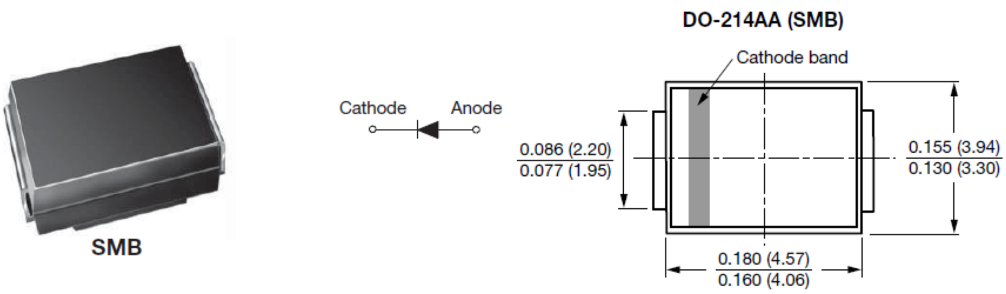


Figure 7.12. Image and connections from MBRS130L diode [A.30]

7.3.4. Inductor L_0

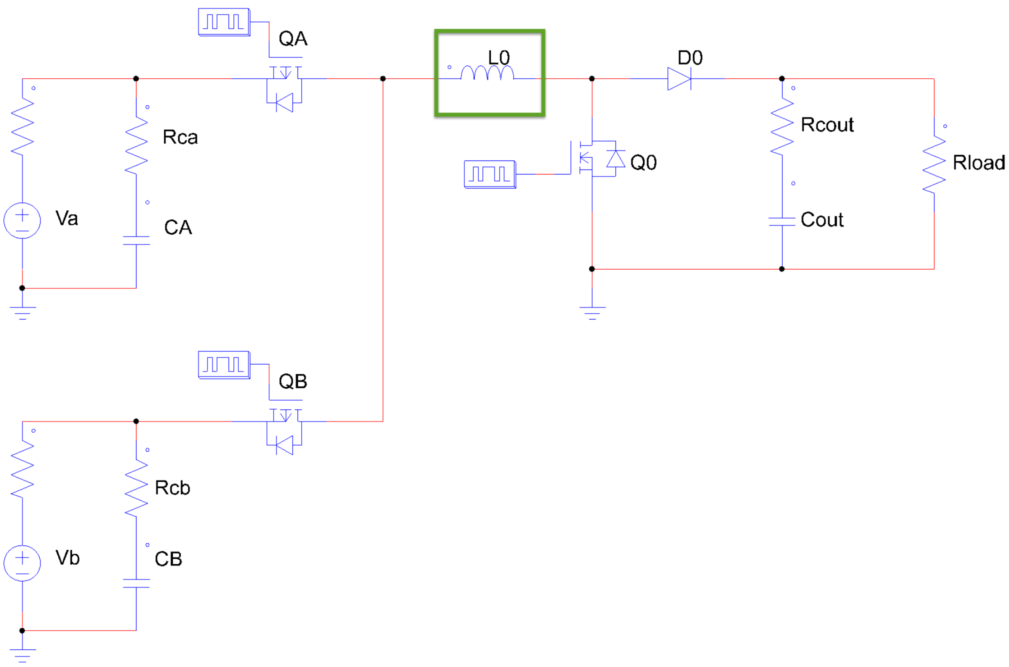


Figure 7.13. Schematic diagram module 4 with L_0 highlighted [PSIM]

Inductor has to be in µH order as calculated before in 22 µH – 120 µH range with low resistance in series model. Coilcraft is giving samples and is the one recommended by the original EVMs.

The inductor chosen is **LPS6235** (22 µH /56 µH /82 µH /120 µH) from Coilcraft [A.31].

- Type: Inductor
- Package L5650M
- Inductance: 22 µH/56 µH/82 µH/120 µH
- DC resistance max: 0,145 Ω/0,280 Ω/0,315 Ω/0,435 Ω

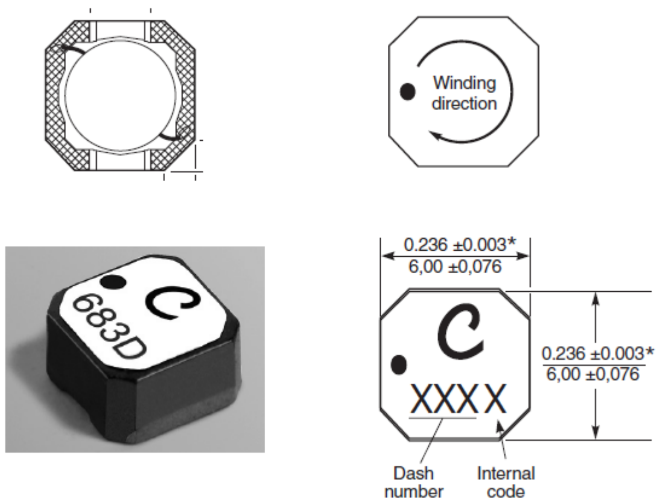


Figure 7.14. Image and connections from LPS6235 inductor [A.31]

7.3.5. Capacitors C_A and C_B

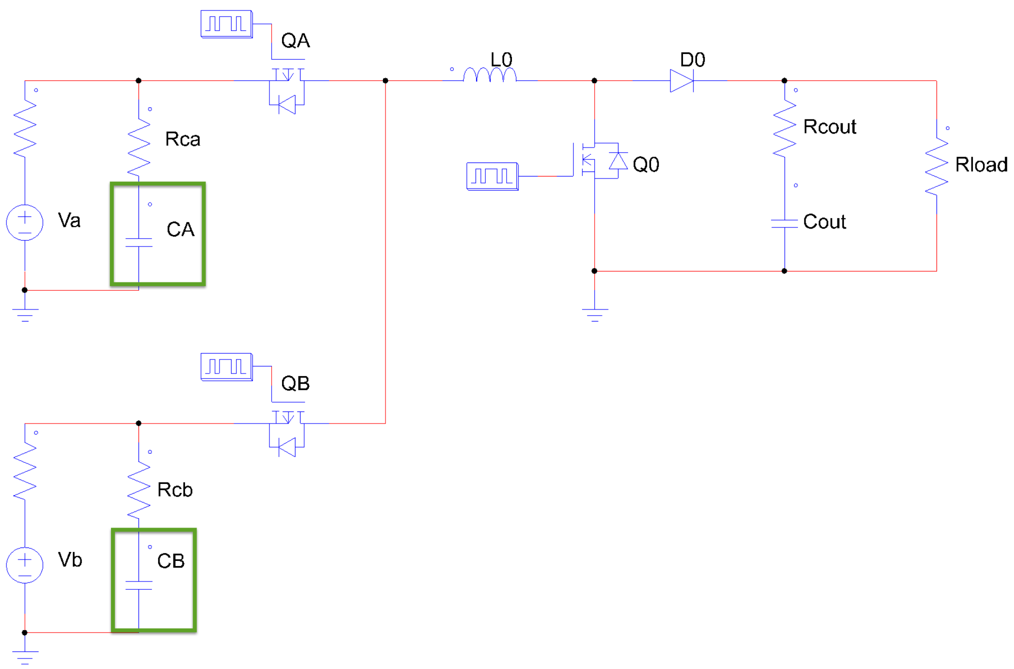


Figure 7.15. Schematic diagram module 4 with C_A and C_B highlighted [PSIM]

These input capacitors must have enough capacitance to store all energy depending on the harvester on the input and at the same time, they must be high enough to never reach the full capacity for not losing power. The perfect combination is a very low series equivalent resistance to avoid consuming and the high capacitance in the order of µF.

The capacitors chosen on the input are **TPSD107K010R0100** from AVX [A.32].

- Type: Tantalum capacitor
- Package 2917 (7343 metric)
- Capacitance: 100 µF
- Equivalent Series Resistance: 100 mΩ

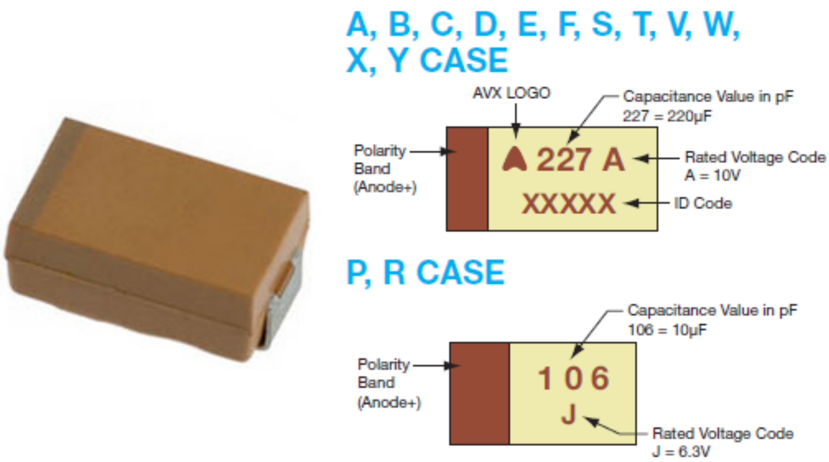


Figure 7.16. Image and connections from TPSD107K010R0100 capacitor [A.32]

7.3.6. Capacitor C_{out}

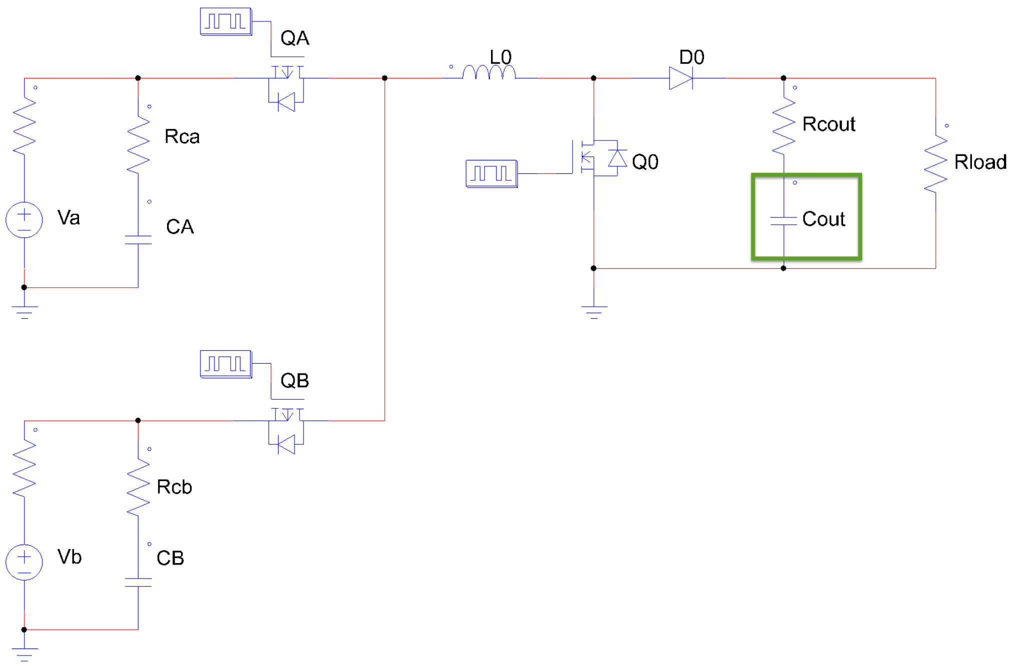


Figure 7.17. Schematic diagram module 4 with C_{out} highlighted [PSIM]

Same capacitor as before to store voltage coming from inductor and inputs. Affects on the ripple and let voltage flow to the load.

The capacitors chosen on the input are **TPSD107K010R0100** from AVX [A.32].

- Type: Tantalum capacitor
- Package 2917 (7343 metric)
- Capacitance: 100 µF
- Equivalent Series Resistance: 100 mΩ

7.4. Bill of Materials (BOM)

Component	Manufacturer	Value	Quantity	Price by unit	Total price
R1, R1’	Vishay	7,5 MΩ	2	0,0034 €	0,0068 €
R2, R2’	Vishay	5,76 MΩ	2	0,10 €	0,20 €
R3, R5, R3’, R5’	Vishay	4,99 MΩ	4	0,10 €	0,20 €
R4, R4’	Vishay	10 MΩ	2	0,007 €	0,014 €
R6, R6’	Vishay	887 KΩ	2	0,10 €	0,20 €
R7, R7’	Vishay	6,98 MΩ	2	0,097 €	0,194 €
R8, R8’	Vishay	5,36 MΩ	2	0,10 €	0,20 €
C1, C1’	Kemet	4,7 µF	2	0,45 €	0,90 €
C10, C10’	Murata	4,7 µF	2	0,032 €	0,064 €
C2, C2’	Murata	10 4,7 nF	2	0,008 €	0,016 €
C3, C3’	Murata	100 µF	2	2,85 €	5,7 €
C4, C6, C4’, C6’	AVX Corporation	100 nF	4	0,47€	1,88 €
C5, C5’	Taiyo Yuden	4,7 µF	2	0,12 €	0,24 €
C13, C13’	Murata	1 µF	2	0,044 €	0,088€
CKAP	AVX Corporation	100 µF	3	0,64 €	1,28 €
L1, L1’	Wurth Electronics	22 µH	2	1,48 €	2,96 €
L0	Coilcraft	82 µH	1	1,47 €	1,47 €
QA, QB	Vishay	PMOS 20 V	2	1,97 €	3,94 €
Q0	Texas Instruments	NMOS 60 V	1	1,81 €	1,81 €

HARV1	Laird Technology	40 mm	1	29 €	29 €
HARV2	Powerfilm	4,8 V @ 100 mA	1	14 €	14 €
HARV1'	CUI Inc	15 mm	1	13 €	13 €
HARV2'	Powerfilm	3,6 V @ 100 mA	1	15 €	15 €
PRI_BAT	-	3 V	1	0,75 €	0,75 €
SEC_BAT	RS	3,6 V	2	5,99 €	11,98 €
BQ25505	Texas Instruments	-	2	5,13 €	10,26 €
SUPER_CAP	Panasonic	0,22 F	2	1,98 €	3,96 €
MSP-EXP430FR5969	Texas Instruments	-	1	15,18 €	15,18 €
MASC_PINS	-	-	100	0,74 € (20 u)	3,7 €
FEM_PINS	-	-	40	0,74 € (20 u)	1,48 €
JUMPERS	-	-	6	0,74 € (20 u)	0,74 €
QFN_SOCK	-	QFN – DIP20	2	0,48 €	0,96 €
TOTAL	-	-	-	-	141,37 €

Table 3. Bill of Materials

8. Implementation and Prototyping

It is recommended to follow the next procedure when implementing a prototype: first trying the circuit in a protoboard to verify its correct functioning, then soldering it in a stripboard with insertion components to test it and finally soldering SMD (surface mount device) components in a designed and optimized PCB (printed circuit board).

In this project, the protoboard option has been discarded due to the energy losses and error possibility that it implies. For an energy harvesting application, connections and distances between components are crucial so precision must be very present. The process missed the first step to go directly to the stripboard option with insertion components and then the PCB design and soldering. Now the process will be explained in detail.

8.1. Stripboard Insertion Prototype

The circuit is made of four modules so there are four small circuits to implement individually. The first module implemented has been the module 1, as it was the simplest and the one who was supposed to give fewer problems. The design was clear as it was the same Texas Instruments proposed for BQ25504 boost converter, which is simpler than BQ25505, and both can be used for TEG application in module 1 as it has been explained in Main Computations (chapter 5). This chip has also fewer pins and therefore less connections to do, so it has been the first option to implement to verify the correct functioning and to do so, it is needed the following material:

- Stripboard.
- Insertion Components (Resistors, Capacitors, Inductors…).
- BQ25505 boost converter chip.
- QFN-DIP16 socket.
- Soldering material (tin, soldering iron, flux…).

Before continuing with the implementation, it is interesting to emphasize the process of obtaining that kind of material.

Insertion components, stripboards and soldering material to do some prototyping are not hard to found. Through internet, all of that can be purchased without a minimum quantity required in some worldwide suppliers and distributors as AliExpress, Amazon and Ebay; there are also some of them specialized in electronics which are RS, Mouser, Farnell and Digikey among others. Finally, in Barcelona there are some specialized physical shops regarding electronics: Diotronic, OndaRadio, Charles Electronics, Metroelectrónica, etc.

However, BQ25504 chip is not that easy to solder and operate with; the chip is SMD and QFN type, which means that to be used as an insertion component it must be soldered to a socket which has QFN connections converted in DIP configuration. The boost converter can be found in online electronic shops but commonly shipment costs are expensive compared to the chip itself. It can also be found in Texas Instruments web and besides that; user can have some samples for free if owning a web domain. This final grade project has become a kind of enterprise beginning and its domain is actually www.wearekap.com, so samples request has not been a problem. This domain expects to collect all interesting data in this project and as well as other interesting documents or work done related. The domain is the base of other entrepreneur projects coming from now on as well as a tool to contact the authors of this project by the mail info@wearekap.com. Sample request instructions in Texas Instruments enterprise through its webpage can be found as an easy guide in annex [A.17].

Finally, socket needed for BQ25504 usage must be 16 pins socked and must have the correct measures requested for QFN type components. This element can also be found in online shops mentioned before. Once all components gathered, soldering can begin.

Insertion soldering is not a complicated process, authors' method is described in annex [A.16] but here are a few recommendations to solder insertion components:

- Hot both elements to solder before applying tin (45 degrees with soldering iron).
- While soldering, stay the less time possible to avoid burning components.
- Use soldering iron of maximum 25W to avoid component harming.
- Move the tin away before the soldering iron.

On the contrary, BQ25504 soldering is more complicated, especially if the package is QFN type.

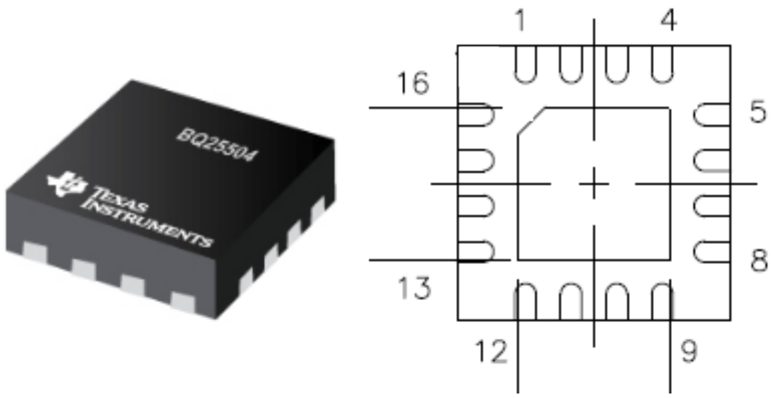


Figure 8.1. QFN package example [A.22]

Again, the way of soldering this kind of chip is explained in the annex mentioned before but here are some recommendations:

- Use flux to apply tin on it.
- Minimum soldering time to avoid burning the chip.
- Use soldering iron of maximum 13W to avoid chip harming
- Use of a magnifying glass to help.

The final result once all welded is the following:

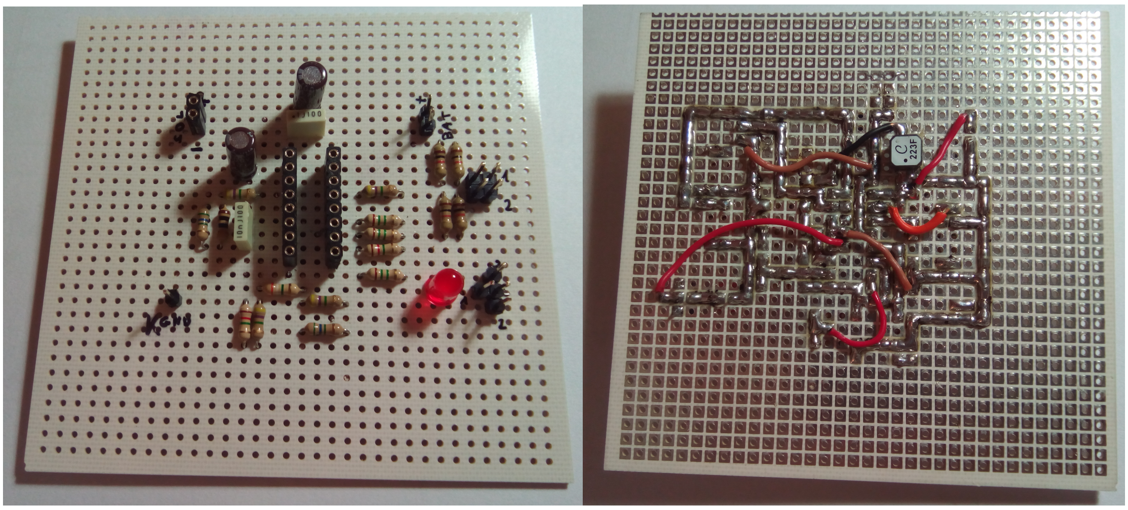


Figure 8.2. Final result of the insertion prototype [self-made]

This prototype does not work due to connection losses in come components and mainly because insertion components are not as accurate as SMD ones, the most precise values in insertion model components is not fair enough and varies a lot with temperature changes. As a consequence, the insertion implementation regarding other modules is automatically discarded; this type of configuration does not allow the circuit to be tested correctly. All modules will be implemented directly in PCB board.

8.2. PCB Surface Mount Prototype

As it can be seen in the previous section, the way to test the modules individually and all together will be PCB process: material obtaining, PCB designs, PCB manufacturing, SMD component soldering and module testing.

Module 1 and 2 prototyping in PCB implies the following elements:

- SMD Components (Capacitors, Resistors, Inductors…)
- Printed Circuit Board
- BQ25504/BQ25505 chip.
- QFN-DIP16/QFN-DIP 20 socket.
- Soldering material (tin, soldering iron, flux…).

The place to get this material must be mentioned. SMD components are difficult to get as a user as they are usually available in huge quantities only, for enterprises. Almost all online shops request a minimum quantity purchase and for this kind of project it is useless to purchase 1000 resistors when only 5 are needed, for instance.

Again, a good solution is to ask for samples. Sample requesting in Texas Instruments has already been commented before so now there is a list of manufacturers which provide fast deliver good quality samples. All of them tested by the authors of this project. The list is ordered from top to bottom as the best and the worst respectively; despite this, all 5 enterprises have good response to sample request.

1. TE
2. Fairchild
3. Coilcraft
4. Wurth
5. Copper/Eaton

Other than that, Texas Instruments as been the best in terms of boost converters as BQ25504 and BQ25505 samples have been useful and easy to obtain. N-Channel MOSFET transistors have also been quite easy to get through TI webpage. Microchip is also a good supplier of PIC microcontrollers, already described in chapter 2.4.

There also exists a BQ25570 similar boost converter chip from Texas Instruments. But this has also a buck converter integrated to the output, which is not interesting for the present project as some power will be lost in buck converting operation. Here is better to boost as much as possible to obtain maximum power to the output.

In annex [A.21] a summary of the mentioned manufacturers communication and mailing is shown but here there is a brief guide of obtaining samples from a manufacturer following author advice:

1. Go to manufacturer web.
2. Go to sample section (if available).
3. Product searching.
4. Sample requesting.
5. Registering (if needed).
6. Completing required data.
7. Product receiving.

Sample requesting is an option, but sometimes not all components needed for this MIMO boost converter implementation can be obtained this way. So the option is buying the components in the cheaper site of internet electronic shops. Later on another solution will be explained but first, PCB design takes place in the report.

For the designing of modules, software must be chosen; in this case, EAGLE PCB design is the one that is well-considered and used in many cases for many manufacturers, it has many advantages respect others: there is a lot of information on internet as is commonly used, there are many components libraries included in the software, numerous design options, intuitive operation and a fair community behind to give support.

Using this software, module 1 and 2 was first designed following the datasheets of boost converters evaluation modules from TI; EVM-BQ25504 and EVM-BQ25505 for module 1 and module 2 respectively. See the following figures and deeper in annexes [A.24] and [A.25].

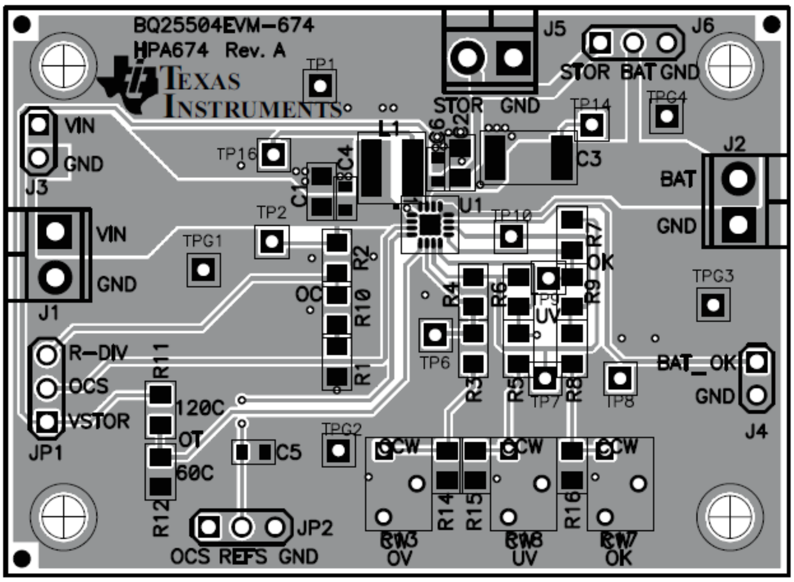


Figure 8.3. EVM-BQ25504 top assembly [A.24]

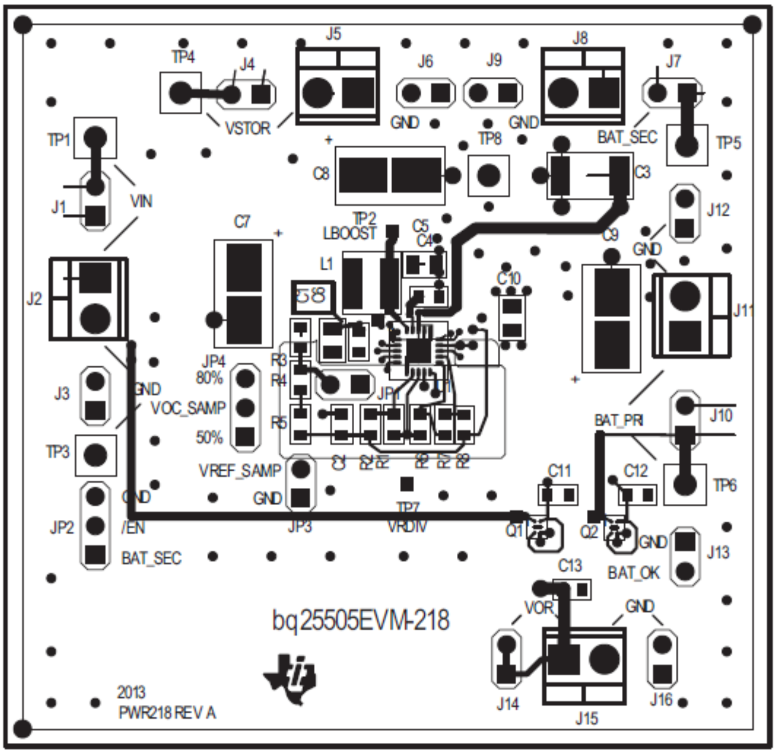


Figure 8.4. EVM-BQ25505 top assembly [A.25]

The PCB design was done by EAGLE software following some specifications [4]:

- Place the chip on the center
- Place pinout on the close to the square edges as desired
- Avoid 90 degrees paths in routes
- Place input and bypass (input) capacitors as close to the pin 1 as possible
- Place output and bypass (output) capacitors as close to the pin 19 as possible
- Place the components and copper routes on top layer preferable
- Place the resistors as close as possible between them
- Power line should be as wide as possible
- Inductor as close as possible to pin 20
- Use short traces
- Connect power path from BQ25505 to GND

Schematics of first order in .sch format as well as the .brd layout files can be found in [A.41] and [A.43]. Also, top and bottom layers can be found graphically in [A.19].

The size of the PCB design is 5 cm x 5 cm and FirstPCBs manufacturer offers PCBs of size 10 cm x 10cm as the cheapest, so it has been decided to implement 4 circuits in each PCB ordered and cut them to obtain the circuit designed.

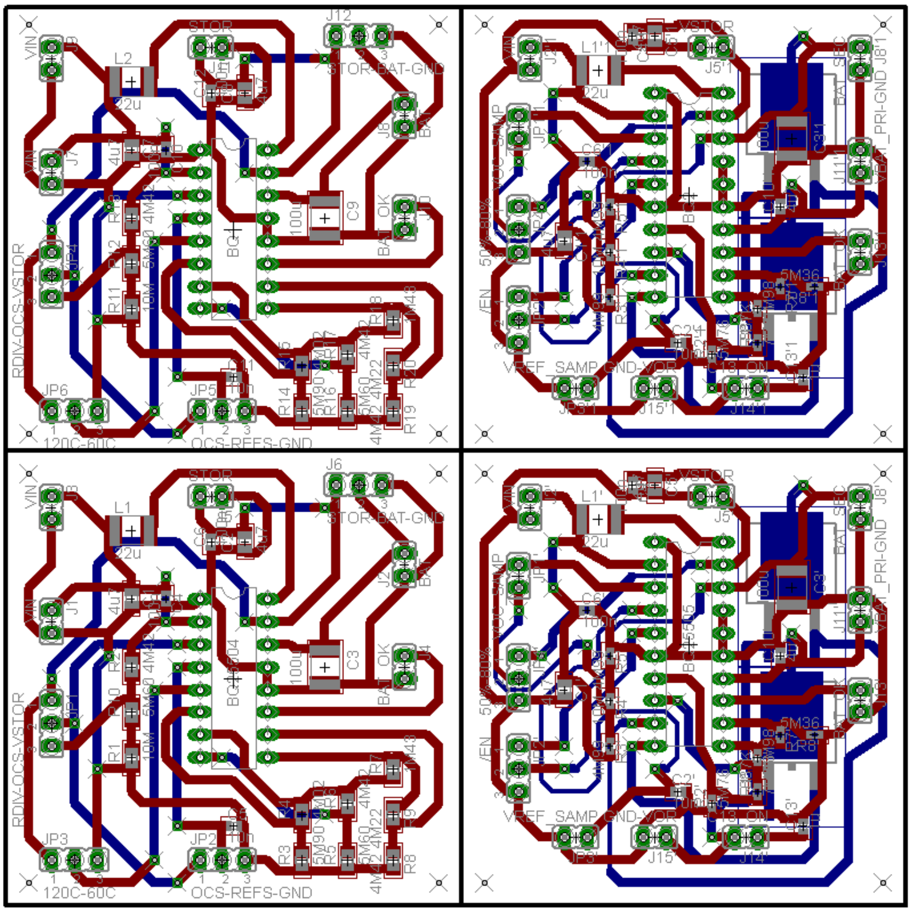


Figure 8.5. 1st order layout [EAGLE]

Then, a gerber file must be created [A.44]. The following steps describe how to do it:

- Schematics window → File → CAM Processor
- Create Folder called Gerbers
- Select Gerber_RS274X
- Create 5 sections:
- Components (Top, Pads, Vias) → Write %P\Gerbers\%N.cmp
- Solder (Bottom, Pads, Vias) → Write %P\Gerbers\%N.sol
- Component Silk (Dimensions, tPlace, tNames, tValues) → Write %P\Gerbers\%N.plc
- Component Stop (tStop) → Write %P\Gerbers\%N.stc
- Solder Stop (bStop) → Write %P\Gerbers\%N.sts

- Select EXCELLON
- Create Drill Section:
- Drill (Drills, Holes) → Write %P\Gerbers\%N.ncd
- File → Save Job → Name
- Process Job

Once design is done, revised and *gerber* files are exported, there is a need to search a PCB supplier. A deep research on PCB manufacturers from all around the world has been made to choose the optimal one. The combination of reasonable price and board quality is the better option, nevertheless as authors in this project are university students, and PCB quality cannot be tested until a sample is got; the board performance was only based on price and recommendations. Here, the 'ranking' of all PCB manufacturers searched and studied can be seen:

1. FirstPCBs
2. DirtyPCBs
3. PCBWay
4. KIKIPCB
5. Futurlec

The first and second option were both good ones but regarding price, as the first order in First PCBs has a considerable discount, this Chinese enterprise was chosen. Later, authors discovered in the website that, while ordering the boards, there was also the option of buying SMD components in a cheap price and without minimum quantity request. So this factor finally make the authors opt for First PCBs without any doubt because, from one site it is the cheaper option and, from the other site, is the only way of getting SMD precise components unit by unit and good price.

The treating through mail and board quality overcame our expectations. Printed circuit boards seemed professional and the design was consistent. Even though there were some mistakes to correct for the next version:

- Bigger diameter of screw support holes
- Bigger inductor package
- Pins were communicating with TOP and BOTTOM sides so there was no need of using so many bias.
- Place names in a correct way because all of them are printed on the pcb
- Bigger BQ25505 package
- Resistors, capacitors and inductor closer to the pins
- Holes on the division lines in order to cut the different circuits (5 cm x 5cm each) easily.
- Change NMOS Mosfets by PMOS Mosfets and redesign this part of the circuit

The component order option was taken after with errors corrected on the board and adding module 4 design. There was also the possibility of ordering the PCB with all components welded by First PCBs crew but the price was too much and there was no sense on learning from student point of view. Then, soldering process takes place when the boards and component, coming from either samples ordered or from First PCBs, were available after waiting 3 weeks; a bit more than expected.

Flux is not recommended to do this operation and especially for energy harvesting applications. It is confirmed by the authors in the present project that all components listed in BOM (chapter 7.4) can be welded without using flux substance. Furthermore, with flux usage, circuit seems ‘dirty’ for presentation or purchasing. Nevertheless, if some component is too small flux can be used in a proper way.

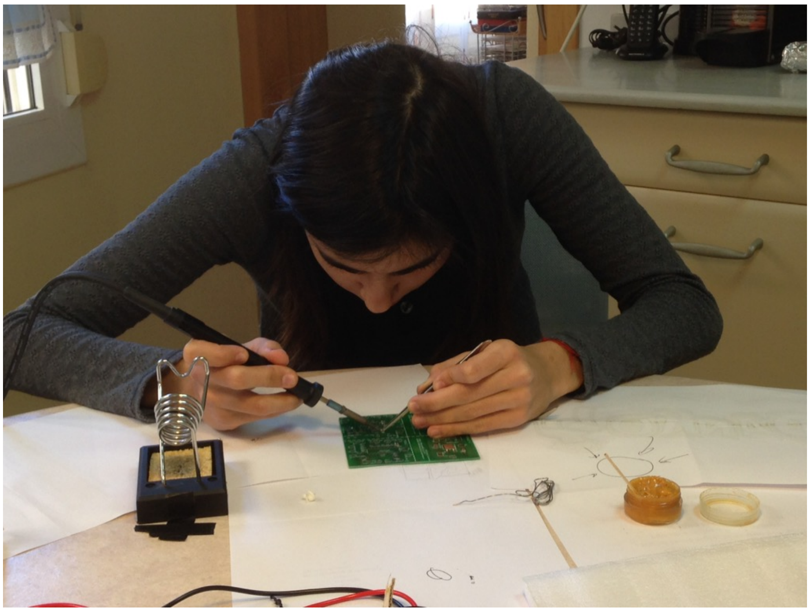


Figure 8.6. Soldering SMD components [Self-made]

Circuits from the first order of PCBs was checked and tested and all features were taken into account for the second version. This one included module 4 in it, and all corrections ensured that order to be the definitive. This time module 4 was implemented twice on the same board as the boost converter was not tested yet so the idea was having different kind of circuits to test both. Changing some inductor and capacitor values, the layout would be equally valid.

Schematics of second order in .sch format as well as the .brd layout files can be found in [A.45] and [A.47]. Also, top and bottom layers can be found graphically in [A.20].

Some improvements were made. Some of them are:

- Big surface of GND
- Change of the MOSFETS used
- All the components on the top layer
- Solution of the errors mentioned previously

To implement a big surface of GND on EAGLE the steps presented should be followed:

- Create a Polygon 

- Parameter Solid
- Select Isolation Distance
- Name the polygon with the same name as GND desired
- Click Ratsnest 
- Hint: For different GND in different circuits, Name the cable with Name 

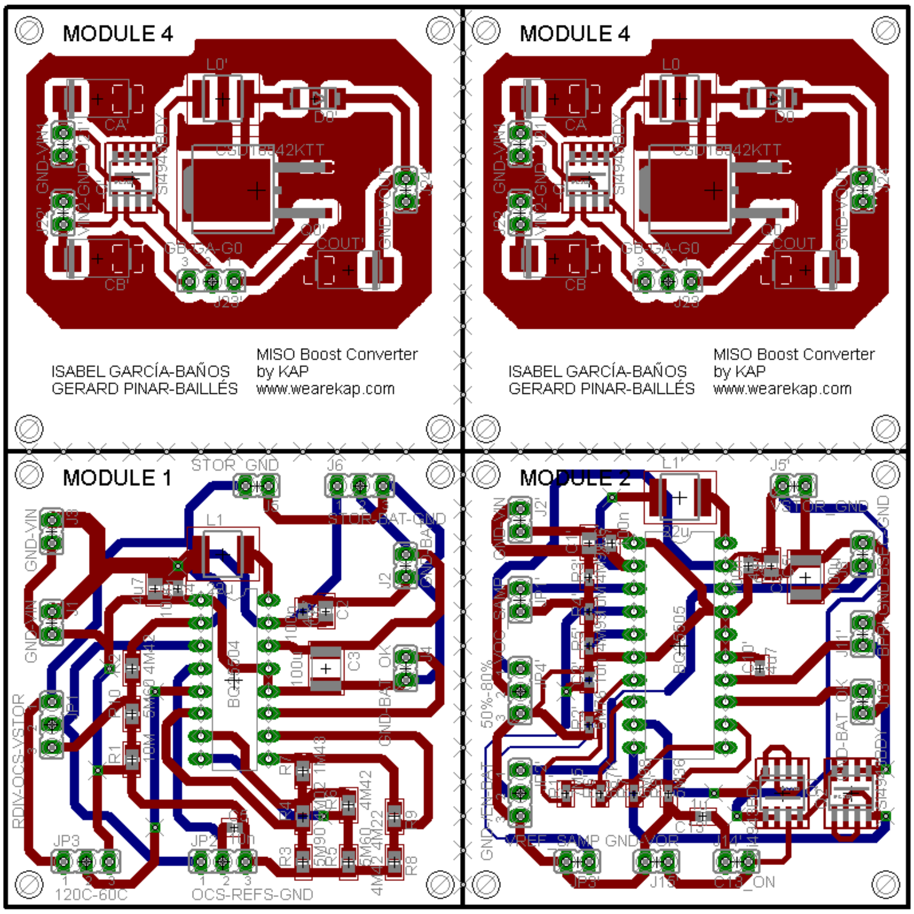


Figure 8.7. Soldering SMD components [Self-made]

Once the order was get, the components were welded with accuracy and patience and continuity between routes was checked. All modules 4 modules work correctly and with no error. This could be possible thanks to a correct design in EAGLE, an appropriate component selection and a correct soldering process. The essays and testing is explained in detail in Experimental Results (chapter 10).

The process of soldering 2nd order prototype is organized below:

Module 1 and 2

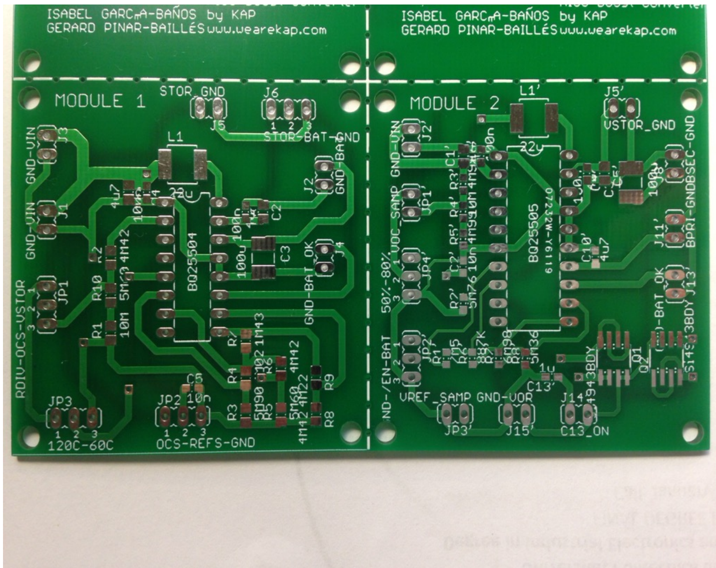


Figure 8.8. Soldering module 1 and 2 initial part [Self-made]

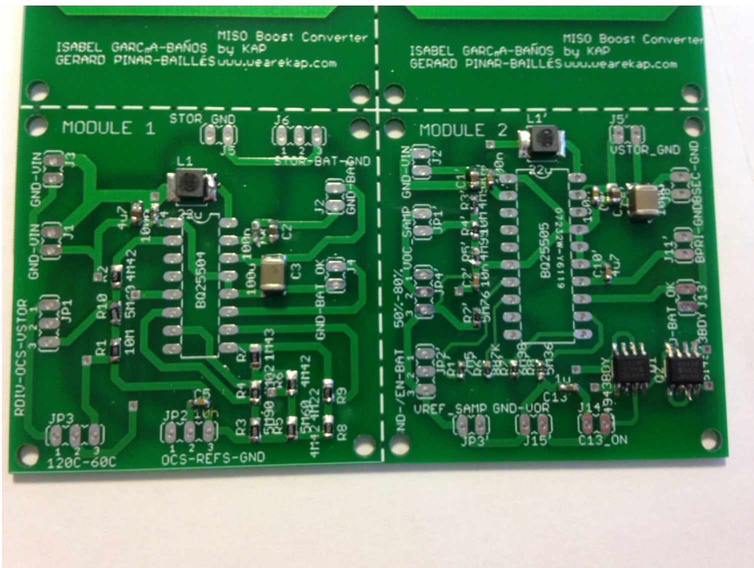


Figure 8.9. Soldering module 1 and 2 small components [Self-made]

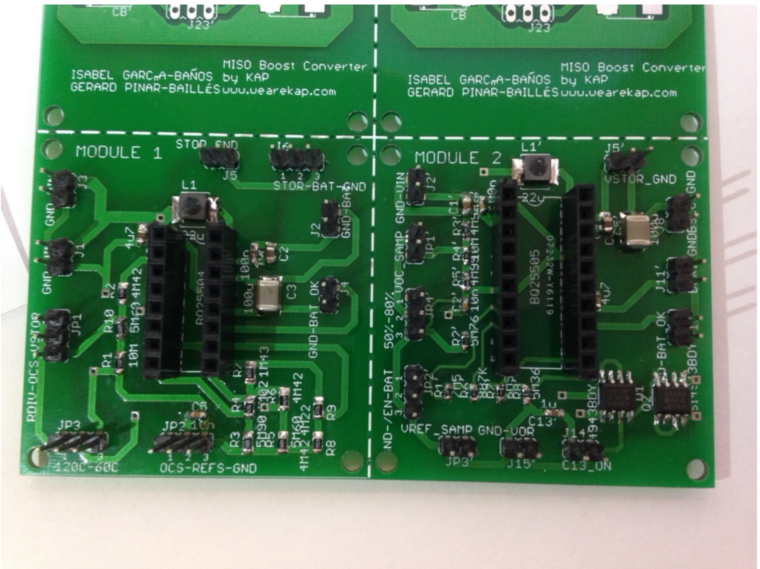


Figure 8.10. Soldering module 1 and 2 pins [Self-made]

Module 4

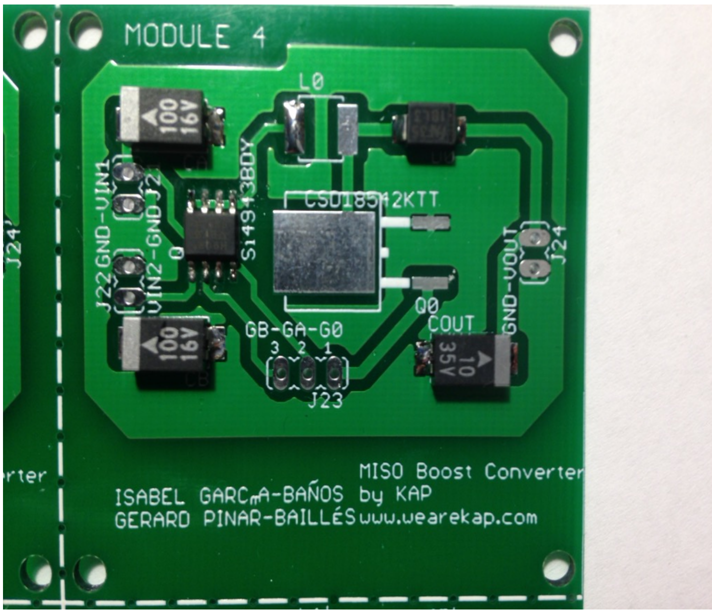


Figure 8.11. Soldering module 4 small components [Self-made]

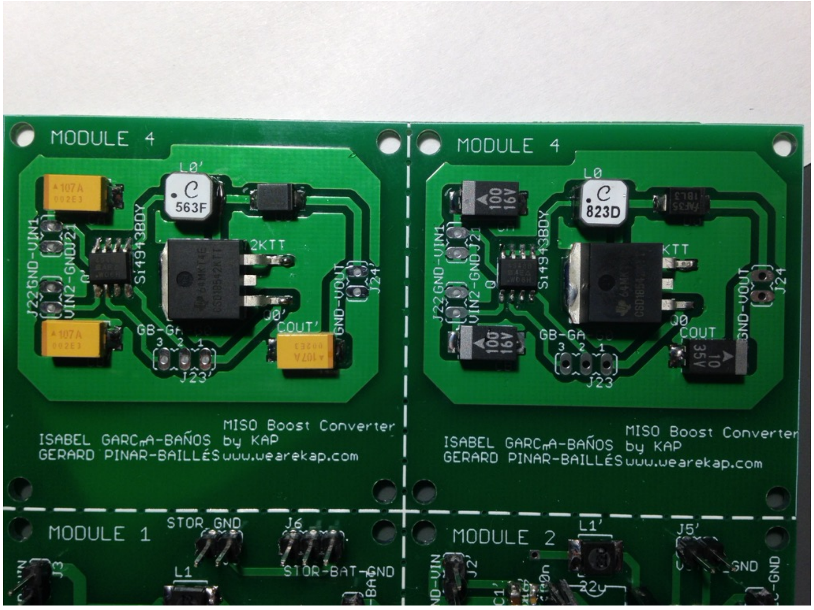


Figure 8.12. Soldering module 4 big components [Self-made]

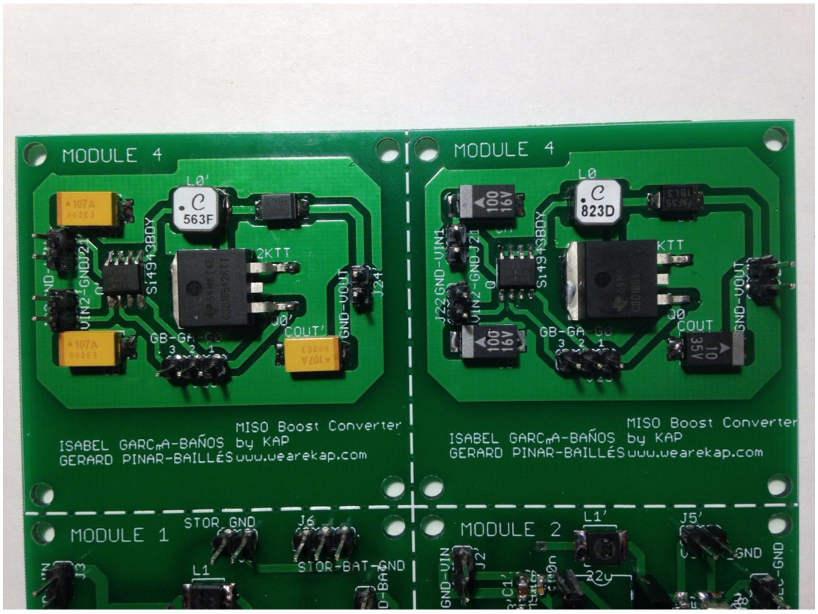


Figure 8.13. Soldering module 4 pins [Self-made]

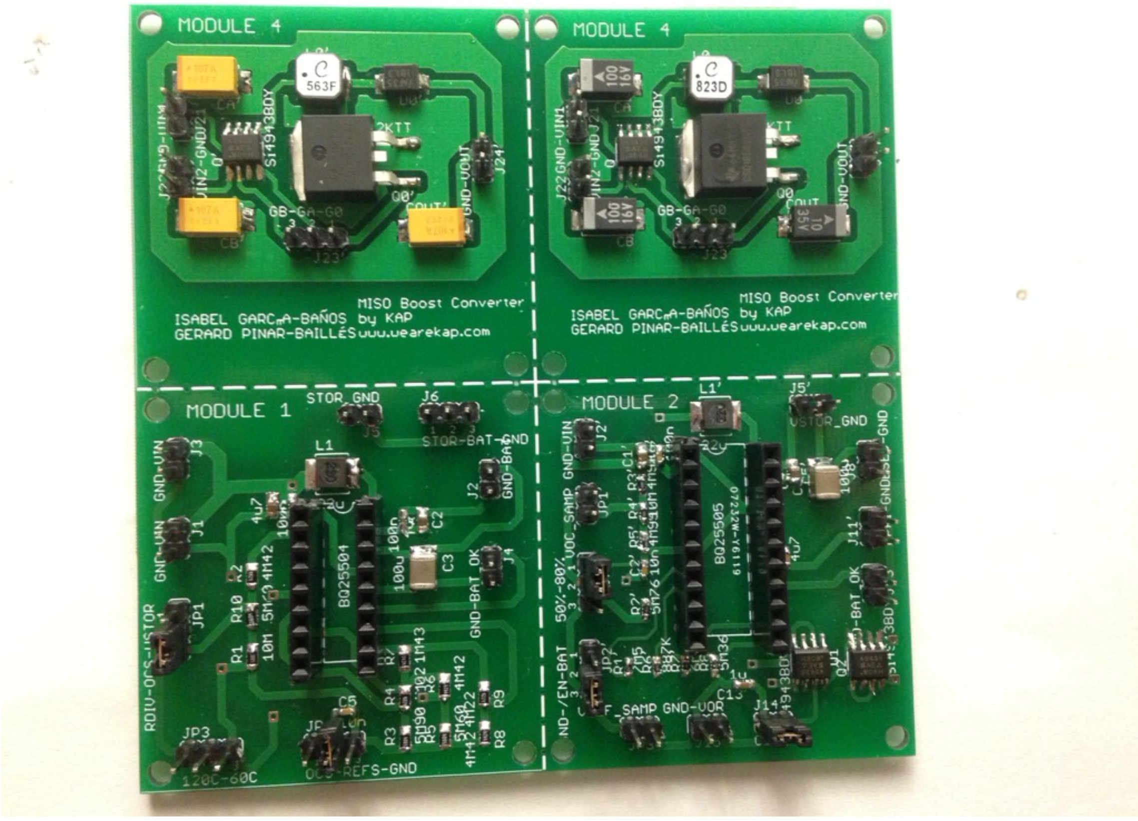


Figure 8.14. Complete 2nd order prototype welded [Self-made]

After all, a good PCB design is considered the best way to build circuits. Protoboard and stripboard could help in testing but the implementation done in this project is for sure the most robust model between these three options; in special, if the prototype is for energy harvesting applications.

9. Programming

In this section the program to be introduced in the microcontroller MSP430FR5969 will be studied. It will perform the desired function. This function is mainly to control the switching of module 4. As it has been seen in the section Main computations (chapter 5), this project will use two different types of switching, so there will be two different programs, depending on the chosen switching.

The procedure to follow to design these programs will begin with a simple code that fulfils the basic function and then will be improved to obtain the definitive program. This entire programming process will be done with the Texas Instruments' 'Energy' software. This tool is very similar to the programming environment of Arduino and that makes the task much easier, since the authors of the present project know well and have used this resource a lot. The first program designed will be responsible for performing the second type of switching, that is, the one that is prepared for two complementary inputs at all times. This code will be the first one to be worked on because the programming level required is simpler. The first implemented code that worked correctly was the following:

MIMOBoost_ComplenentarySwitch_Trial §

```
/*Trial of the complementary switching*/
int i = 0;
int state = 0;

void setup()
{
  pinMode(11,OUTPUT);
  pinMode(12,OUTPUT);
  pinMode(13,OUTPUT);
  analogWrite(12,LOW);
  digitalWrite(13,HIGH);

}

void loop()
{
    digitalWrite(11,HIGH);
    delayMicroseconds(5);
    digitalWrite(11,LOW);
    delayMicroseconds(5);
  if ((i==5) && (state == 1)){
      digitalWrite(12,HIGH);
      digitalWrite(13,LOW);
      state = 0;
      i = 0;
  }
  if ((i==5) && (state == 0)){
      digitalWrite(12,LOW);
      digitalWrite(13,HIGH);
      state = 1;
      i = 0;
  }
    i = i+1;
}
```

Figure 9.1. Complementary switching trial program [A.50]

The comments describe the function each instruction pursues. This code was useful for doing the first tests but was not efficient at the code level. This is basically due to the use of delay(), since this instruction stops the operation of the uC completely during the indicated time. Modifications must be made to allow the device to continue working while counting the time before a change. This was done using the micros() instruction. The following code was the improved option:

MIMOBoost_ComplementarySwitch

```
/* Module 4
 MISO Boost Converter

 Isabel Garcia-Banos
 Gerard Pinar-Bailles
 1 November 2016
 www.wearekap.com

 Title: Complementary switching

*/

// Variables:

int i = 0;
int state = 0;
float previousMicros = 0;
float interval = 5;
int stateA = 1;

void setup()
{
  pinMode(11,OUTPUT); // G0
  pinMode(12,OUTPUT); // GA
  pinMode(13,OUTPUT); // GB
  digitalWrite(12,LOW);
  digitalWrite(13,HIGH);

}
```

```
void loop()
{
  float currentMicros = micros(); // Save the time since the program start running

  if ((currentMicros-previousMicros >= interval) && (stateA == 1)){
   digitalWrite(11,HIGH);  // Q0 is turned on
   previousMicros = currentMicros; // save the last time you switch the transistor
   stateA == 0;
  }
  if ((currentMicros-previousMicros >= interval) && (stateA == 0)){
   digitalWrite(11,LOW); // Q0 is turned off
   previousMicros = currentMicros; // save the last time you switch the transistor
   stateA == 1;
  }

  if ((i==5) && (state == 1)){
     digitalWrite(12,HIGH); // QA is turned off (PMOS)
     digitalWrite(13,LOW); // QB is turned on (PMOS)
     state = 0;
     i = 0;
  }
  if ((i==5) && (state == 0)){
     digitalWrite(12,LOW); // QA is turned on (PMOS)
     digitalWrite(13,HIGH); // QB is turned off (PMOS)
     state = 1;
     i = 0;
  }
   i = i+1;

}
```

Figure 9.2. Complementary switching program [A.49]

Again in the comments you can see the function that each instruction performs.

This program worked well and would therefore be used for the switching of complementary inputs. In the Experimental Results (section 10) you will see the programmed switching in an oscilloscope to compare it with the theoretical one showed in the section Main Computations (chapter 5).

On the other hand, a program was designed for the first switching, that is the one proposed by the article [1]. A first basic program that fulfils the basic function was also made for this switching. The program with the commented code is presented below:

MIMOBoost_NONComplementarySwitch_Trial §

```
/*Trial of the Non-complementary switching*/

int i = 0;
int state = 0;

void setup()
{
  pinMode(11,OUTPUT);
  pinMode(12,OUTPUT);
  pinMode(13,OUTPUT);
  digitalWrite(12,LOW);
  digitalWrite(13,HIGH);
}

void loop()
{
    digitalWrite(11,HIGH);
    delayMicroseconds(5);
    digitalWrite(11,LOW);
    delayMicroseconds(5);
  if ((i==5) && (state == 1)){
      digitalWrite(12,HIGH);
      digitalWrite(13,LOW);
  }
  if ((i==10) && (state == 1)){
      digitalWrite(12,LOW);
      digitalWrite(13,LOW);
      state = 0;
      i = 0;
  }
  if ((i==5) && (state == 0)){
      digitalWrite(12,LOW);
      digitalWrite(13,HIGH);
  }
  if ((i==10) && (state == 0)){
      digitalWrite(12,LOW);
      digitalWrite(13,LOW);
      state = 1;
      i = 0;
  }
    i = i+1;
}
```

Figure 9.3. Non-complementary switching trial program [A.52]

Also on this occasion the delay() instructions were replaced with the ones of micros() to improve the program, obtaining a finally much more efficient program. This program with the appropriate comments is the following:

MIMOBoost_NONComplementarySwitch §

```
/* Module 4
 MISO Boost Converter

 Isabel Garcia-Banos
 Gerard Pinar-Bailles
 10 November 2016
 www.wearekap.com

 Title: Non-complementary switching

*/

// The user must indicate the following parameters:

// All variables and constants are float because they can have decimals

const float freq = 1.0; // Frequency specified by the user
const float duty_cycle_Q0 = 0.5; // Example: 0.4 (40% Time ON, 60% Time OFF)
const float duty_cycle_QA = 0.2; // Example: 0.4 (40% of the time QA
//is connected to the circuit, 60% of the time QA is disconnected from the circuit)
const float duty_cycle_QB = 0.5; // Example: 0.4 (40% of the time QB is connected
//to the circuit, 60% of the time QB is disconnected from the circuit)

// Using the previous parameters, the program con calculate the following variables:

float period = 1.0/(freq); // Period of Q0
float timeON = period*duty_cycle_Q0; // Time Q0 is on
float timeOFF = period-timeON; // Time Q0 is off
float freq_hrv = (freq)/10.0; // Frequency of the harvester (10 times less
//than the frequency of Q0)
float period_hrv = 1.0/freq_hrv; // Period of the harvester (10 times longer
//than the period of Q0)
float time_hrv1_on = period_hrv*duty_cycle_QA; // Time harvester 1 is on
float time_hrv1_off = period_hrv-time_hrv1_on; // Time harvester 1 is off
float time_hrv2_on = period_hrv*duty_cycle_QB; // Time harvester 2 is on
float time_hrv2_off = period_hrv-time_hrv2_on; // Time harvester 2 is off
float cyclesON1 = duty_cycle_QA*10; // Cycles ON of the first hervester
float cyclesOFF1 = 10.0-cyclesON1; // Cycles OFF of the first hervester
float cyclesON2 = duty_cycle_QB*10.0; // Cycles ON of the second hervester
float cyclesOFF2 = 10.0-cyclesON2; // Cycles OFF of the second hervester

// Pinout
const int GA = 19;
const int GB = 13;
const int G0 = 11;

// Variables will change :
int Q0State = HIGH;          // Transistor state: LOW = off, HIGH = on
int QAState = HIGH;          // Transistor state: LOW = off, HIGH = on
int QBState = LOW;          // Transistor state: LOW = off, HIGH = on
```

```
// Delays
// Generally, you should use "unsigned longs" for variables that hold time
// The value will quickly become too large for an "int" to store

// Variables that hold the last time the transistors state changed

float GApreviousMicros = 0;
float GBpreviousMicros = 0;
float G0previousMicros = 0;

// Intervals
// constants won't change :

// Interval at which to switch every transistor (milliseconds)

float GAintervalON = time_hrv1_on*1000.0;
float GAintervalOFF = time_hrv1_off*1000.0;
float GBintervalON = time_hrv2_on*1000.0;
float GBintervalOFF = time_hrv2_off*1000.0;
float G0intervalON = timeON*1000.0;
float G0intervalOFF = timeOFF*1000.0;

// The setup routine runs once when you press reset:
void setup(){
  // Initialize pins

  pinMode(G0, OUTPUT);
  pinMode(GA, OUTPUT);
  pinMode(GB, OUTPUT);
  Serial.begin(9600);

}

// The loop routine runs over and over again forever:
void loop(){
  //

  float currentMicros = micros(); // Save the time since the program start running

  // QA is turned on
  if ((currentMicros - GApreviousMicros >= GAintervalOFF) && (QAState == 0)) {
    // save the last time you switch the transistor
    GApreviousMicros = currentMicros;
    QAState = HIGH;

    // set the transistor with the negated QAState as the transistor is PMOS
    digitalWrite(GA, !QAState);
  }

  // QA is turned off
  if ((currentMicros - GApreviousMicros >= GAintervalON) && (QAState == 1)) {
    // save the last time you switch the transistor
    GApreviousMicros = currentMicros;
    QAState = LOW;

    // set the transistor with the negated QAState as the transistor is PMOS
    digitalWrite(GA, !QAState);
  }

  // QB is turned on
  if ((currentMicros - GBpreviousMicros >= GBintervalOFF) && (QBState == 0)) {
    // save the last time you switch the transistor
    GBpreviousMicros = currentMicros;
    QBState = HIGH;
```

Figure 9.4. Non-complementary switching program [A.51]

In the Experimental Results section you can also see in an oscilloscope the switching that implements this program.

Finally, it should be mentioned that these switches are not intended to be used alternatively one or the other, but the intention is to decide which of them is most appropriate. That is why it has not been useful to design a program that contained both and we could decide between them with an input to the uC. Thus, we will work with both in this prototype with the purpose of deciding which of the two offers the best results in each given situation. Once the experimental tests are done it will be possible to conclude which of them is most appropriate for each case.

10. Experimental Results

This section gathers all tests and experiments related with the MIMO boost converter. All verifications, hands on and checking of the circuits implemented, harvesters or electronic devices related are documented in the chapter.

The structure is divided in two sections: tests related with the 4 modules that build the main circuit's body and from the other side the rest of tests done in the project.

10.1. Module Testing

All 4 modules must be tested once they are implemented. Their correct functioning is crucial for getting reasonable results and conclusions. Circuits are first checked and tested individually and later on they are going to be connected and tested together with all modules.

10.1.1. Module 1

This is the circuit section which boosts energy coming from the thermoelectric generator and adjusts the output voltage to be added later in module 4. It is important to remember that this module can be implemented with BQ25505 configuration and also with BQ25504 settings.

First, implementation of BQ25505 is checked following same instructions and steps in its datasheet [3]. This process is deeply described in annex [A.4].

As it is confirmed before, module 1 using BQ25505 is working correctly. Furthermore, its output impedance has been computed in [A.9].

Now, the same procedure is done with BQ25504, following again all steps indicated in datasheet [A.22]. Testing is also described in detail with all instruments used and numerical results in annex [A.3].

As it can be seen, module 1 using BQ25504 works also well but the one used for the final complete device is using BQ25505 as module 1 because of its advantages compared with BQ25505 chip.

10.1.2. Module 2

This circuit section adjusts and powers up the voltage coming from the sun, transformed by a photovoltaic cell. The circuit is exactly the same before as it is using the BQ25505 boost converter charger but, the only changing on its configuration is the maximum power point tracking (MPPT), that is set by a jumper to 50%; the correct for TEG applications. This means the testing done in 10.1.1 section is also valid for this module.

10.1.3. Module 3

Decisions made by MSP430 microcontroller makes this module become the 'brain' of the circuit, so this implies switching control in module 4 circuit. In main computations (section 5) both switching options are explained and represented in **Figure 6.2** and **Figure 6.3**.

For this job, two different programs are designed with *Energia* software from TI, which can be seen in programming (section 9). Each program corresponds to a different kind of switching. Now it will be checked 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.

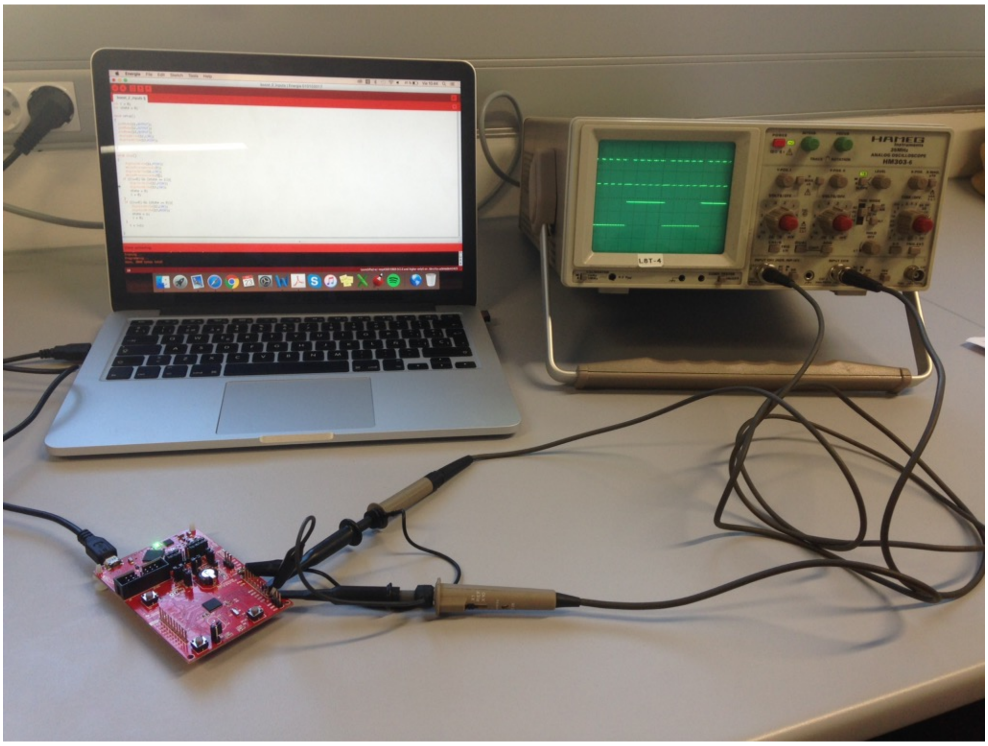


Figure 10.1. Connections testing Module 3 [self-made]

The following figures compare the theoretical switching with the one got in the present test; both corresponding to the complementary switching option.

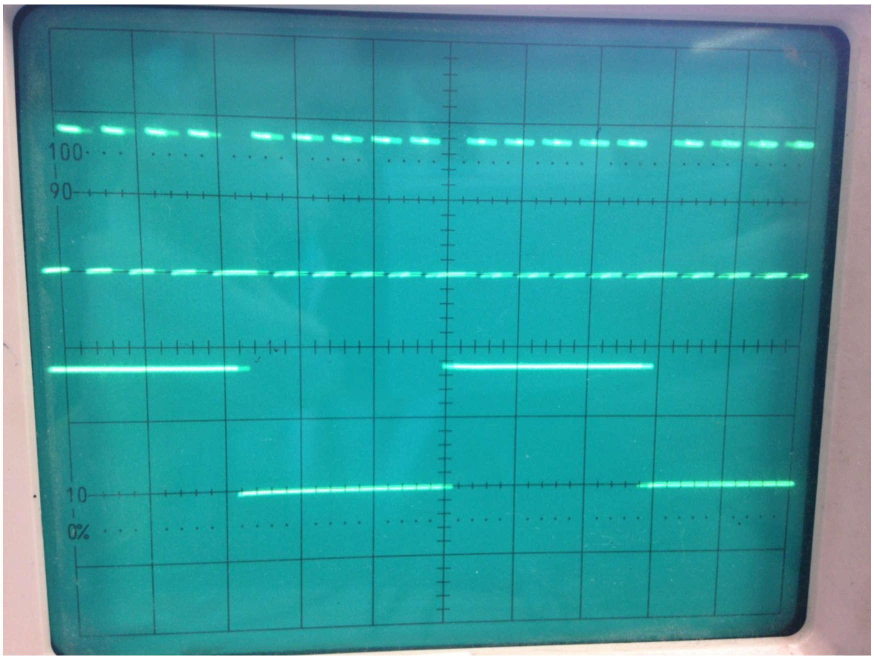


Figure 10.2. Complementary switching [self-made]

D = 50%; f = 100 kHz; TDIV = 20 µs; CHI-Pin12 (2 V/DIV); CHII-Pin11 (2 V/DIV)

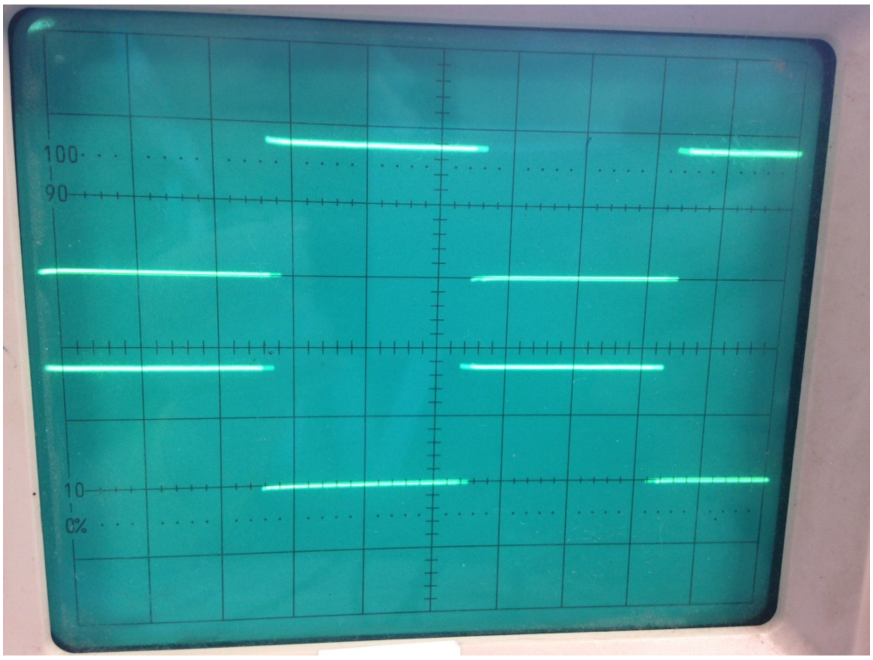


Figure 10.3. Complementary switching [self-made]

D = 50%; f = 100 kHz; TDIV = 20 µs; CHI-Pin12 (2 V/DIV); CHII-Pin13 (2 V/DIV)

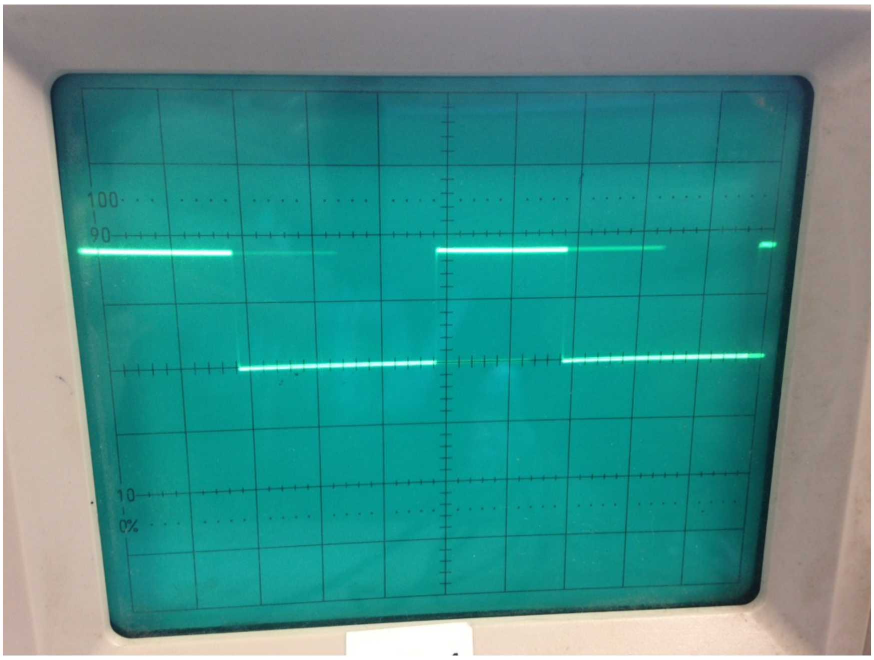


Figure 10.4. Complementary switching [self-made]

D = 40%; f = 100 kHz; TDIV = 2 µs; CHI-Pin13 (2 V/DIV)

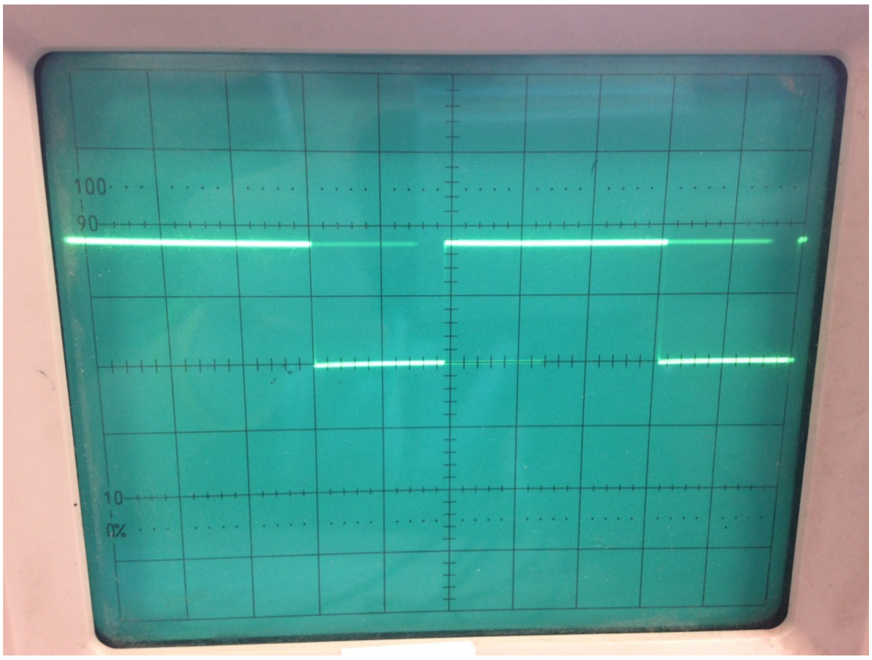


Figure 10.5. Complementary switching [self-made]

D = 60%; f = 100 kHz; TDIV = 2 µs; CHI-Pin11 (2 V/DIV)

Then, the procedure continues with the same comparison with the non-complementary switching option. The figure in the oscilloscope corresponds to the signals in gate output once the other program is load on the microcontroller.

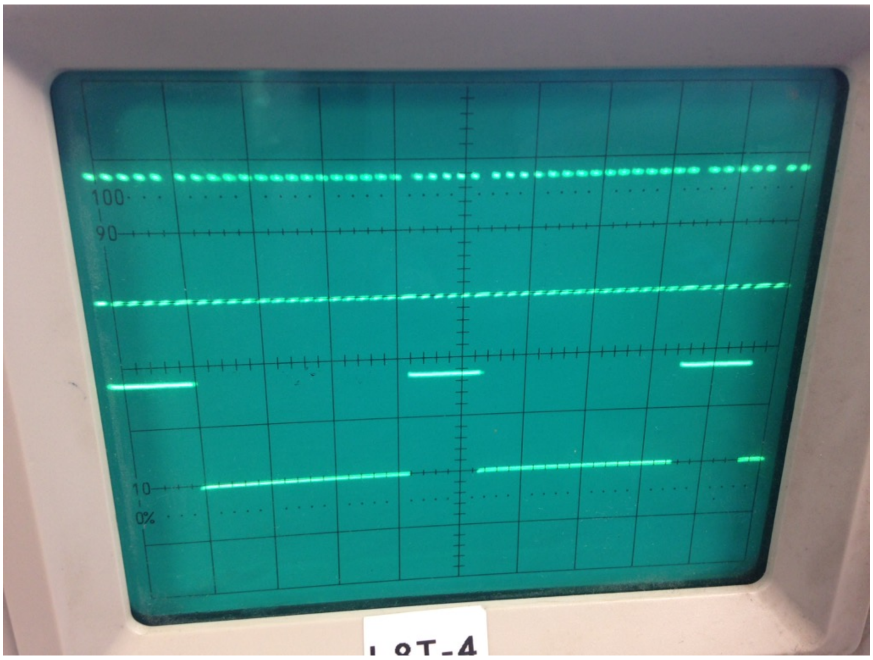


Figure 10.6. Non-complementary switching [self-made]

D = 50%; f = 100 kHz; TDIV = 50 µs; CHI-Pin12 (2 V/DIV); CHII-Pin11 (2 V/DIV)

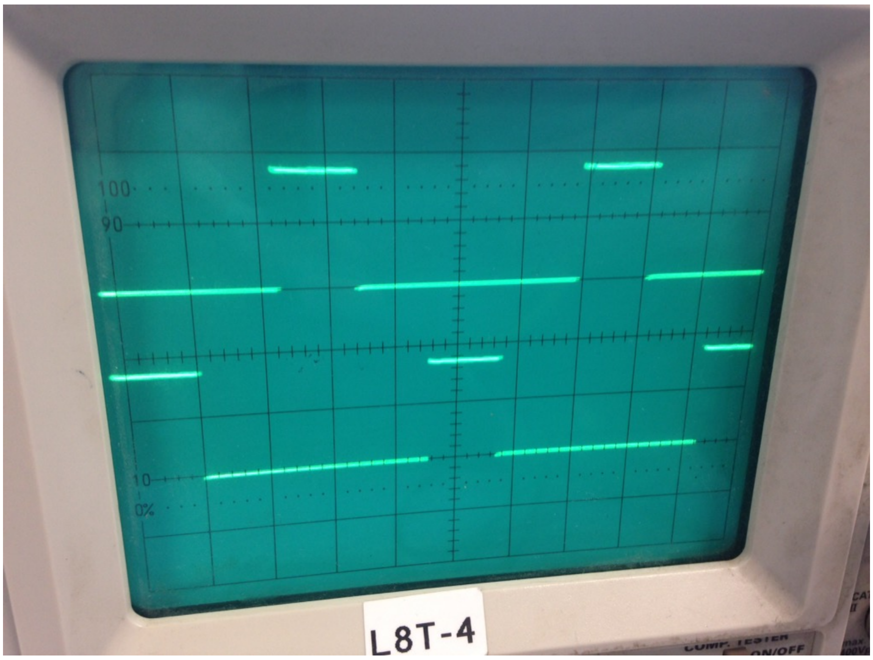


Figure 10.7. Non-complementary switching [self-made]

D = 40%; f = 100 kHz; TDIV = 2 µs; CHI-Pin13 (2 V/DIV)

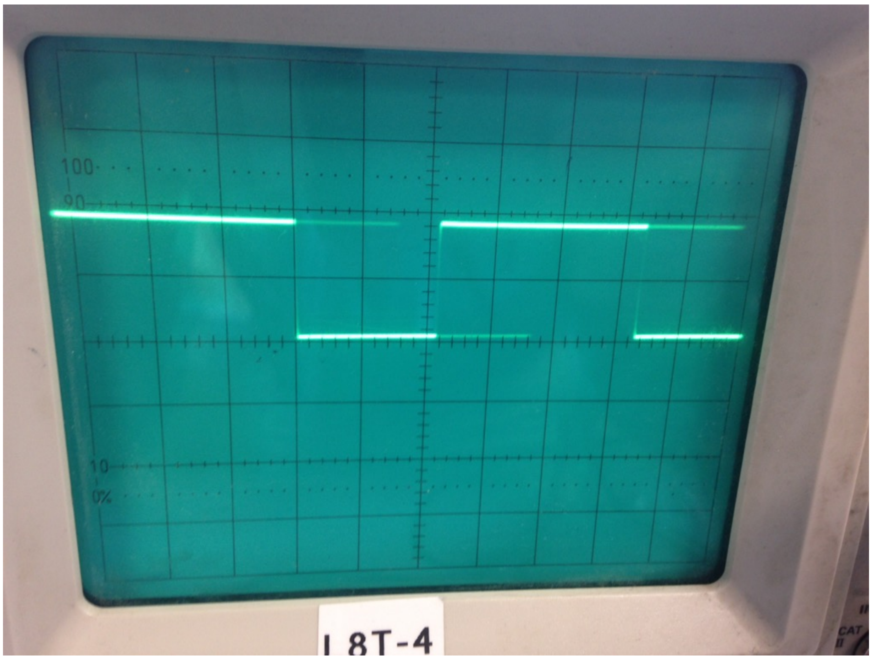


Figure 10.8. Non-complementary switching [self-made]

D = 60%; f = 100 kHz; TDIV = 2 µs; CHI-Pin11 (2 V/DIV)

Concluding with the switching verification, it can be ensured that switching in module 4 is the one desired and, as a consequence, transistors in multiple input boost converter are switching in a proper way.

10.1.4. Module 4

As this is the most innovative and self-made circuit part, tests should be more rigorous and accurate; the more experiments done, the more conclusions to get from this module. To do so, testing is going from simple to complicate level, ensuring this way a good procedure following simulations and a good result comparison. This module has been implemented with different components to check their behaviour in reality.

First test verifies the correct functioning of the circuit working as a normal one-input boost converter and the experience is done equally for all implemented circuits representing different versions of module 4. Once circuit is working as a normal boost, connectivity and components operation is automatically considered good. Next test corresponds to the multiple input function, so module 3 will control switching of P-Channel MOSFETs in the inputs. Using this second option program, power in V_{OUT} node must be higher as the module is gathering all power coming from the two inputs. So when one of the inputs is not connected, its power is accumulated in a capacitor to be included afterwards in the circuit; when this input is connected again to the boost converter.

10.1.5. General Circuit

Once four 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 the connection diagram below:

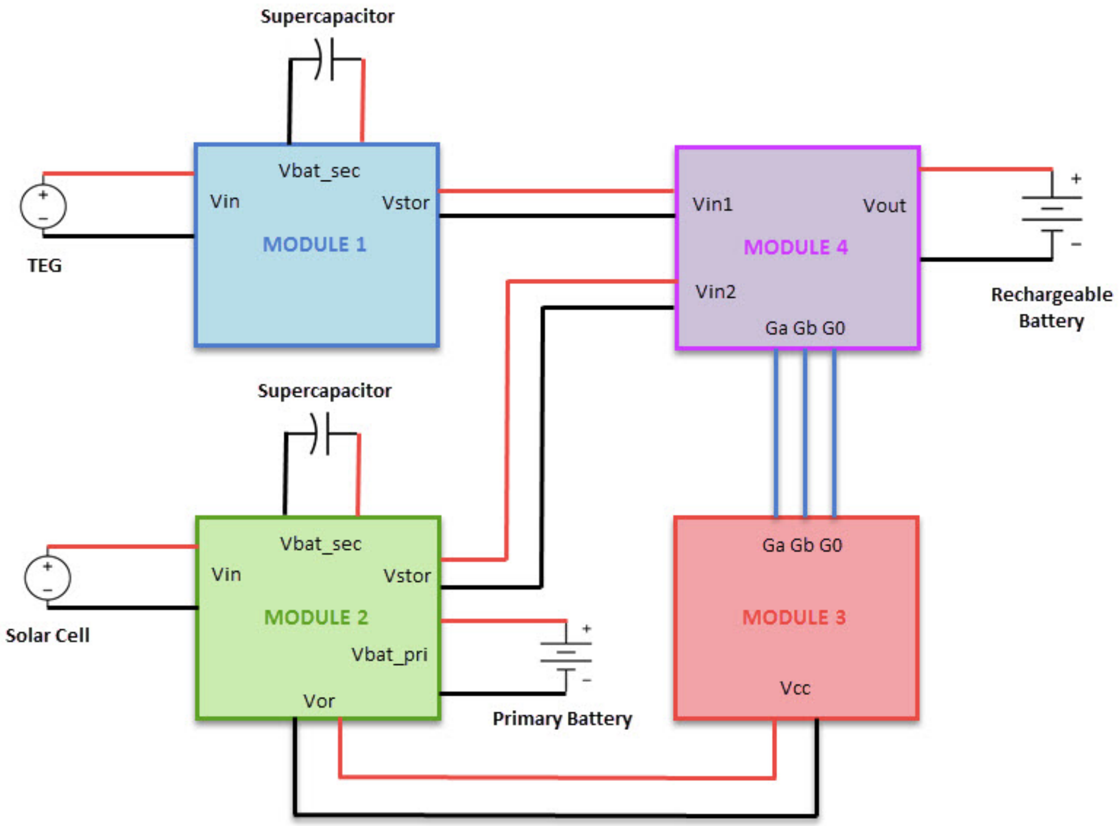


Figure 10.9. Connection diagram [self-made]

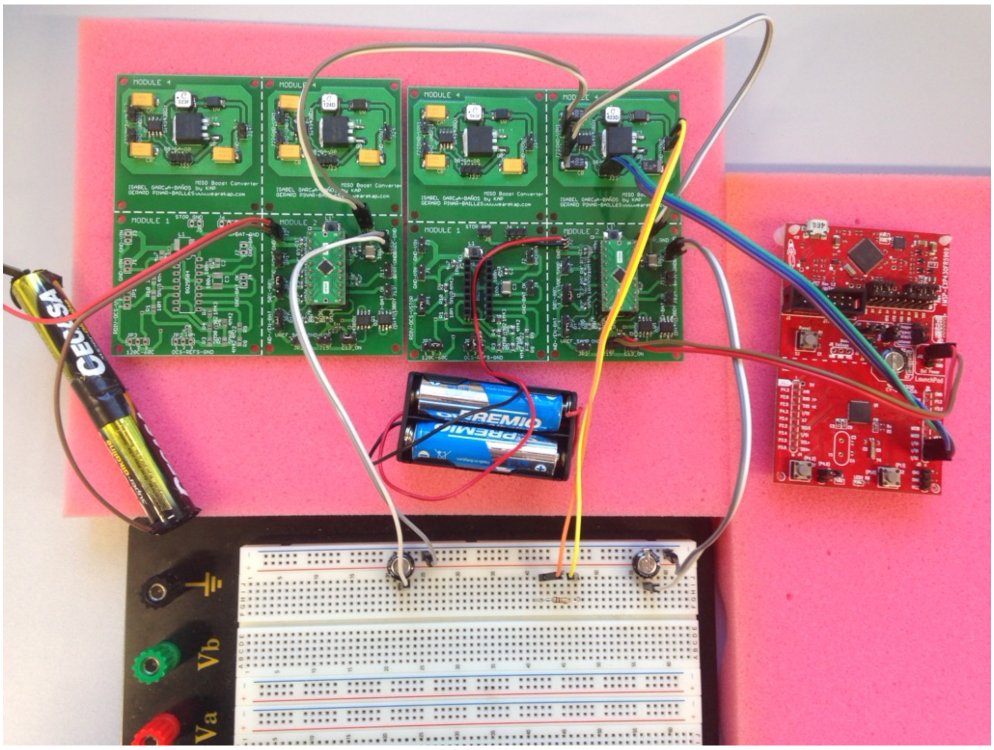


Figure 10.10. Prototype connected [self-made]

For the test, a know voltage is applied to both inputs using AA alkaline batteries; avoiding this way errors coming from harvesters. The table below demonstrate how results from simulations and testing are quite the same.

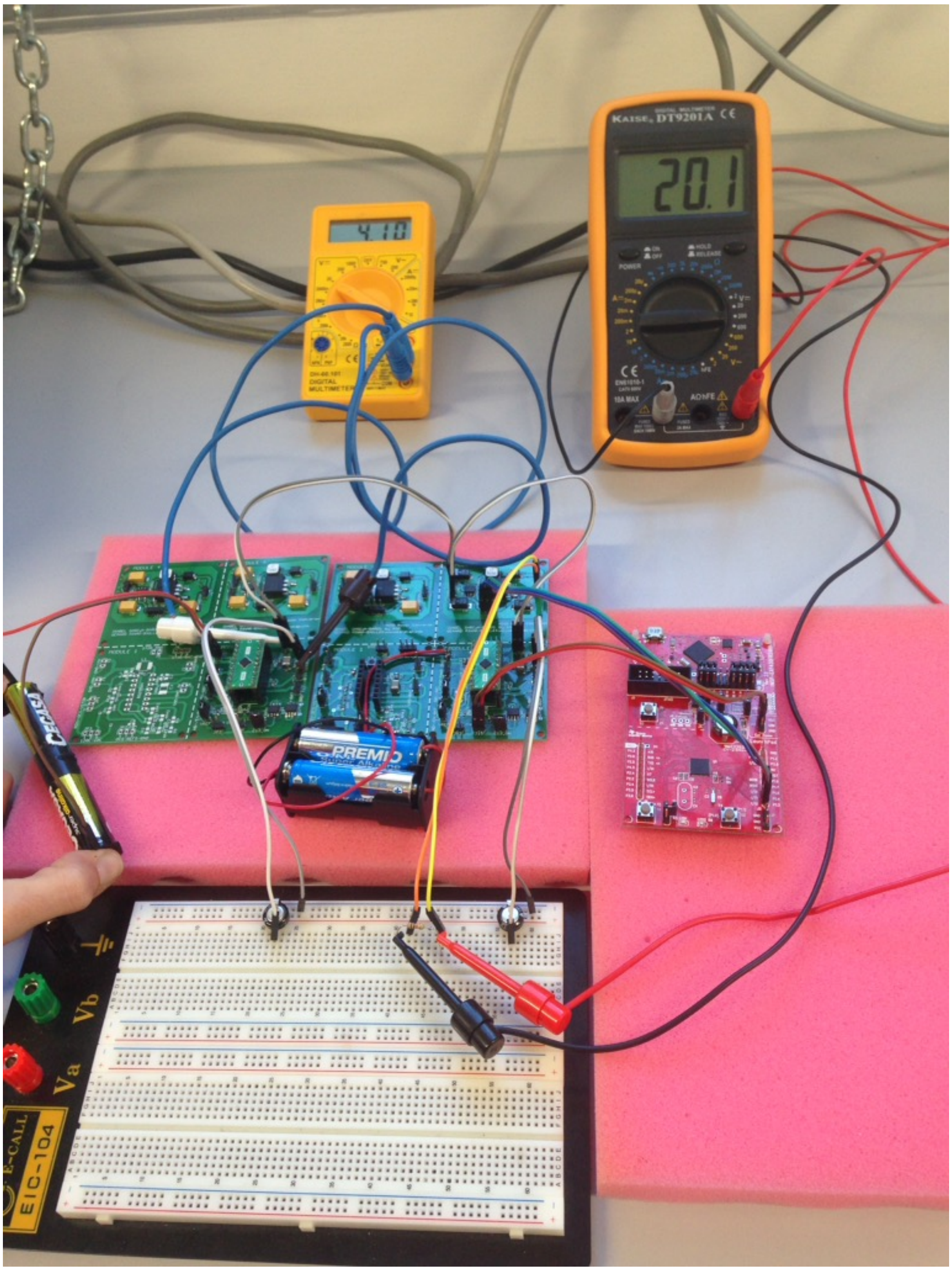


Figure 10.11. Prototype tested [self-made]

In the previous figure it can be seen how 4,1 V in both inputs is boosted up to 20,1 V. The circuit works properly.

Next schematic diagram presents the final Multiple-Input Multiple-Output Boost Converter circuit based on conclusions obtained from experimental results.

GENERAL SCHEMATICS
DIN-A3

10.2. Other Test

All tests done for the project that are not related with modules in the circuit are explained in this section.

10.2.1. Harvester Characterization

In the present project harvesters devices are explained in theoretical background (chapter 2) but the ones used for the prototype are TEG and photovoltaic cell. As electric models and specifications are already known in this point, real harvesters can be studied taking these specifications into account. Starting with solar cell, efficiency is an important factor to experiment with so MPPT of the given harvester is verified experimentally. Thermoelectric generator offers a real equivalent resistance to be checked in practice too. Annex [A.10] describe in detail all process to obtain the mentioned results but here there are the basics to get them.

The steps to follow the process are:

1. Measure the voltage in open circuit directly to the harvester (V_{OC}). **Figure 4.4.**
2. Measure the voltage in the load coming from a known resistor (V_L, R_L) **Figure 4.5.**
3. Calculate the desired taking into account the resulting circuit as a voltage divider (R_{TEG}).

The harvesters can be used from now on as they functioning have been tested and revised.

10.2.2. Power OR-ing

This phenomenon explained in theoretical background (chapter 2) is tested in real life using two AA alkaline batteries following the next figure:

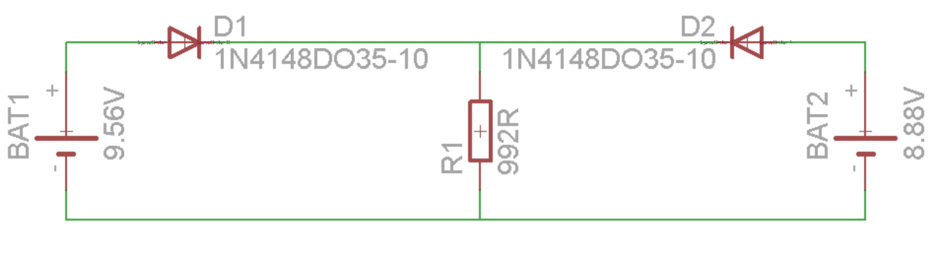


Figure 10.12. Power OR-ing [self-made]

The results of the Power OR-ing test [A.13] have shown that two sources in parallel with a diode each of them don't add their currents. The source with higher voltage is the one that gives all the current and the other source is disconnected from the circuit. That is because of the diode, which avoids the current circulation when the voltage between its terminals is negative.

This Power OR-ing system is the more used option in energy harvesting applications, so that only the source with the highest value of voltage is the one that gives energy to the circuit.

10.2.3. Boost Converter Trial

There is also a test done with common components to check how a boost converter can be build in a stripboard. The circuit implemented is the following:

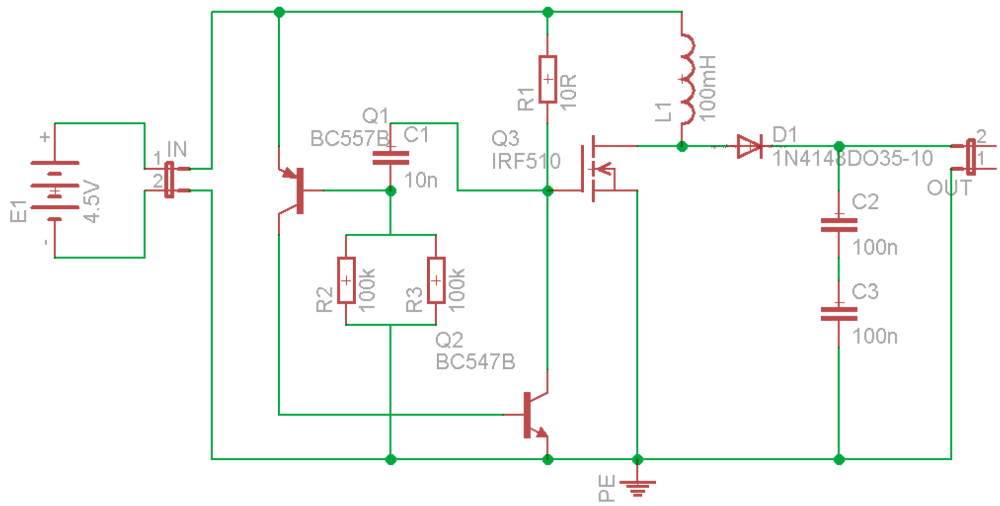


Figure 10.13. Implemented boost converter circuit[self-made]

This test has allowed to understand the boost converter by building this device with simple components. The circuit has been analysed and all its parts has been studied. This has been the first step to be able to design a multiple-input boost converter. All the details can be seen on the report in annexes [A.12].

10.2.4. Instrumentation

Following the same procedure that harvesters, the internal resistance of the power sources can be determined. This is useful in order to know what is being connected as an input to the circuit implemented when different tests are carried out.

One of the more used power sources in this project has been the FAC-662B, so this procedure was followed in the report [A.11] and its internal resistance was determined. The value of this resistance is 8 mΩ approximately, which is coherent according to its datasheet, so the procedure works properly.

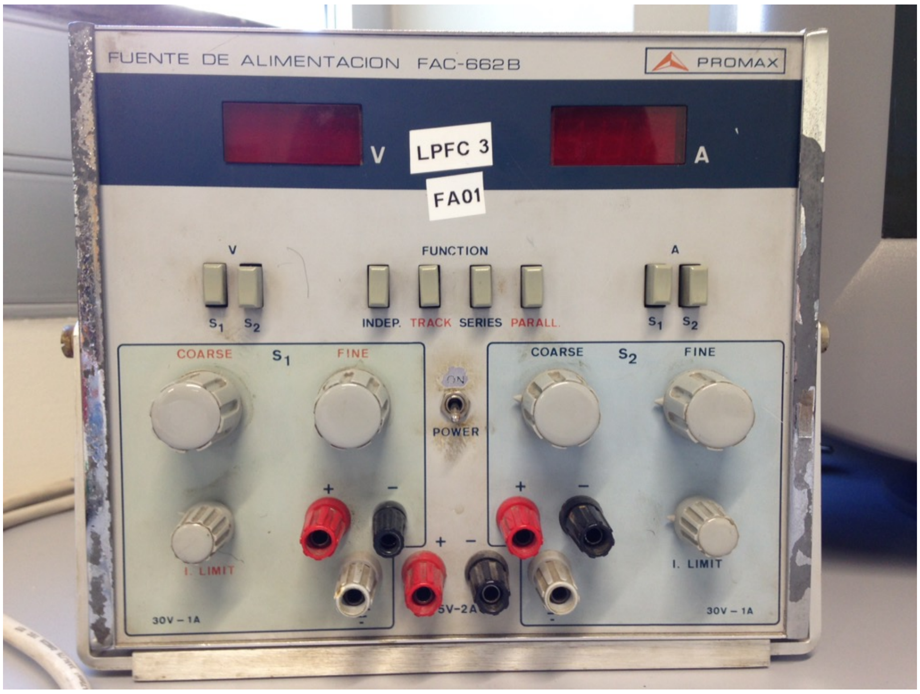


Figure 10.14. Lab power source: FAC-662B [self-made]

11. Environmental Impact

This project is closely related to the environment and is designed to avoid the use of non-renewable energies, which can damage our environment. From this point of view, the impact that this application can offer in the environment is very positive and its habitual use is not harmful, but very favourable.

However, it should be considered the problems or breakdowns that any application can present and how they can influence our environment. Next we will see how to avoid these problems or how to react to them if they occur.

Precautions for correct use:

- User agrees that this operation module must not be used as a finished product.
- User assumes all responsibility for proper safe handling of the electronic device.
- MIMO Boost converter is not designed for consumer use.
- Make sure to make all connections and parameters are settled as described in the manual.
- User agrees that similar modules and circuits may not be designed by KAP Company.

Precautions for safe use:

- Checking continuity and connections is recommended before power on.
- Confirming each module working separately is recommended before power on.
- If tested with a laboratory power supply, low voltages and current limiter are recommended.
- Use all electronic devices in normal temperature conditions to avoid components harm.
- Take the circuit away conductor fluids as water to avoid short-circuits.
- Save the board from dust to avoid connection between components to be cut.
- Operation module may be affected by electromagnetic interferences when not shielded.
- Prevent the device against blows, dents and damage; this may cause irreversible effects.

By taking these precautions it is very unlikely that the user will be harmed or receives any type of damage. However, like any electronic device, it has a useful life and will stop working.

When the electronic part of the circuit does not work, a good recycling of this part must be done. The electronic components can be very polluting, but a correct treatment can take advantage of 70% of the recycled device to obtain raw materials.

The ECOLEC Foundation [15] is dedicated precisely to the recycling of electronic components and to provide all the information and support needed to carry it out. Thus, in case the device stops working, it is strongly recommended to take it to a clean point so that a good treatment can be carried out.

On the other hand, if the batteries that accompany the circuit stop working, we must take even more precaution. These devices are very polluting and their biodegradation can take more than 1000 years (See more information in [15]). That is why there is a procedure to treat them ranging from collection to treatment. The collection takes place in clean points or in small containers distributed in stores, for those batteries from domestic use; or directly for those used in a professional manner. After collection they are taken to temporary storage centres (see procedure in [16]). Later they will be taken to specialized sites for the final treatment of batteries. So it is recommended to take the batteries to one of the collection points mentioned so that a good treatment can be made and its effect on the environment can be minimized.

As a conclusion, it must be said that the use of this device is very favourable to the environment and that the only critical point is its recycling when it stops working. If we carry out the recommendations mentioned, this critical point will be greatly reduced.

12. Conclusions

Conclusions in the project are not easy to extract, so in this chapter, all information is divided in two blocs. First, boost converter circuit in particular will have its own conclusions related with the application it is designed for. Then, we will suggest some personal and professional reflection this project implies. That actually is more than initially expected.

Multiple-input boost converter design for energy harvesting applications has been a tough and promising project from the beginning. Our director's advice and actual documentation study made us notice that energy harvesting word is huge; there are lots of small and autonomous devices that are so in usage and constantly increasing such as sensors, wearable components and even smartphones.

This power collection has multiples advantages and they are illustrated on the present report. All of this got us involved in the investigation ambit with no doubt; the innovation of the project, the fact of being useful for a better and cleaner future, energetically talking.

The possibility of adding energy coming from different sources in our environment becomes a new world where autonomous devices are increasing more and more. This fact was a relevant motivation to work on this project.

As a comment, one of the goals that made us invest our time on this innovative device was the prototype presentation in Texas Instruments Innovation Challenge 2016. As a consequence, the time spent to do the project was doubled to focus the first part in the TI contest. This way, until the month of July in 2016 the goal was guiding the electronic device in that innovation challenge field to submit a winner report on time. The document, delivered in the mentioned date, contains all Texas Instruments requirements and specifications; it is included in Annexes [A.1].

Finally, in October the finalists were known and our project was one of the 7 winner reports inside innovation category; the certificate is attached in [A.2]. Only for participating in the Challenge, all tools and module boards ordered were given as a present and, furthermore, there was a 1000$ award. The price was a huge incentive to keep working on the project and the money allowed us to invest more on the prototype manufacturing quality and therefore, to obtain better results.

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.

In addition, the methodology in the project has been very efficient and the project has been increasing step by step regarding contents.

There have been many problems during this year; 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, PCB was the only option as energy harvesting applications requires low distances between components and stable connections. 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.

Nevertheless, all this obstacles have been overcome and goals have been achieved with positive results. Then, we can say this project is the first step to implement a commercial application using this device to charge low-power devices using renewable energies. In the present project, there are lots of things that can be optimized and designed in a better way, but the corroborated idea is the beginning of something that can be very useful in the future. We think that, improving the device, circuit will be able to charge a smartphone battery adding many inputs and this becomes a powerful motivation to keep working on the project.

Other than the prototype, authors have acquired knowledge regarding renewable energies, which will be for sure the ones most used in the future as it can be read in [12]. Then, we have had the opportunity to meet many technologic enterprises in the sector, which have offered their support. When the project goes further or also when working on other projects, the possibilities will increase with the collaboration of the enterprises [A.21].

From another site, we would like to emphasize how this project has influenced us personally. Our mentalities has grown up working on it and what started as a project done by two students in UPC university, can become the beginning of an enterprise. The two authors have found the way of working in team to achieve goals in a project with entrepreneurship.

With this project we have met real world. From the beginning we have believed in the usability and innovation of the multiple-input boost converter. There have been a constant communication with enterprises and formal e-mail messaging ability has increased during the project. These contacts have allowed us to obtain some samples, possible business partners, technical support and help, advices and polite feedback. Overall, we have discovered that we can develop great projects and grow as engineers. Furthermore, we got the experience of designing and concluding an innovative project starting from zero: time invested to do a correct investigation, build a professional electronic circuit, simulate with results as close to reality as possible, obtain useful and reliable information, how to obtain all components used in the project, how to do a good components selection and how to find the interesting information in a datasheet. Also there have been some skills owned as English formal e-mail and report writing, teamwork method and long-term organization.

To sum up, this project has been an inflection point and has become the union between two university partners to reach the same objectives regarding electronics and future job. The positive mindset and entrepreneurship have exponentially increased and this turns into a decision of making our own projects. Moreover, this project has been the base to build an enterprise and to set the methodology and ideals. Everything done here is useful as a tool to work with and has been the way of knowing better each other; making a one-year-project efficient and funny.

This is not the end of a project but the first step of a different working lifestyle.

13. Future Work

This chapter illustrates how the project will continue and the next steps to follow to go further on it. All improvements and extra possibilities are written down to show how this project can be a real revolution on energy harvesting industry.

During the project, there are some contacts related with the main topic which can collaborate, help or even participate on the project from now on. Starting with the harvesters, solar cells and TEG suppliers have already dealt with the present application and discussed with authors so this can be an advantage to keep going with the conversations and treatments.

With a higher budget, better qualified solar cells can be purchased to collect more power and increment the efficiency. *Powerfilm*, despite being one of the enterprises on the top, has delayed a lot the order done for this project and they have not very good communication with their distributor *Flex solar cells*. TEGs have also been hard to find as they are very expensive in relation with the energy they give. Instead of using the thermoelectric generator directly with a flat surface, it could be very interesting to study other possibilities. The idea of arranging them around a tubular surface and connecting them in series may be a good one to get more power and to get more temperature difference, especially if there is air flowing outside the tube and some hot fluid going inside. *EverGen* has also TEG harvesters with cylindrical forms precisely designed for this kind of industrial applications. In general, on the future harvesters can of course be improved and optimized from the one hand in terms of price and quality (output power), and from the other hand regarding modules 1 and 2, which play a very important role when adjusting harvester's energy.

Talking about software, the program in module 3 can be improved a lot. Starting from the programming language used in *Energia* program: the delay function, which implies the time loosing from microcontroller MSP430FR5969, has been improved using function microseconds. To go in a lower lever in the MCU options and registers Code Composer Studio (CCS) programming language can be useful and finally, with CCS there are tools to modify that are not available in *Energia* software. Anyway, for the present application, *Arduino* programming platform based in C language, is more than enough. Actually, from a product marketing point of view, it is better to work with an easy program to let the used play with and investigate; and *Energia* can be easily understand and reachable for much more users.

Regarding switching, the duty cycle in P-Channel MOSFETS on each input can also be modified. If the source giving more power has more priority than others, power in output capacitor may be incremented. The clue in this case is to let the MCU know which is the more powerful input to change PMOS transistors' duty cycle depending on that.

Independently of the language used for giving instructions and conditions to MSP430 microcontroller, there are also some features that can be contemplated and taken into account. There are several signals that can come as input information signals to the controller chip and can be useful to optimize power adding and modules controlling:

- VBAT_OK signal can be useful to let the MCU know if VOR output voltage is taking the energy from the module or for the primary battery. A *watchdog* control or a timer configuration can determine if the load is taking power only from the primary battery.
- Enable negated signal can be used to turn the module off in case of alarm or incident. Despite the boost inside BQ25505 integrated circuit (IC) stops switching automatically to avoid an overvoltage in the secondary battery stored, setting /EN signal to logic '0' or logic '1' from the microcontroller can be useful in any unexpected event.
- Alarm output signals coming out from MSP430FR5969 can be used to light up a low consume LED or a small buzzer to indicate a warning situation. In the program, some dangerous or non-desired situations can be programmed as conditions and visually indicate the problems to the user. These alarming messages must be only used in case of real alarms as the devices attached consume some amount of energy that will not be delivered to the battery or output load. Nevertheless, sometimes the priority is to show an alarm to avoid any module harming.
- Close loop load variation could be a profitable improvement because, if the load in module 4 Vout changes while the circuit is operating, switching will be the same while it could be modified to be the optimal; as the optimal switching and therefore, the maximum power transfer varies with the load value. The solution should be a closed loop regulating system. That is introducing the output load value to a MCU's input and using this numerical value to modify the duty cycle depending on the load. Ranges could be the best option; the more number of ranges comparing resistance/voltage value, the more accurate will be the switching transferred to module 4.

Lastly, MSP430 microcontroller can even consume less despite working with ultra-low power. There is a software option available in *Arduino* platform called the *sleep mode*. This mode allow the chip consume the less possible without turning off and keeping RAM memory. So for example in case of cold and night with the present MIMO boost converter circuit, as there is no light and not enough temperature difference, instead of consuming all voltage in the capacitors to give power to the load, MCU can go to sleep mode and stop switching module 4; this way the circuit will stay in standby to save energy to keep working when the harvesters get some energy again. This is a way of not turning off waiting for cold start again. In *sleep mode*, the 'wake up' signal can come as a logic '1' hardware signal to a pin in the MCU as an interruption. This mode can also combine the signals mentioned before to stop also modules 1 and 2, the /EN signal is also controlled from MCU.

The main goal of this project is the power adding, so of course the most important improvement, as said in the beginning of the report, is to connect as many inputs as possible. Each input coming from a different energy harvesting source, see all kinds in theoretical background (chapter 2).

Regarding hardware in module 4, more input sources will only affect the PMOS transistor commutation and will imply an adequate capacitor in parallel for each one. Obviously, each harvester will be connected to an optimized module to adapt its voltage to make it as equal as possible with other inputs; that way, power coming from each harvester will be added better. Depending on the source, some harvesters will require an intermediate AC/DC rectifier as the voltage coming into the module 1 must be Direct Current. Piezoelectric and windmill are examples of that fact.

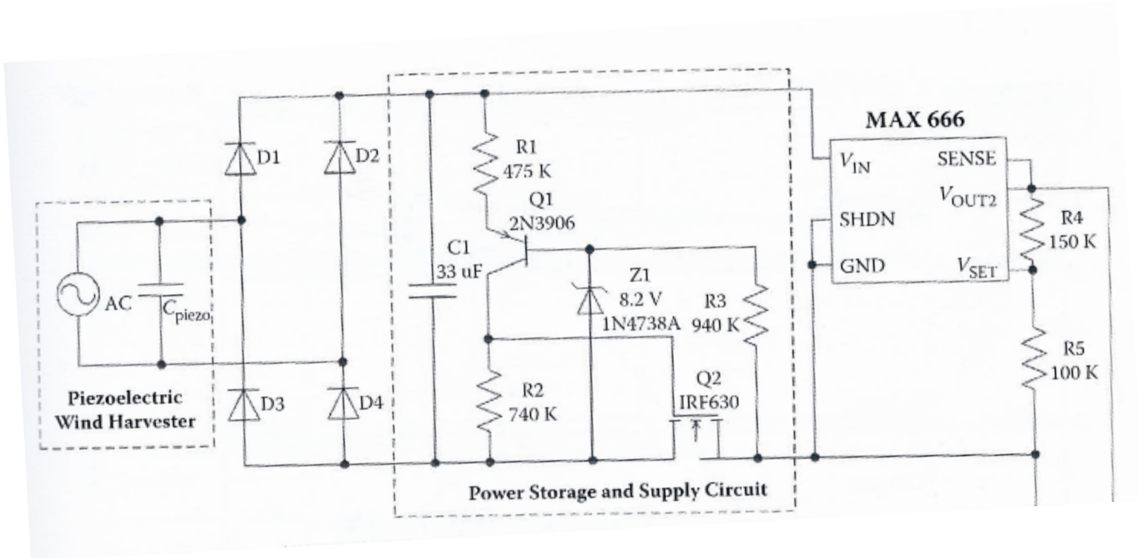


Figure 13.1. Piezoelectric and wind harvester voltage rectifier circuit example [7]

In the case of 3 inputs to the MIMO boost converter, the circuit would be like it can be seen below:

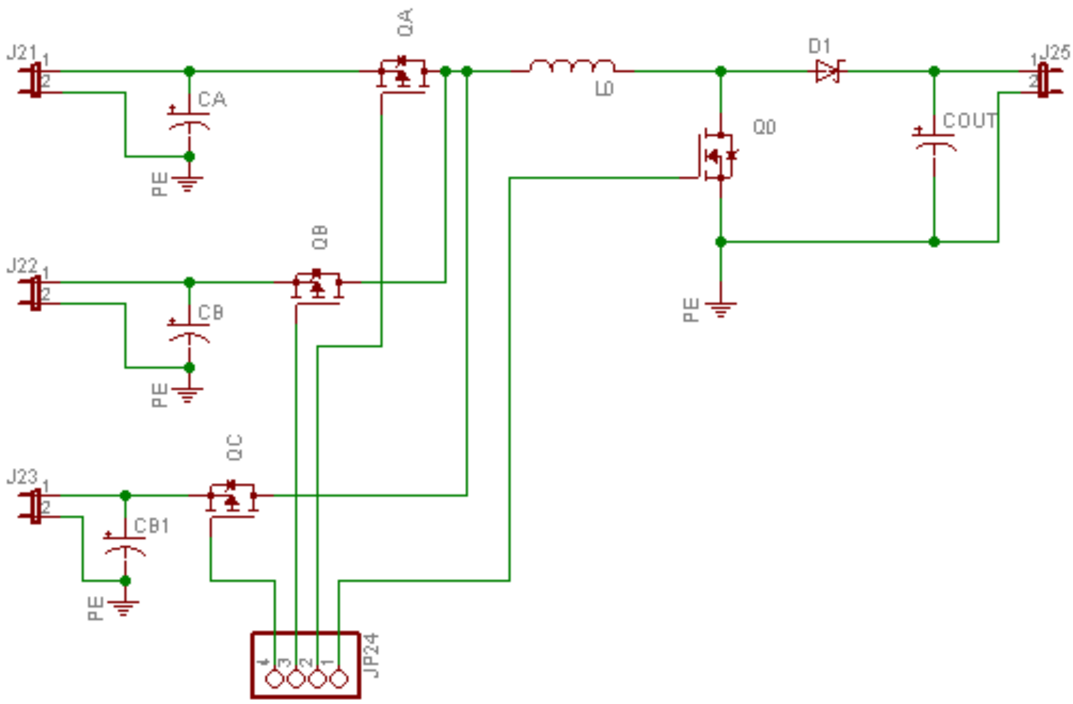


Figure 13.2. 3-input model 4 schematics example [EAGLE]

The program would also change a bit to include one more power input and PMOS switching. In the case of adding more and more inputs, the process would be the same, but studying each harvester optimization in particular.

Other than that, if the current circuit is designed not as a prototype but as a commercial power adder to save energy from daily actions, all 4 modules will be attached together. The circuit will be optimized in hardware and software level and thought to be sold; customers will decide applications and specialized uses.

It will be different kinds of models from a compact design with internal connections to a separate shields selling with jumper connection options between modules to apply all improvements mentioned before. The mixed option will also be available with the possibility of splitting each module separately if wanted. Module 3 can also be designed as shields from Texas Instruments to add on the present modules and to be programmed separately with a eZ-FET board connected by JTAG header or even USB.

Another possibility is to distribute a standard circuit with 5 or 6 inputs and use only the desired ones by disconnecting the P-Channel MOSFETS in module 4 off the non used inputs. If not, extension modules can also be contemplated to be added as shields to increase the number of inputs.

To sum up, the implementation and exploitation of this circuit can be huge. The only purpose is to use the ‘loosed’ energy in daily transport or actions to be transformed in electricity and add this power to other energy to supply some electronic device that can afford this power to work. In business application, this micro-power gathering increases as it implies working with machinery.

The enterprise founded with this project can go also further. The methods acquired for ordering, operating and organizing all parts of this is something the authors already owe. So it is easy to continue with this or any related project as the contacts and the way to get the material is studied and achieved. The teamwork has been the base of all and KAP can follow same ethical and procedural philosophy to keep going with energy topic. Goal is learning and having some direct social effect to grow personally. Thanks to this project, KAP is now the beginning of an entrepreneurship.

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