SOFT-SWITCHING DESIGN FOR DC-DC CONVERTERS

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A Thesis submitted in partial fulfillment for the Degree in
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Thesis Adviser:
Eng. Edwin Francisco Forero García

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Declaration

With this statement we declare to be the authors of this written thesis and that we have not used sources, different to the ones encountered within the references section. We also declare that any work related or used for the development of this investigation has been properly listed and documented.
Finally we declare that the content of this document has been written by us with the adequate assessment and assistance of our thesis advisor.

Lina Marcela Arias Ortiz

Jorge Hernán Franco Rivera

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SUMMARY

In this document is presented a reality that each day is taking more and more strength in the in the environmental safety and as a result a exponential growing in the market. When people talk about cars and mobility, they're talking about a tool and a necessity, thus something that everyone in the population will always look. But, there has been a series of problems in the environmental balance with the existence of cars, years passed and with them, the constant contamination, and it is produced not only by cars, but this is one of the machines most used in the world, and has a cycle of energy consumption that isn't any friendly with a healthy planet.

The resources for the car functioning, are mostly given from the earth, the production of gas and gasoline to impulse our cars, airplanes, bikes and an enormous number of machines, is a process that cost us health and quality of life. It generates more exposure of damaging gases to the atmosphere, contamination of the air we breathe and many other problematics.

Looking to help with a recovery, the existence of Electric Vehicles (EV) is one step that could offer people the option to continue with their lives normally, having less impact to contaminating the environment, according to the EPA, a regular gasoline car produces 8,887 grams of CO_2 per gallon, and a diesel one produces 10,180 grams of CO_2 per gallon, in comparison to EV's that don't produce this tailpipe emissions, or Fuel cell which only produce water vapor.[1]

However, the production, the fabrication and the consumption of energy for the EV's, is kind of delayed in comparison with the years of development that the combustion car machines have had, in a lifetime an internal combustion car will burn around $17,000$ liters of petrol or $13,500$ of diesel, on the other hand for EV's the waste in metals will be around 160 kilograms, but by recycling the waste will reduce to around 30 kilograms [2]. For that, we

present an analysis of little steps and adjusts in the conversion of energy, trying to improve the efficiency, the life cycle of components and at the end, the benefits it could bring to us as a population.

We dedicate this work specially to our parents and our families, who have supported us through this process of writing and designing this thesis.

To our college friends, who accompanied us in the road to finish this project.

And finally, to all people involved in the project since its beginning, including professors, advisors and the authors we researched to develop this document.

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We present our deepest gratitude to everyone who was involved in the making of this project, to the people who with their hard work put up a precedent for us to continue investigating, and to be inspired to start this project. Also our thanks to our adviser and our juries who corrected us and showed us the right path.

Also special thanks to

- Amparo Ortiz and Jorge Arias, for the love and patience over the years and making me who I am.
- Luz Dary Rivera and Jorge Franco, for the constant motivation not only in the development of this thesis, but in my growth as a professional.

CONTENT

List of Abbreviations

BEV Battery Electric Vehicle

EV Electric Vehicle

GHG Green House Gases

HEV Hybrid Electric Vehicle

ICEV Internal Combustion Engine Vehicle

ISG Integrated Starter Generator

MOSFET Metal Oxide Semiconductor Field Effect Transistor

PEV Pure Electric Vehicle

PHEV Plug-in Hybrid Electric Vehicle

PRC Parallel Resonant Converter

PWM Pulse Width Modulation

QSW Quasi-Squarewave

REV Range Extended Electric Vehicle

SRC Series Resonant Converter

SS Soft Switching

ZCC Zero-Clamped-Current

ZCS Zero Current switching

ZCT Zero-Current Transition

ZCV Zero-Clamped-Voltage

ZVS Zero Voltage switching

ZVT Zero-Voltage Transition

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INTRODUCTION

There is a serious problem in the world and the environment due to the contamination because of fossil fuels, which according to the Emissions Gap report where of $37,9$ Gigatones of CO_2 in 2019, and by 2020 due to the restrictions it was reduced to $36,0$ Gigatones of CO_2 [3], this problem was the first motivation of this thesis, we have been looking for different ways in which we can help the environment. Since the beginning of the automotive industry and the major changes that have followed them particularly we have been seeing more and more fuel being used and this leads to more resources and waste, which contributes to a planet that already has trouble controlling these contamination issues. In the last few years we have seen how this industry is trying to change and evolve into a more conscious kind, this by developing hybrid and electric vehicles that use less or not at all fossil fuels and are looking for a much comfortable and easy technology, during the years there have been many changes to ensure a performance similar to gas or fuel based vehicles, this industry is also looking to produce less waste to help mitigate the impact, as mentioned before in this document the difference in lifetime consumption is between $17,000$ Lt of petrol and 30 kg of battery waste[2].

Since we are aware that the EV's industry is still in development and even when there have been many advances is still working towards a more reliable one. We wanted to contribute by looking into ways to improve the power dissipation, leading into more power that can be used by the vehicle itself instead of losing it through switching or temperature dissipation, by using a resonant stage, we pretend to lower the power loss and to improve the usage of this power by the DC- DC converter incorporated in the vehicle.

This thesis consists in the simulation design of two different bidirectional converters, the first one is the Buck-Boost using a topology adequate for soft switching, and the second one is a Non-isolated Sepic Zeta converter, these were chosen because of the adaptability that we can see for the electric vehicles industry, which is our main purpose. During the development of this project we will be able to analyze the possibility and adaptability of this technique in the automotive industry.

1 PROBLEMS AND PROBLEMIC QUESTION

1.1 PROBLEMS ENCOUNTERED

In order to truly understand the main flow of this thesis, we have to start with a topic that has been recently discussed a lot, climate change, it is a very important topic in our time, mainly because the sustainable development could be directly affected by it, Earth's climate has changed throughout the centuries, having seven glacial ages, and then adapting itself to human life, the problematic climate change started in the 20th century and has escalated to a point that makes us take action in order to maintain all kinds of lives on Earth, some of the side effects are for example the global temperature has raised around 0.9 degrees Celsius, the Oceans have also increased their temperatures, the ice in Greenland and the Antarctic has reduced, to list some of the problems encountered by the NASA, since the current problem is very significant to all forms of life on Earth and the further development in most of the investigation areas.[4]

As an alternative to improve the air quality we believe a partial solution are the Electric Vehicles, there is a problem with the implementation of this technologies and it is divided in two.
On one side the high cost of the materials and implementation itself, the manufacturing of EV's at this time is trying to reduce the production costs to be able to compete in the same market as fuel based vehicles, around 2020 EV's price was around $40,000$ euros while internal combustion ones where around $20,000$ euros according to a study by BloombergNEF[5].
The second problem seen is the difficulty with the implementation of the technology and the lack of infrastructure that allows this vehicles to be charged, according to statistics, Colombia has 203 points of recharge with 471 connectors [6]. In Colombia, there is no major development of Electric Vehicles and charging stations which makes complicated to acquire one of this vehicles, and worse to be able to charge it easily and efficiently.

Delving into this topic, and as it was mentioned before the materials and the implementation are expensive and also there is an important issue to stand out and is the poor energy efficiency, because when the converter works with the typical switching techniques like hard switching, the components are taken to the limit work zone risking the functionality of the system by producing damages in the converters or other parts that could be important on the complete system that can or can not be part of the converter implemented for the EV energy consume. By this constant work with ripples of voltage or current, depending on the converter, appear a thermal dissipation of power, causing a progressive damage to the material until in some point affects the work of the converter.

1.2 PROBLEMIC QUESTION

Which is why, this thesis is guided by the following main question **¿Which is the improvement of commuted converters for Electric Vehicles by applying Soft Switching techniques in comparison with the common hard switching technique?**

2 STATE OF THE ART

2.1 ELECTRIC VEHICLES

As first approaches to taking the impulse in the manufacturing, there were found some opportunities at the end of the nineteenth century related to one service in particular, people's mobility, it refers specifically to the Hackney Cabs, London's classic transportation of the time, which in simple words was a cabin impulsed typically by a horse, here's when Gastón Planté's development of the first batteries, began to show the path to the construction of Charles Jeantaud's car, famous in this EV topic, for catch itself in fire near of completing the first one hundred meters on his first departure from the lab. This first adaptation of the Electric Vehicles to the daily life of humanity, gave the possibility to subsequently, take this Taxi-Cab strategy to France and United States.

Of course the improvements to this technology kept a continuous growing in different scopes, because of some particularities that provoked the interest of many people like the lower sound in their functioning, the easy use and the hardiness. However, during these years, the implementation of this type of technology was 'ad hoc' and didn't fulfill all the advances that these kind of machines required. In addition, the speed and time of autonomy were so minimum that in some point, the fuel-based motor were gonna surpass this autonomy and therefore, become the first option to buy as a car. Adding to it, the oil industry started to consolidate his process to extract,convert and use the energy obtained from this particular source.

Then, starting the new century(1900) where just a few Electric Vehicles were being used. But, between 1909 and 1910 Ford mass-produced his Model T and give everyone a vision of the viability to automate the manufacturing, improve time and costs of dedication to impulsed by fuel machines. This led to the disappearance or instead in the migration to this oil industry of many businesses and truncate the flux of advances given through the past years.

Moreover, when the 20's arrived, in the region of France started looking how to minimize his dependency of petroleum, as result they began to develop electric trucks and merchant transport cars. Then, the United States of America joined to this idea, although through this process, the particular vehicles used by the people people in their daily were not involved and still kept using oil-based motors.

Thereafter, began one of the most hardest and historical events humanity has faced, world war two (WW2), right at this moment, the research to be independent of petroleum gets more urgent and intense, because the shortage produced by the war, not only in petroleum but also in all kind of materials. It caused many companies to start with different models of EV (Renualt, Peugeot, Mildé-Krieger, etc), where certain models reached the quantity of one hundred kilometers of autonomy.

Alternatively for this influence given by the war and for other subsequent reasons, the people started to give relevance to previously ignored topics, now the car could be related to danger, with a more conscious humanity, to more contamination and violence too, even so the car is one of the most functional tools for people, so it was needed to reconsiderate the way, proposal, development, automation and more important, the impact in the world as it was known, this machine could made.

As a result, the big enterprises started to produce some products searching the scope of a cleaner transport medium, Ford that once mark a difference for oil industry, now began to influence and claim the attention due to some electric prototypes (Ford Comuta and Ford Berliner) that of course weren't alone, because along with them Fiat bring an electric model of its own based in the Fiat 1100.

It is important to mention that, the cost of the vehicle propelled by fuel had approximately half the cost of any electric vehicle, the production of electric vehicles stopped until around the 70's for sales reducing, when the energy crisis and oil shortage started, in the 1980's people started developing once more the Electric Vehicles.

Between these decades, appear the first series production of a car by the Sebring-Vanguard company. Then, Renault and Peugeot appear with a car which had an autonomy of 140 kilometers. In these moment of history, the companies still were figuring out what king of batteries could work better in this use case. At the end, the ion-lithium battery has been one of the most common and with the time growing for this industries, right know is known the concept of superconductors which is applied in some vehicles.[7]

Presently, the world faced an opportunity in this area as one of the multiple steps that needs to start changing the mentality about the environmental impact, for that reason the big car brands are incorporating and innovating around this concept, accompanied by some new brands dedicated one hundred percent in the development of full EVs.[8] Even so, the number of EVs compared with conventional fuel vehicles are minimum, and here's where the industry needs to force and clarify all the benefits and the real impact that this industry could bring to us.

In particular in Colombia, the scene of EVs is considered specifically in the principals cities, such as Bogotá, where the biggest challenges to face are basically, the present infrastructure and accessibility to this technology. Looking at this matter, seeing part by part of this type of cars, there's an opportunity of analysis in the energy conversion process, here is when starting to look about the transformation of the energy, is noticed that there's a different type of converters implemented in the cars, trying to go further, the expectation is to see what techniques could be considered to apply in this type of systems. [9]

2.2 SOFT-SWITCHING

When the term switching is mentioned in electronics, it usually consists in a three pin element that, with the voltage activation in one of its pins, allows the flow current between the other two ends. Of course, talking about electronics, there's always the ideal situation, where the parasitic resistances and capacitors are ignored and there's the real scenario, with a non-ideal switching process considering this parasitic elements. As physics conservation of energy law states, energy cannot be created or destroyed (and in an utilization process of this resource, it just change its emission form, but it never disappear). Taking this into account in the use of electronic switches, it needs to be cleared that during a switching state, there's a drastic change in terms of voltage and current, to change from a state zero to a level determined by the circuit configuration, the process of power dissipation occurs in the switching element which will transform said energy consumption in thermal emissions of energy before the switching process goes from an initial state to the final stage.[10]

In particular is needed to clarify that speaking of switching, the most common technique is the hard switching, this type of state changing is characterized for the typical power dissipation and thermal losses that happens through the activation of the drain source path. The addition of resonant elements could help in this process to solve the power losses in the changing of stages, this because it could add a preparation stage for the switch to activate in a scenario where the energy transformation will not bring losses thanks to the switching preparation.[11]

In other words, instead of the hard switching techniques used by power converters they could use soft-switching using a oscillatory circuit to shape the current or voltage form so that the power switches had a zero-current or zero-voltage effect, some of the advantages include:[12] [13]

- The switching loss is practically zero, which means it has high efficiency
- The converter enhance high power density and reduce the size and wight of the converter
- It is improved the switching stress
- Electromagnetic interference decrease and the machine insulation is less stressed
- Acoustic noise very small since the operation is on high frequency

Even when all this advantages are presented, the converters that are being discussed can not be directly applied to dc motors for propulsion, some of the reasons for this include suffering excessive voltage and current stress and left them unable to convert backward power during regenerative braking, this is important because this storage can extend the driving range about 25%, there have been converters designed for this application, using the bidirectional power flow for motoring and regenerative braking.[12]

3 JUSTIFICATION

The main motivation to delve into this topic of electric vehicles is directly related to the actual society and the environmental issues that fossil fuels and pollution are causing nowadays, moved by this reappeared factors and driven by two main accords The Kyoto protocol and the Paris Agreement, created to minimize these issues and improve the air quality and many more issues created under the actual conditions of pollution, there are new developments and innovations related to EV's which is the topic of this draft-thesis. [14][15]

Going deeper into this subject, one of the main issues with the EV's is that they are expensive and in order to decrease the actual cost, this draft-thesis will be guided towards the investigation on how to increment the lifetime of the elements used for this vehicles. The target to face is focused in the converter parts which in a process of energy transformation suffer from ripple changes, stress, thermal losses and efficiency in the energy transformation.

The technique to approach in this document is the Soft-Switching, it is considered to be power saving depending on the approach needed. There are two main types, the first one uses a resonant circuit that reduces the ripple of current, the second one also uses an additional resonant stage to reduce the voltage ripple, by reducing this ripples the power factor is also reduced and it minimizes. There are different topologies and schematics that are variations of the chopping mode and this depends of the type of converter being used. These variations provide different options that include the energy recovering from the brakes, or from the motion of the vehicle while in reverse, by the respective power source that feeds the different configurations. It is not necessary to mention the relevance of recovering energy from the brakes has in this type of vehicles which is enormous.

4 SOCIAL IMPACT

More than simply applying a concept and adapt it to the converter topology existing in an electric vehicle, is the change that this concept will generate. Due to an efficiency near to the 100%, there is no high power dissipation by temperature, is reduced the stress on the components an by the way, their useful life and the possibility of increase the reliable in specific and general components. As a plus, treatment with the battery is direct and highly more efficient than leaving the system working alone with the typical hard switching.

The improvement and all the factors previously taken into account, are shared and directed to all who want invest, search, investigate in the EV topic or by the other hand, for all those who want to buy or acquire an EV. Moreover, looking for a improve to the planet, one of the important factors taking account is the batteries issue, being this element one of the hardest in the recycle process, it becomes, in the way of this project could help, one of our interest sector by prolonging the useful life of the batteries at least in their application on EVs for the good of the planet. Finally, adding to all of this, one of the goals is to make lower the cost in a long term of the vehicle, adding soft-switching it becomes possibly consider some benefits even for the costumer in a monetary way.

5 OBJECTIVES

5.1 GENERAL OBJECTIVE

Design and simulate DC-DC Converters that use the Soft Switching technique.

5.2 SPECIFIC OBJECTIVES

The specific objectives that will be reached are the following:

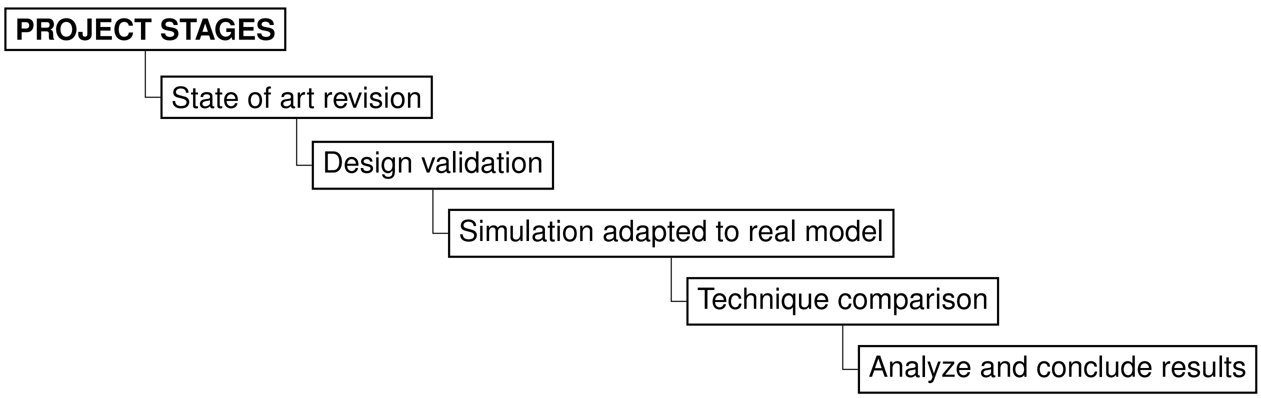
1. Create blocks/functions to recreate through simulation the semiconductor devices as a real model, with switching and temperature losses.

2. Design a Buck-Boost Bidirectional DC-DC Converter with the typical configuration and another one adding the resonant elements in order to implement the Soft Switching technique, then compare the techniques hard switching and soft switching used, and explain the advantages and disadvantages of each one according to their behaviors.

3. Design a SEPIC-ZETA Bidirectional DC-DC Converter with the typical configuration and another one adding the resonant elements in order to implement the Soft Switching technique, then compare the techniques hard switching and soft switching used, and explain the advantages and disadvantages of each one according to their behaviors.

6 METHODOLOGICAL DESIGN

The methodological design will be explained by the next two charts.



PROJECT STAGES

- **State of art revision:** Revision of the technique that will be used and the regular ones
- **Design validation:** Validate the design of the soft-switching converter using the information obtained in the state of art .
- **Simulation adapted to real model:** Adapt the model using the tool Simulink®, creating a realistic simulation.
- **Technique comparison**
  - Hard Switching
  - Soft Switching
- **Analyze and conclude results:** Analyze advantages and disadvantages of each technique and conclude using the results.

7 CONCEPTUAL FRAMEWORK

7.1 Types of DC-DC Converters

The DC voltage varies with the batteries an the operational conditions, which is why DC-DC converters are required for electric vehicles, and the efficiency has to be above 95%. [16]. DC-DC Converters for electric vehicles are classified in two:

- **Unidirectional:** Provides to different on-board loads such as sensors, controls and others, they are also used in DC motor drives and electric traction.
- **Bidirectional:** These are used for battery charging, regenerative braking, usually used when backup power is required, The power flow starts from low voltage to high voltage (Boost mode), but it could also flow backwards to charge the battery (Buck mode).[17] [18] [19] [20]

7.2 FUNDAMENTALS OF MOSFET

MOSFET technology has been in constant development since the 1960's, this happened while finding the metal oxide semiconductor adequate for power systems, the advances made in the semiconductor field, have helped improve the switching speed and power handling capabilities, these developments have been made with the new semiconductor manufacturing techniques and the packages used, this characteristics allow the semiconductors being developed to endure higher voltage and current values, and faster turn on and off, these qualities make the power semiconductors one of the most studied fields, looking for constant improvement.[21]
MOSFET are three terminal devices where the gate controls the current flow between the source and the drain, in power electronics these devices are used as switches to control the power in the load, this is because the three states have different characteristics that allow or cut-off the power flow, the first state is the cutoff, this occurs when the voltage between

Gate and Source is less than the threshold voltage, in this state the device works as an open circuit. When the voltage between Gate and Source is large, the device enters the ohmic region, in this region the voltage between Drain and Source is small, the equation that describe this region is

$$V_{GS} - V_{GS(th)} > V_{DS} > 0 \tag{1}$$

Lastly in the active region the Drain current depends on the voltage found between Gate and Source instead of the Drain to Source voltage, in this region the i_D current is given by

$$i_D = K(V_{GS} - V_{GS(th)})^2 \tag{2}$$

When the device is in a state between the ohmic and the active region the Equation (2) becomes

$$i_D = KV_{DS}^2 \tag{3}$$

Equations taken from [22].

The C_{GS} and the C_{GD} capacitors correspond to the geometry of the device instead, the C_{DS} capacitor is the capacitance formed by the body diode. The following are equations for estimate the values of the capacitors,

$$C_{GD} \approx \frac{C_{GD,0}}{1 + K_1 * \sqrt{V_{DS}}} \tag{4}$$

$$C_{DS} \approx \frac{C_{DS,0}}{1 + K_2 * \sqrt{V_{DS}}} \tag{5}$$

But, in the data sheets of the transistors there's not values defined so, the form is calculate the approximated values from C_{ISS}, C_{RSS} and C_{OSS} as shown

$$C_{GD} = C_{RSS} \tag{6}$$

$$C_{GS} = C_{ISS} - C_{RSS} \tag{7}$$

$$C_{DS} = C_{OSS} - C_{RSS} \tag{8}$$

Furthermore, the transconductance could be found as

$$\frac{dI_D}{dV_{GS}} = g_{fs} \tag{9}$$

Then, in the linear region we could find the maximum current

$$I_D = (V_{GS} - V_{th}) * g_{fs} \tag{10}$$

Now, rearranging the previous equation, could get closed to a Miller plateau value

$$V_{GS,Miller} = V_{th} + \frac{I_D}{g_{fs}} \tag{11}$$

In order to understand the power losses of the MOSFET we will need to know about the junction temperature that it can tolerate and also take into account the switching losses.

To do this, usually the Drain temperature is calculated with the Equation (12)

$$T_D = T_j - (P_j \times \theta_{jD}) \tag{12}$$

In Equation (12) T_j is the junction temperature, T_D drain temperature, P_j is the total heat power generated, and θ_{jD} is the thermal resistance from junction to drain. Using this equation an approximate of the total heat power can be found, nevertheless this value is not as accurate, since some of the power could be dissipated through heat.[23]

7.3 BIDIRECTIONAL BUCK-BOOST CONVERTER

The Buck-Boost converter is the cascade between a regular Buck and a Boost converter, which causes the output to be around the same as the input voltage with the opposite polarity, in the regular literature this converter is used in only one direction, but to achieve the objectives set up at the beginning of this work, this converter will be used in it's bidirectional form, in order to do this, the starting point will be with the equations that describe the regular Buck Boost in steady state which is shown in *Figure 1*. Below the equations that describe the respective circuit will be shown.

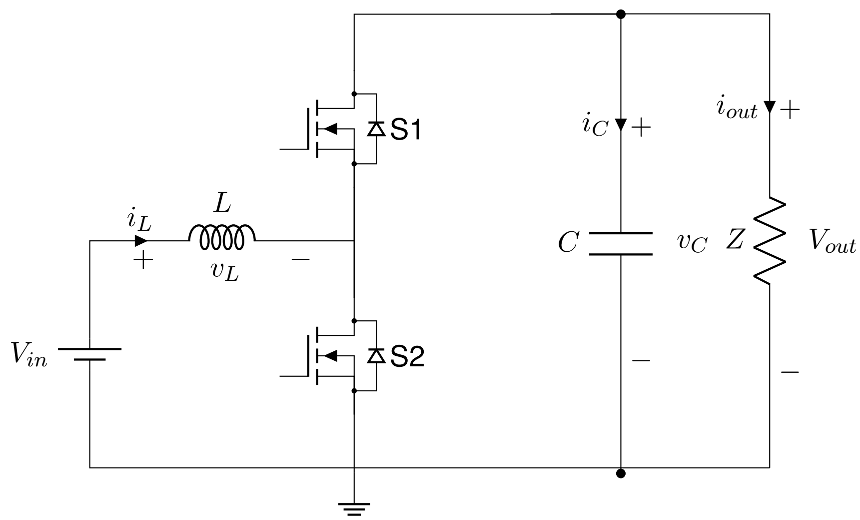


Figure 1: Schematic circuit diagram of the bidirectional Buck-Boost converter [24]

For this design the equations taken in account will be the two states with at least one MOSFET OFF.

For the first switching mode the equations will be described according to the *Figure 2*.

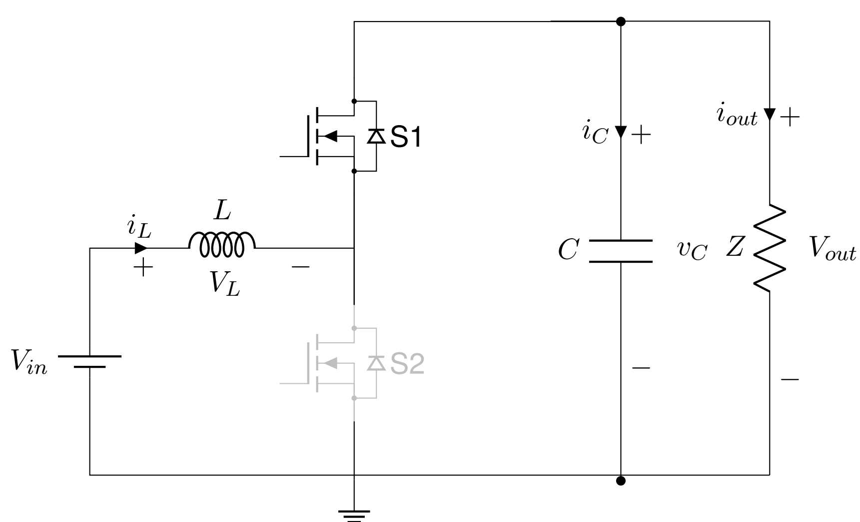


Figure 2: Schematic circuit diagram of the bidirectional Buck-Boost converter S1 ON S2 OFF

Because of the current law the equation to describe the circuit will be the *Equation (13)*

$$v_L = v_{in} - v_{Zout} \tag{13}$$

But there is an equivalence between the V_{out} and V_{Co1}

Using the equality, the correlation on diferential equations is: *Equation (14)*

$$\boxed{\frac{di_L}{dt} = \frac{v_{in} - v_{out}}{L} = \frac{v_{in} - v_C}{L}} \tag{14}$$

Also by using the voltage law there is a new equation

$$i_L = i_C - i_{out} \tag{15}$$

$$\boxed{\frac{dV_C}{dt} = \frac{i_L - i_{out}}{C}} \tag{16}$$

It is important to remember the equivalence of i_{out}.

$$i_{out} = \frac{V_{out}}{Z_{out}} \tag{17}$$

State Equations	
$\frac{di_L}{dt}$	$\frac{V_{in} - V_C}{L}$
$\frac{dV_C}{dt}$	$\frac{i_L}{C} - \frac{V_{out}}{CZ}$

Table 1: Bidirectional Buck-Boost S1 ON S2 OFF Mode Operation

For the second set of equations the circuit taken into account will be the *Figure 3*

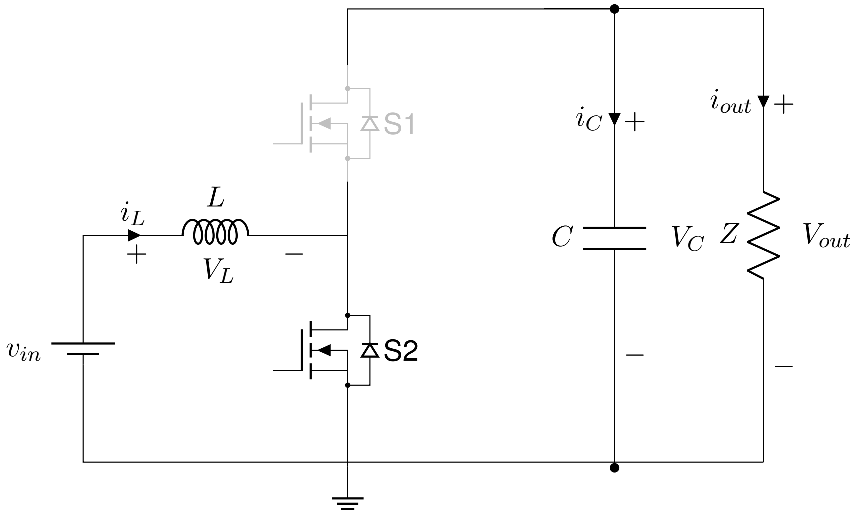


Figure 3: Schematic circuit diagram of the bidirectional Buck-Boost converter S1 OFF S2 ON

For this particular circuit the equation found using the current law is *Equation (18)*

$$v_L = v_{in} \tag{18}$$

Solving this equation to obtain the fraction, the result is *Equation (19)*

$$\boxed{\frac{di_L}{dt} = \frac{v_{in}}{L}} \tag{19}$$

Solving the voltage law For this schematic, the result is the following.

$$i_C = -i_L - i_{out} \tag{20}$$

$$\boxed{\frac{dv_C}{dt} = \frac{-i_L - i_{out}}{C}} \tag{21}$$

State Equations	
$\frac{di_L}{dt}$	$\frac{V_{in}}{L}$
$\frac{dV_C}{dt}$	$\frac{V_{out}}{CZ}$

Table 2: Bidirectional Buck-Boost S1 OFF S2 ON Mode Operation

Since the topology being studied is bidirectional, there must be a set of equations For the other direction, which will be developed below, according to *Figure 4*

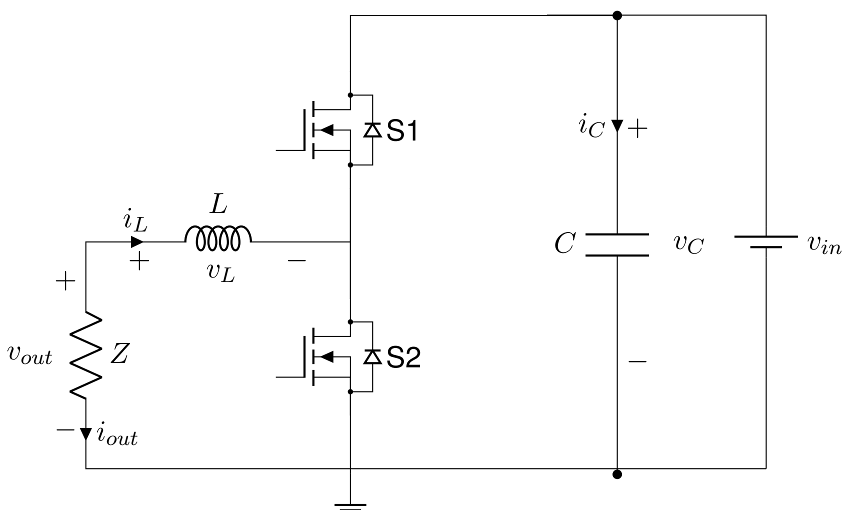


Figure 4: Schematic circuit diagram of the bidirectional Boost-Buck converter

For this design the equations taken into account will be the two states with at least one MOSFET OFF.

For the first switching mode the equations will be described according to the *Figure 5*.

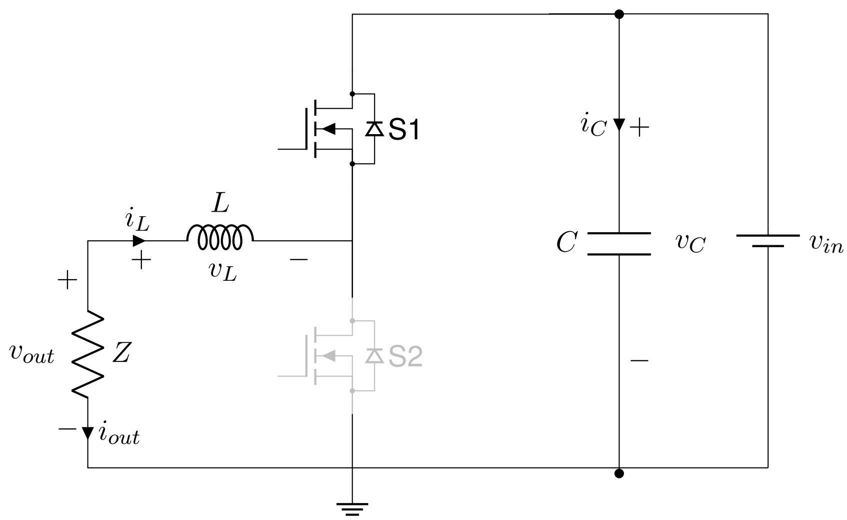


Figure 5: Schematic circuit diagram of the bidirectional Boost-Buck converter

Because of the current law the equation to describe the circuit will be the *Equation (22)*

$$v_L = v_{out} - v_{in} \tag{22}$$

But there is an equivalence between the V_{in} and V_C

Using the equality, the correlation on fractial equations is: *Equation (23)*

$$\boxed{\frac{di_L}{dt} = \frac{v_{out} - v_{in}}{L} = \frac{v_{out} - v_C}{L}} \tag{23}$$

To find the other equation for this state using the nodes law

$$i_L = i_C = -i_{out} \tag{24}$$

$$\boxed{\frac{\partial v_{Co1}}{\partial t} = \frac{i_L}{C_{o1}} = \frac{-i_{out}}{C_{o1}}} \tag{25}$$

State Equations	
$\frac{\partial i_L}{\partial t}$	$\frac{V_{out} - V_{Co1}}{L}$
$\frac{\partial V_{Co1}}{\partial t}$	$\frac{V_{out}}{C_{o1} * Z_{out}}$

Table 3: Bidirectional Buck-Boost S1 ON S2 OFF Mode Operation

For the second set of equations of the second direction the circuit taken into account will be the *Figure 6*

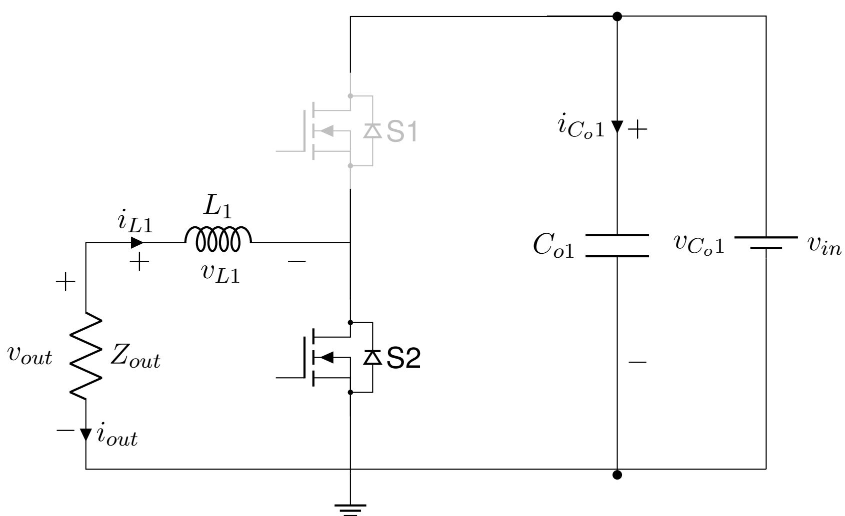


Figure 6: Schematic circuit diagram of the bidirectional Boost-Buck converter

For this particular circuit the equation found using the current law is *Equation (26)*

$$v_L = v_{Zout} \tag{26}$$

Solving this equation to obtain the fraction, the result is *Equation (27)*

$$\boxed{\frac{\partial i_L}{\partial t} = \frac{v_{Zout}}{L}} \tag{27}$$

Also the equation found using the voltage law is *Equation (28)*

$$i_{Co1} = -i_L - i_{Zout} \tag{28}$$

$$\boxed{\frac{\partial v_{Co1}}{\partial t} = \frac{-i_L - i_{Zout}}{C_{o1}}} \tag{29}$$

State Equations	
$\frac{\partial i_L}{\partial t}$	$\frac{V_{out}}{L}$
$\frac{\partial V_{Co1}}{\partial t}$	$-\frac{i_L}{C_{o1}} - \frac{V_{out}}{C_{o1}*Z_{out}}$

Table 4: Bidirectional Buck-Boost S1 OFF S2 ON Mode Operation

7.4 BIDIRECTIONAL BUCK-BOOST CONVERTER WITH SOFT SWITCHING

The design chosen to include the soft switching technique applied to the bidirectional converter is shown in the *Figure 7*

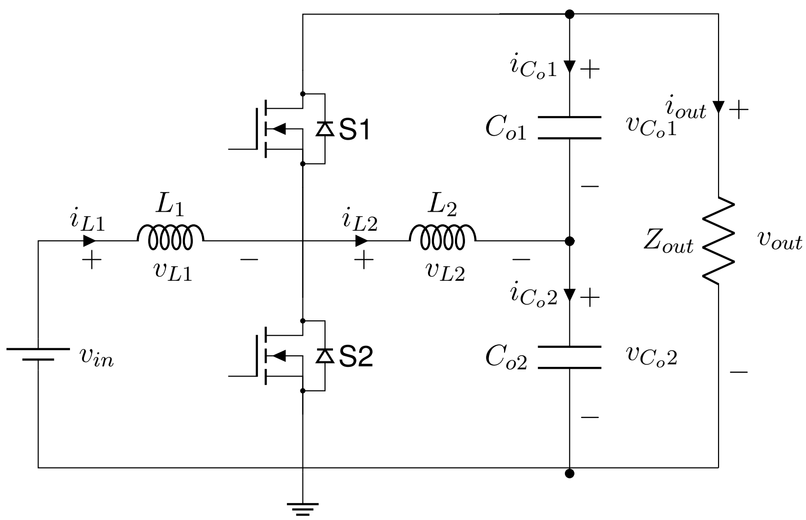


Figure 7: Schematic circuit diagram of the bidirectional Buck-Boost converter

In order to analyze the converter it is imperative to start considering the operation status of the MOSFET.

The following equations will describe the first switching mode for the circuit showing in *Figure 8*

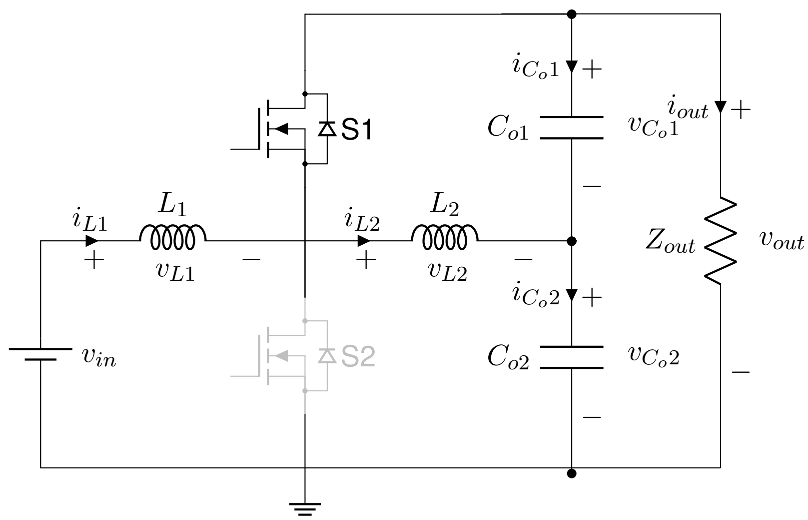


Figure 8: Schematic circuit diagram of the bidirectional Buck-Boost converter state S1 ON S2 OFF

The equations that we get from this state are described below, starting with the nodes equations.

$$i_{L1} = i_{L2} + i_{Co1} + i_{Zout} \tag{30}$$

$$i_{L2} + i_{Co1} = i_{Co2} \tag{31}$$

$$i_{Co2} + i_{Zout} = i_{L1} \tag{32}$$

Therefore we get the following equations

$$\boxed{\frac{\partial V_{Co1}}{\partial t} = \frac{i_{L1} - i_{L2}}{C_{o1}} - \frac{-(V_{Co1} + V_{Co2})}{Z_{out} * C_{o1}}} \tag{33}$$

$$\boxed{\frac{\partial V_{Co2}}{\partial t} = \frac{i_{L1}}{C_{o2}} - \frac{-(V_{Co1} + V_{Co2})}{Z_{out} * C_{o2}}} \tag{34}$$

Now we continue with the branches equations.

$$V_{L1} + V_{L2} + V_{Co2} = V_{in} \quad (35)$$

$$V_{L2} = V_{Co1} \quad (36)$$

$$V_{out} = V_{Co1} + V_{Co2} \quad (37)$$

And for this we get these equations

$$\boxed{\frac{\partial i_{L1}}{\partial t} = \frac{V_{in} - (V_{Co1} + V_{Co2})}{L_1}} \quad (38)$$

$$\boxed{\frac{\partial i_{L2}}{\partial t} = \frac{V_{Co2}}{L_2}} \quad (39)$$

State Equations	
$\frac{\partial i_{L1}}{\partial t}$	$\frac{V_{in} - (V_{Co1} + V_{Co2})}{L_1}$
$\frac{\partial i_{L2}}{\partial t}$	$\frac{V_{Co2}}{L_2}$
$\frac{\partial V_{Co1}}{\partial t}$	$\frac{-i_{L2}}{C_{o1}} - \frac{(V_{Co1} + V_{Co2})}{Z_{out} * C_{o1}}$
$\frac{\partial V_{Co2}}{\partial t}$	$-\frac{(V_{Co1} + V_{Co2})}{Z_{out} * C_{o2}}$

Table 5: Bidirectional Buck-Boost S1 ON S2 OFF Mode Operation

Now the equations of the next switching mode, described in the *Figure 9*

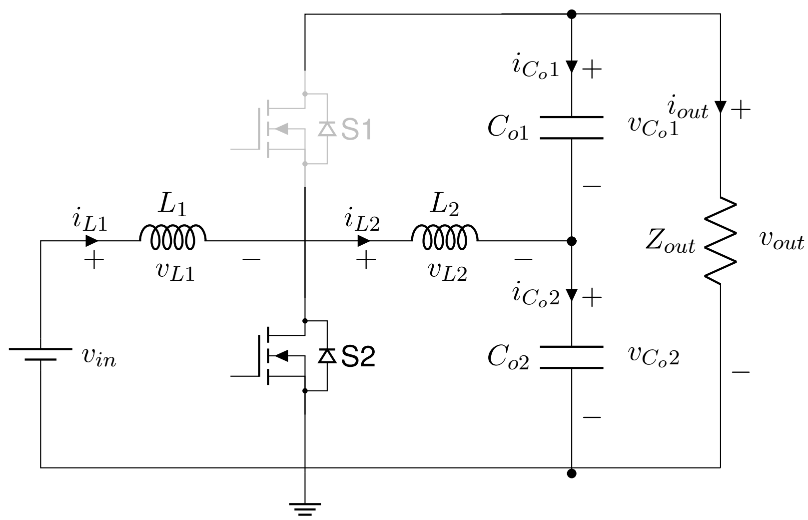


Figure 9: Schematic circuit diagram of the bidirectional Buck-Boost converter state S1 OFF S2 ON

Starting with the nodes equations.

$$i_{L1} + i_{Co2} + i_{Zout} = i_{L2} \tag{40}$$

$$i_{L2} + i_{Co1} = i_{Co2} \tag{41}$$

$$i_{Co1} + i_{Zout} = 0 \tag{42}$$

$$\boxed{\frac{\partial V_{Co1}}{\partial t} = -\frac{V_{Co1} + V_{Co2}}{Z_{out} * C_{o1}}} \tag{43}$$

$$\boxed{\frac{\partial V_{Co2}}{\partial t} = \frac{i_{L2}}{C_{o2}} - \frac{V_{Co1} + V_{Co2}}{Z_{out} * C_{o1}}} \tag{44}$$

We continue with the branches equations.

$$V_{L1} = V_{in} \tag{45}$$

$$V_{L2} = -V_{Co2} \tag{46}$$

$$\boxed{\frac{\partial i_{L1}}{\partial t} = \frac{V_{in}}{L_1}} \tag{47}$$

$$\boxed{\frac{\partial i_{L2}}{\partial t} = -\frac{V_{Co2}}{L_2}} \tag{48}$$

State Equations	
$\frac{\partial i_{L1}}{\partial t}$	$\frac{V_{in}}{L_1}$
$\frac{\partial i_{L2}}{\partial t}$	$-\frac{V_{Co2}}{L_2}$
$\frac{\partial V_{Co1}}{\partial t}$	$-\frac{(V_{Co1}+V_{Co2})}{Z_{out}*C_{o1}}$
$\frac{\partial V_{Co2}}{\partial t}$	$\frac{i_{L2}-i_{L1}}{C_{o2}} - \frac{(V_{Co1}+V_{Co2})}{Z_{out}*C_{o2}}$

Table 6: Bidirectional Buck-Boost S1 OFF S2 ON Mode Operation

For the next part we will see the other direction of this Buck Boost circuit and the corresponding findings.

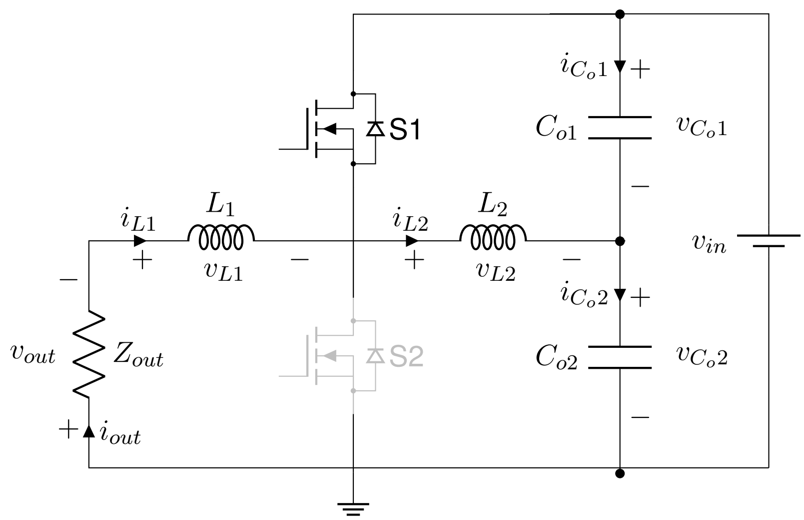


Figure 10: Schematic circuit diagram of the bidirectional Buck-Boost converter state S1 ON S2 OFF

Starting with nodes equations

$$i_{L1} = i_{L2} + i_{Co1} \tag{49}$$

$$i_{L2} + i_{Co1} = i_{Co2} \tag{50}$$

$$i_{Z_{out}} = i_{L1} = i_{Co2} \tag{51}$$

$$\boxed{\frac{\partial V_{Co1}}{\partial t} = \frac{i_{L1} - i_{L2}}{C_{o1}}} \tag{52}$$

$$\boxed{\frac{\partial V_{Co2}}{\partial t} = -\frac{i_{L1}}{C_{o2}}} \tag{53}$$

We continue with the branches equations.

$$V_{out} + V_{L1} + V_{L2} + V_{Co2} = 0 \tag{54}$$

$$V_{L2} = V_{Co1} \tag{55}$$

$$V_{in} = V_{Co1} + V_{Co2} \tag{56}$$

And we get these equations

$$\boxed{\frac{\partial i_{L1}}{\partial t} = \frac{-V_{out} - V_{in}}{L_1}} \tag{57}$$

$$\boxed{\frac{\partial i_{L2}}{\partial t} = \frac{V_{Co1}}{L_2}} \tag{58}$$

State Equations	
$\frac{\partial i_{L1}}{\partial t}$	$\frac{V_{out}-V_{in}}{L1}$
$\frac{\partial i_{L2}}{\partial t}$	$\frac{V_{Co1}}{L_2}$
$\frac{\partial V_{Co1}}{\partial t}$	$\frac{i_{L1}-i_{L2}}{C_{o1}}$
$\frac{\partial V_{Co2}}{\partial t}$	$-\frac{i_{L1}}{C_{o2}}$

Table 7: Bidirectional Buck-Boost S1 ON S2 OFF Mode Operation

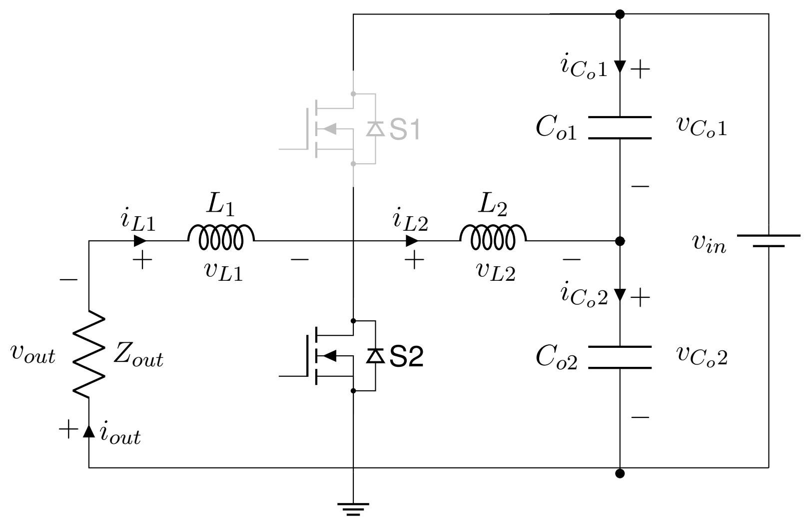


Figure 11: Schematic circuit diagram of the bidirectional Buck-Boost converter state S1 OFF S2 ON

Starting with nodes equations

$$i_{Z_{out}} + i_{L1} = 0 \tag{59}$$

$$i_{Co1} = i_{L2} + i_{Co2} \tag{60}$$

$$i_{Z_{out}} + i_{L1} + i_{L2} + i_{Co2} = 0 \tag{61}$$

$$\boxed{\frac{\partial V_{Co1}}{\partial t} = 0} \tag{62}$$

$$\boxed{\frac{\partial V_{Co2}}{\partial t} = -\frac{i_{L2}}{C_{o2}}} \tag{63}$$

We continue with the branches equations.

$$V_{L1} = V_{out} \tag{64}$$

$$V_{L2} = V_{Co2} \tag{65}$$

$$V_{in} = V_{Co1} + V_{Co2} \tag{66}$$

And we get these equations

$$\boxed{\frac{\partial i_{L1}}{\partial t} = \frac{V_{out}}{L_1}} \tag{67}$$

$$\boxed{\frac{\partial i_{L2}}{\partial t} = \frac{V_{Co2}}{L_2}} \tag{68}$$

State Equations	
$\frac{\partial i_{L1}}{\partial t}$	$\frac{V_{out}}{L1}$
$\frac{\partial i_{L2}}{\partial t}$	$\frac{V_{Co2}}{L_2}$
$\frac{\partial V_{Co1}}{\partial t}$	0
$\frac{\partial V_{Co2}}{\partial t}$	$-\frac{i_{l2}}{C_{o2}}$

Table 8: Bidirectional Boost-Buck S1 OFF S2 ON Mode Operation

7.5 BIDIRECTIONAL SEPIC-ZETA NON ISOLATED CONVERTER

In this section we will explore the Bidirectional Sepic-Zeta converter shown in *Figure 12*, we have to take into account that these types of converters are widely applied to EV's since they allow to use the energy flow in both directions.[25]

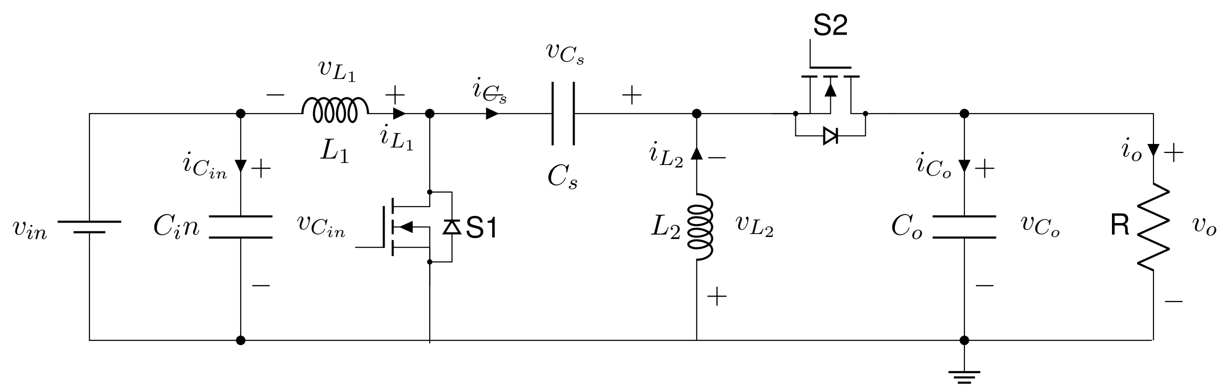


Figure 12: Schematic circuit diagram of the bidirectional SEPIC-ZETA converter based on hard switching

When S_1 is ON and S_2 is OFF

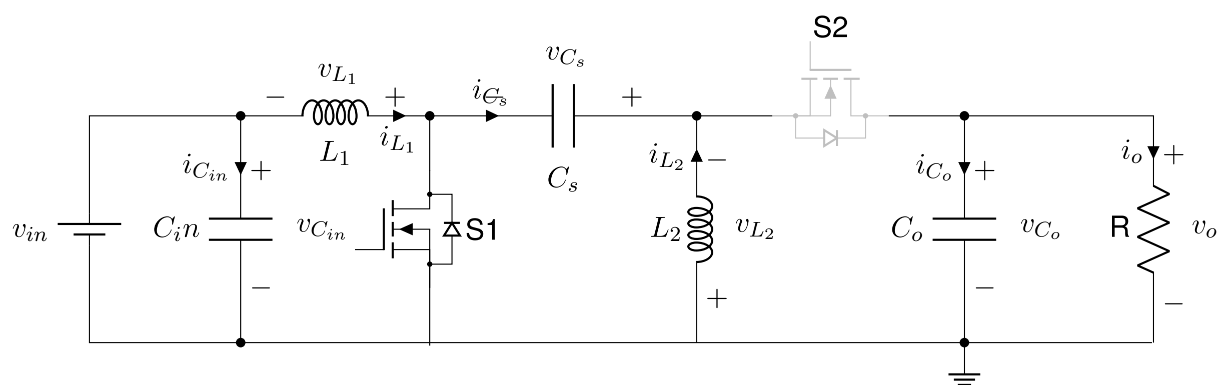


Figure 13: Schematic circuit diagram of the bidirectional SEPIC-ZETA converter, when S_1 is ON and S_2 is OFF

$$i_{Co} = -i_R \quad (69)$$

$$\boxed{\frac{\partial V_{Co}}{\partial t} = -\frac{Vo}{RC_o}} \tag{70}$$

For the voltage in the Inductor L_1 and the input capacitor is given that

$$i_C o = -i_R \tag{71}$$

$$\boxed{\frac{\partial V_C o}{\partial t} = -\frac{Vo}{RC_o}} \tag{72}$$

$$V_g = V_{C_in} = V_{L_1} \tag{73}$$

Solving for ΔL_1

$$\boxed{\frac{\partial i_{L1}}{\partial t} = \frac{Vg}{L_1}} \tag{74}$$

When S1 is ON, it leaves C_s and L_2 as one close circuit. For that,

$$V_{Cs} = V_{L2} \tag{75}$$

Then,

$$\boxed{\frac{\partial i_{L2}}{\partial t} = \frac{V_{Cs}}{L_2}} \tag{76}$$

About the current in C_s and L_2 close circuit, it is similar to the current relation in the output

$$i_{L2} = -i_{Cs} \tag{77}$$

$$\boxed{\frac{\partial V_{Cs}}{\partial t} = -\frac{i_{L2}}{C_s}} \tag{78}$$

State Equations	
$\frac{\partial V_{Cs}}{\partial t}$	$-\frac{i_{L2}}{C_s}$
$\frac{\partial i_{L2}}{\partial t}$	$\frac{V_{Cs}}{L_2}$
$\frac{\partial i_{L1}}{\partial t}$	$\frac{V_g}{L_1}$
$\frac{\partial V_{Co}}{\partial t}$	$-\frac{Vo}{RC_o}$

Table 9: Sepic-Zeta S1 ON and S2 OFF Mode Operation

When S_1 is OFF and S_2 is ON

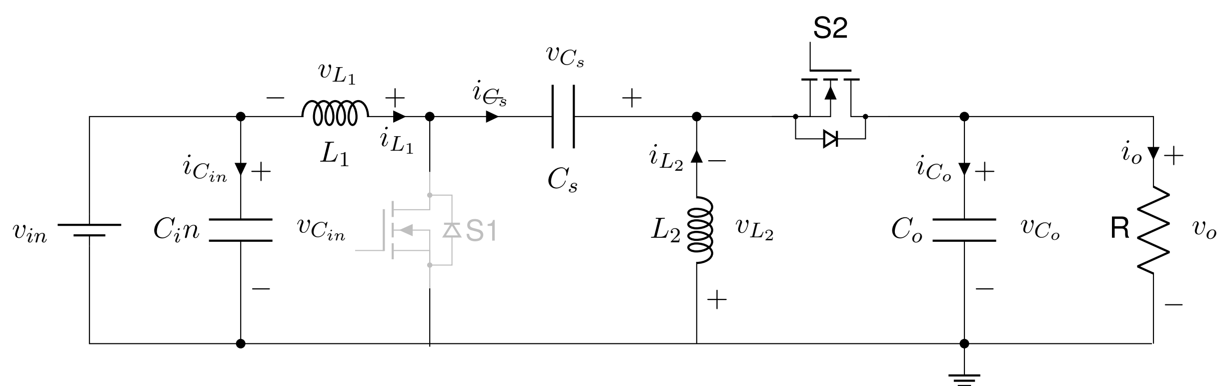


Figure 14: Schematic circuit diagram of the bidirectional SEPIC-ZETA converter, when S_1 is OFF and S_2 is ON

Activating S2 the inductor L_2, the capacitor C_o and the resistor are in parallel, so the voltage is assumed the same

$$V_{L2} = -V_o \tag{79}$$

$$\boxed{\frac{\partial i_{L2}}{\partial t} = -\frac{Vo}{L_2}} \tag{80}$$

Solving Equation (96) for ΔV_{Co}

$$i_{L_1} + i_{L_2} = i_{C_o} + i_R \tag{81}$$

Therefor,

$$\boxed{\frac{\partial V_{Co}}{\partial t} = \frac{1}{C_o}\left[i_{L_1} + i_{L_2} - \frac{V_o}{R}\right]} \tag{82}$$

The current trough L_1 and C_s is the same

$$i_{L1} = i_{Cs} \tag{83}$$

$$\boxed{\frac{\partial V_{Cs}}{\partial t} = \frac{i_{L1}}{C_s}} \tag{84}$$

For the inductor close to the input (L_1)

$$V_{L1} = V_g - V_{Cs} - V_o \tag{85}$$

$$\boxed{\frac{\partial i_{L1}}{\partial t} = \frac{V_g - V_{C_s} - V_o}{L_1}} \tag{86}$$

State Equations	
$\frac{\partial V_{Cs}}{\partial t}$	$\frac{i_{L1}}{C_s}$
$\frac{\partial i_{L_2}}{\partial t}$	$-\frac{Vo}{L_2}$
$\frac{\partial i_{L_1}}{\partial t}$	$\frac{V_g - V_{Cs} - V_o}{L_1}$
$\frac{\partial V_{Co}}{\partial t}$	$\frac{1}{C_o}\left[i_{L_1} + i_{L_2} - \frac{V_o}{RC_o}\right]$

Table 10: Sepic-Zeta S1 OFF and S2 ON Mode Operation

In reverse, we find the equations to model the Zeta-Sepic mode of the converter.

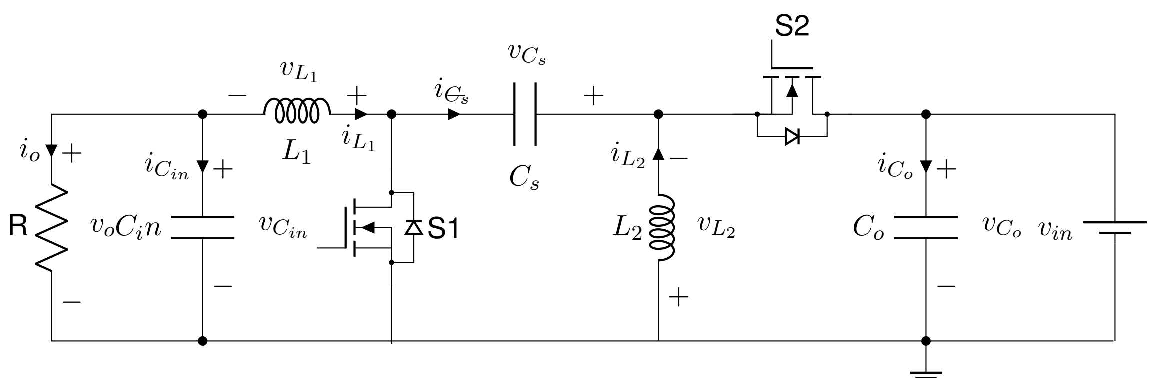


Figure 15: Schematic circuit diagram of the bidirectional ZETA-SEPIC converter

When S_1 is ON and S_2 is OFF

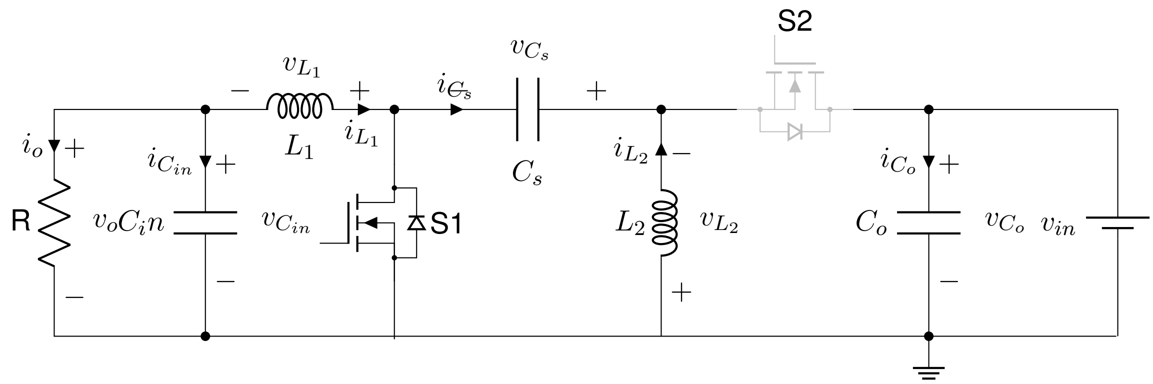


Figure 16: Schematic circuit diagram of the bidirectional SEPIC-ZETA converter, when S_1 is ON and S_2 is OFF

$$\boxed{\frac{\partial V_{Co}}{\partial t} = -\frac{Vo - VCo}{C_o R_{in}}} \tag{87}$$

For the voltage in the Inductor L_1 and the output capacitor is given that

$$\boxed{\frac{\partial i_{L1}}{\partial t} = \frac{Vg}{L1}} \tag{88}$$

When S1 is ON, it leaves C_s and L_2 as one close circuit. For that,

$$\boxed{\frac{\partial i_{L2}}{\partial t} = -\frac{V_{Cs}}{L_2}} \tag{89}$$

$$\boxed{\frac{\partial V_{Cs}}{\partial t} = -\frac{i_{L2}}{Cs}} \tag{90}$$

About the current in C_s and L_2 close circuit, it is similar to the current relation in the output

$$\boxed{\frac{\partial V_{C_{in}}}{\partial t} = -\frac{1}{C_{in}}(i_{L1} - \frac{i_{L2}}{C_s})} \tag{91}$$

State Equations	
$\frac{\partial V_{Cs}}{\partial t}$	$-\frac{i_{L2}}{C_s}$
$\frac{\partial i_{L2}}{\partial t}$	$-\frac{V_{Cs}}{L_2}$
$\frac{\partial i_{L1}}{\partial t}$	$\frac{V_g}{L_1}$
$\frac{\partial V_{Co}}{\partial t}$	$-\frac{Vo-V_{Co}}{C_o R_{in}}$

Table 11: Zeta-Sepic S1 ON and S2 OFF Mode Operation

When S_1 is OFF and S_2 is ON

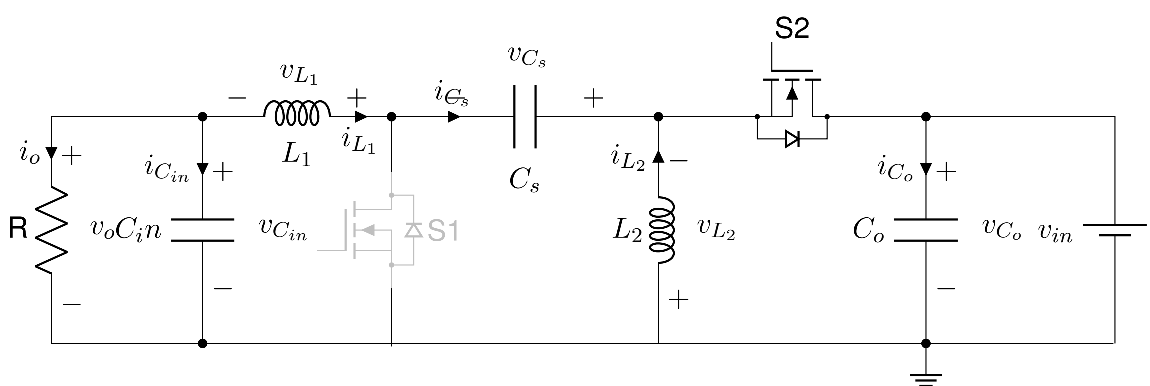


Figure 17: Schematic circuit diagram of the bidirectional SEPIC-ZETA converter, when S_1 is OFF and S_2 is ON

Activating S2 the inductor L_2, the capacitor C_o and the battery are in parallel, so the voltage is assumed the same

$$V_{L2} = V_{in} \tag{92}$$

$$\boxed{\frac{\partial i_{L2}}{\partial t} = -\frac{V_{in}}{L_2}} \tag{93}$$

$$\boxed{\frac{\partial V_{Co}}{\partial t} = \frac{1}{C_o}\left[i_{L_2} - i_{L_1} + \frac{V_o - V_{Co}}{R_{in}}\right]} \tag{94}$$

The current trough L_1 and C_s is the same

$$\boxed{\frac{\partial V_{Cs}}{\partial t} = \frac{i_{L1}}{C_s}} \tag{95}$$

For the inductor close to the output (L_1)

$$\boxed{\frac{\partial i_{L1}}{\partial t} = \frac{1}{L1}(V_{Co} - V_{C_s} - V_g)} \tag{96}$$

State Equations	
$\frac{\partial V_{Cs}}{\partial t}$	$\frac{i_{L1}}{C_s}$
$\frac{\partial i_{L_2}}{\partial t}$	$-\frac{V_{in}}{L_2}$
$\frac{\partial i_{L_1}}{\partial t}$	$\frac{V_{Co}-V_{C_s}-V_g}{L_1}$
$\frac{\partial V_{Co}}{\partial t}$	$\frac{1}{C_o}\left[i_{L_2} - i_{L_1} + \frac{V_o-V_{Co}}{R_{in}}\right]$

Table 12: Zeta-Sepic S1 OFF and S2 ON Mode Operation

7.6 BIDIRECTIONAL SEPIC-ZETA NON ISOLATED CONVERTER WITH SOFT SWITCHING

For the resonance element in order to couple with the Sepic-Zeta Bidirectional converter, it is added one auxiliary path with two faced Mosfet to control the current flux and its direction.

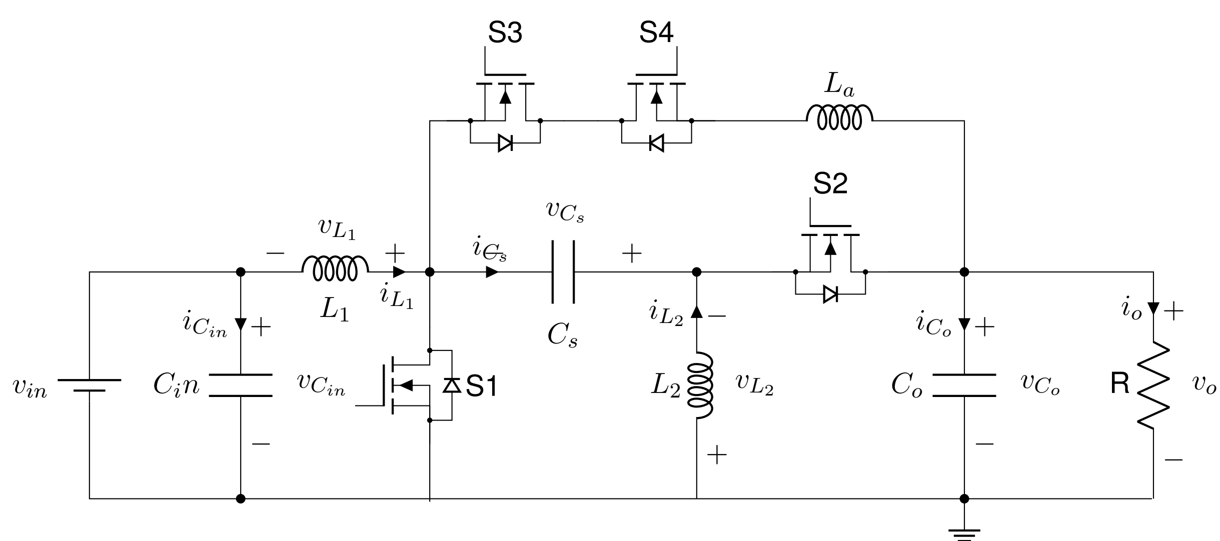


Figure 18: Schematic circuit diagram of the bidirectional SEPIC-ZETA converter based on soft switching

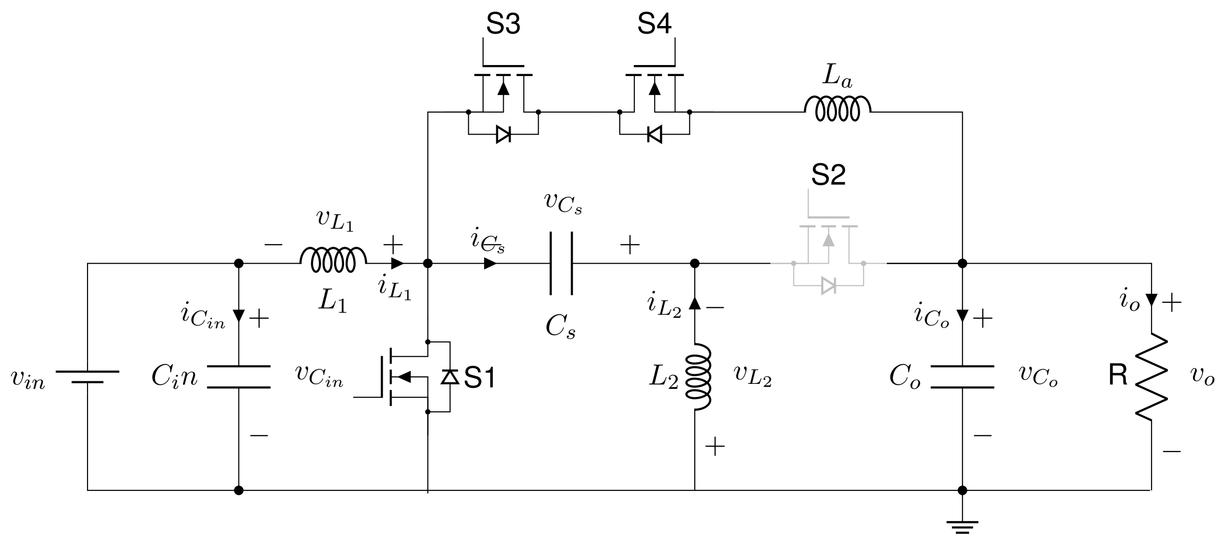


Figure 19: Schematic circuit diagram of the bidirectional SEPIC-ZETA converter with SS, when S_1 is ON and S_2 is OFF

$$V_{L_1} = V_{C_{in}} = V_g \tag{97}$$

$$\boxed{\frac{\partial i_{L1}}{\partial t} = -\frac{Vg}{L1}} \tag{98}$$

For the voltage in the Capacitor C_{in} is given that

$$i_{C_{in}} = -i_{L1} \tag{99}$$

$$\boxed{\frac{\partial V_C in}{\partial t} = -\frac{i_{L1}}{C_{in}}} \tag{100}$$

$$V_{C_s} = V_{L_2} \tag{101}$$

Solving for ΔL_2

$$\boxed{\frac{\partial i_{L2}}{\partial t} = \frac{V_{C_2}}{L_2}} \tag{102}$$

When S1 is ON, it leaves C_s and L_2 as a close circuit. For that,

$$V_{Cs} = -V_{L2} \tag{103}$$

Then,

$$\boxed{\frac{\partial V_{Cs}}{\partial t} = -\frac{i_{L2}}{C_s}} \tag{104}$$

In the auxiliary path, the inductor L_3 result connected to ground, so it can be get that

$$V_{L3} = -Vo \tag{105}$$

$$\boxed{\frac{\partial i_{L3}}{\partial t} = -\frac{V_o}{L_3}} \tag{106}$$

$$i_{C_o} + i_R + i_{L_3} = 0 \tag{107}$$

$$\boxed{\frac{\partial V_{C_o}}{\partial t} = -\frac{1}{C_o}\left[\frac{V_o}{R} + i_{L_3}\right]} \tag{108}$$

State Equations	
$\frac{\partial i_{L_3}}{\partial t}$	$-\frac{V_o}{L_3}$
$\frac{\partial i_{L_2}}{\partial t}$	$\frac{V_{Cs}}{L_2}$
$\frac{\partial i_{L_1}}{\partial t}$	$-\frac{Vg}{L1}$
$\frac{\partial V_{Cs}}{\partial t}$	$-\frac{i_{L2}}{C_s}$
$\frac{\partial V_{Co}}{\partial t}$	$-\frac{1}{C_o}\left[\frac{V_o}{R} + i_{L_3}\right]$

Table 13: Sepic-Zeta with SS S1 ON and S2 OFF Mode Operation

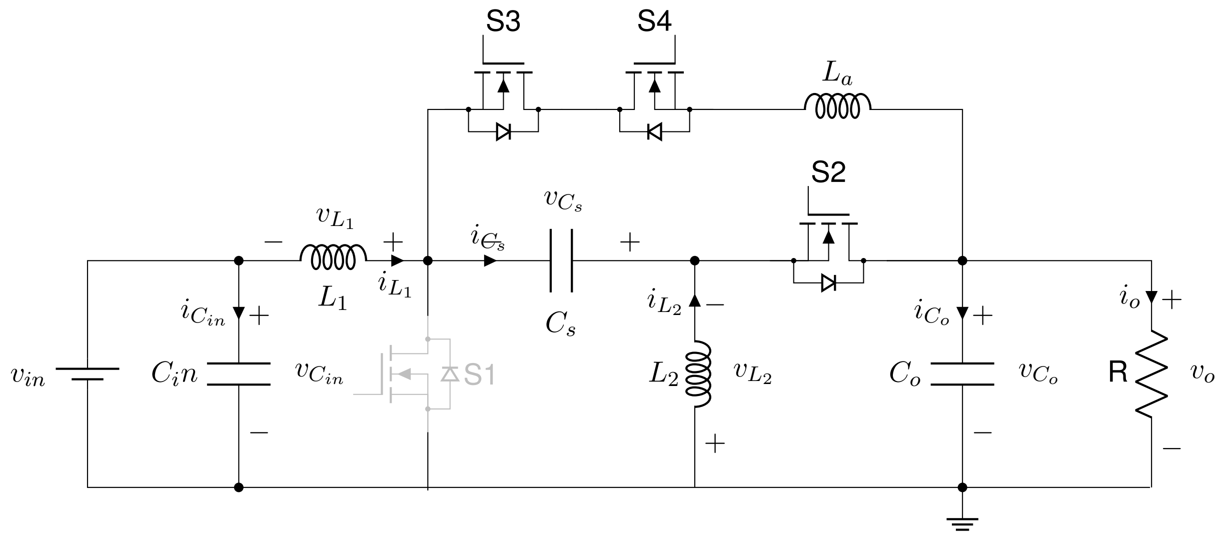


Figure 20: Schematic circuit diagram of the bidirectional SEPIC-ZETA converter with SS, when S_1 is OFF and S_2 is ON

$$V_{L3} = V_{Cs} \tag{109}$$

$$\boxed{\frac{\partial i_{L_3}}{\partial t} = \frac{V_{Cs}}{L_3}} \tag{110}$$

$$V_{L2} = V_{Co} \tag{111}$$

$$\boxed{\frac{\partial i_{L_2}}{\partial t} = \frac{V_{Co}}{L_2}} \tag{112}$$

$$i_{L1} = i_{L3} + i_{Cs} \tag{113}$$

$$\boxed{\frac{\partial V_{C_s}}{\partial t} = \frac{i_{L1} - i_{L2}}{C_s}} \tag{114}$$

$$i_{L1} = i_{L3} + i_{Co} + i_R \tag{115}$$

$$\boxed{\frac{\partial V_{C_o}}{\partial t} = \frac{V_{Cs}}{L_3}\left[i_{L_1} - i_{L_2} - \frac{V_o}{R}\right]} \tag{116}$$

$$V_{L1} = V_g - V_{Co} \tag{117}$$

$$\boxed{\frac{\partial i_{L_1}}{\partial t} = \frac{V_g - V_o}{L_1}} \tag{118}$$

State Equations	
$\frac{\partial i_{L_3}}{\partial t}$	$\frac{V_{Cs}}{L_3}$
$\frac{\partial i_{L_2}}{\partial t}$	$\frac{V_{Co}}{L_2}$
$\frac{\partial i_{L_1}}{\partial t}$	$\frac{V_g - V_o}{L_1}$
$\frac{\partial V_{Cs}}{\partial t}$	$\frac{i_{L1} - i_{L2}}{C_s}$
$\frac{\partial V_{Co}}{\partial t}$	$\frac{V_{Cs}}{L_3}\left[i_{L_1} - i_{L_2} - \frac{V_o}{R}\right]$

Table 14: Sepic-Zeta with SS S1 ON and S2 OFF Mode Operation

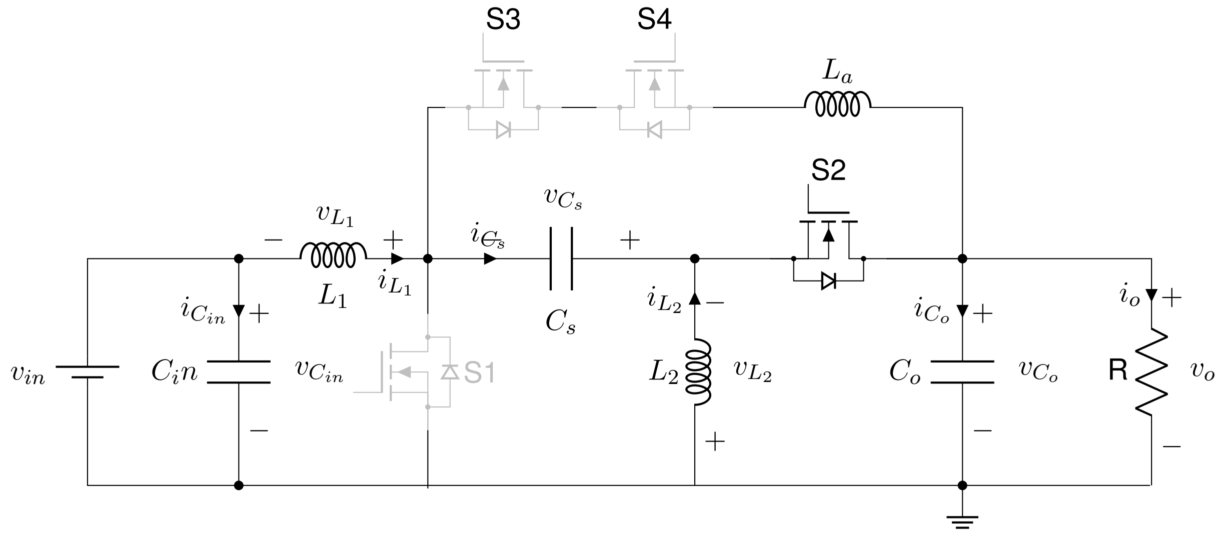


Figure 21: Schematic circuit diagram of the bidirectional SEPIC-ZETA converter with SS, when S_1 is OFF,S_2 is ON and the auxiliary path S_3 and S_4 is ON

The equations that describe this model are listed in the table 10

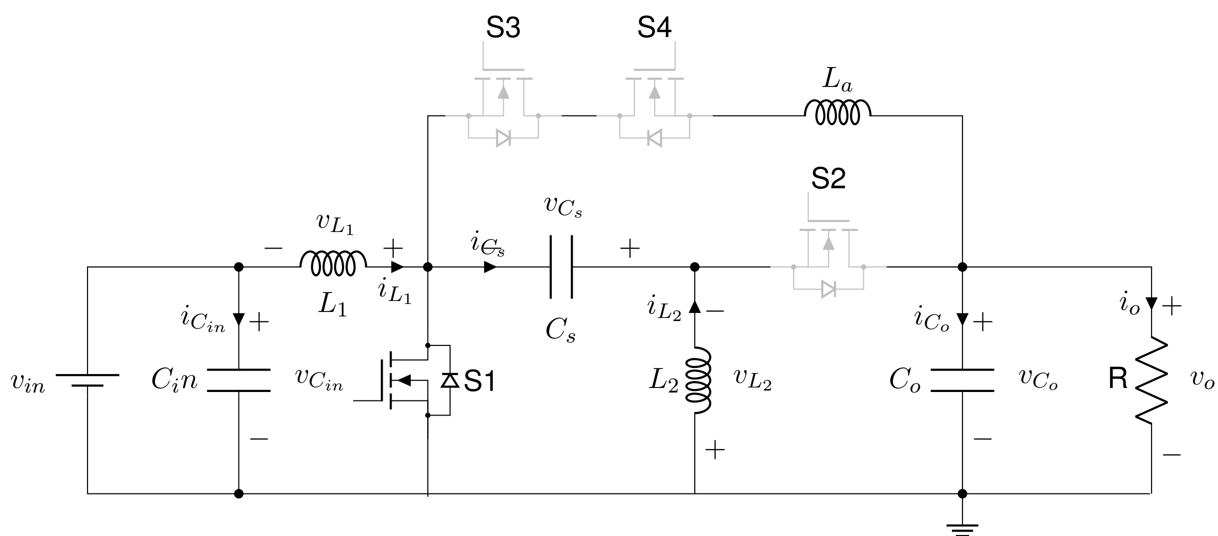


Figure 22: Schematic circuit diagram of the bidirectional SEPIC-ZETA converter with SS, when S_1 is ON,S_2 is OFF and the auxiliary path S_3 and S_4 is ON

The equations that describe this model are listed in the table 9

8 DESIGN

In this chapter the equations found during the mathematical analysis of the circuits will be shown and solved to find the proper values, this values will be used to simulate and show the difference between a regular converter, and the one with soft switching.

8.1 BIDIRECTIONAL BUCK-BOOST CONVERTER

The equations used to design the converter are the following:

First the calculation of the duty cycle, which will be used to find other variables

$$\langle V_L \rangle = \int_0^{DTs} V_{in} - V_{out} + \int_{DTs}^{Ts} V_{in} \quad (119)$$

$$\langle V_L \rangle = \frac{1}{Ts}\left[v_{in} - V_{out}\left(DTs\right) + V_{in}\left(Ts - DTs\right)\right] \quad (120)$$

$$\langle V_L \rangle = V_{in} - V_{out}\left(D\right) \quad (121)$$

The equation is solved by equating to zero.

$$D = \frac{V_{in}}{V_{out}} \quad (122)$$

Then the partial fraction equations found for the converter will be used.

$$\frac{2\Delta i_l}{T_s} = \frac{V_{in}}{L}D \quad (123)$$

Solving Δi

$$\Delta i_l = \frac{V_{in}D}{2FsL} \quad (124)$$

The value of Δi can also be obtained as a percentage of the maximum output current, in the case of this thesis the proposed value is 2%.

Continuing with the design equations

$$\frac{2\Delta V_{Co1}}{T_s} = \frac{V_{out}}{C_{o1}Z_{out}}D \tag{125}$$

Solving ΔV

$$\Delta V_{Co1} = \frac{V_{out}D}{2C_{o1}Z_{out}Fs} \tag{126}$$

Also to find the charging resistance the equation used is the following

$$Z_{out} = \frac{V_{out}^2}{P_{out}} \tag{127}$$

8.2 BIDIRECTIONAL BUCK-BOOST CONVERTER WITH SOFT SWITCHING

The equations presented next are based on the soft switching topology proposed, this design is based in the state equations of the converter mentiones in 7:

$$\frac{2\Delta i_1}{T_s} = \frac{V_{in}}{L_1} \tag{128}$$

$$L_1 = \frac{V_{in}T_s}{2\Delta i_1} \tag{129}$$

$$\frac{2\Delta i_2}{T_s} = \frac{V_{Co1}}{L_2} \tag{130}$$

$$L_2 = \frac{V_{Co1}T_s}{2\Delta i_2} \tag{131}$$

$$\frac{2\Delta v_1}{T_s} = \frac{-iL_2}{C_{o1}}\frac{-V_{out}}{C_{o1}Z_{out}} \tag{132}$$

$$C_{o1} = (-iL_2 \frac{-V_{out}}{Z_{out}}) \frac{T_s}{2\Delta v_1} \tag{133}$$

$$\frac{2\Delta v_2}{T_s} = \frac{-V_{out}}{C_{o2} Z_{out}} \tag{134}$$

$$C_{o2} = (\frac{-V_{out}}{Z_{out}}) \frac{T_s}{2\Delta v_2} \tag{135}$$

8.3 SEPIC-ZETA NON ISOLATED BIDIRECTIONAL CONVERTER

For this specific design we have the following equations:

$$D = \frac{V_o}{V_i + V_o} \tag{136}$$

$$\frac{2\Delta i_1}{T_s} = \frac{V_{in}}{L_1} \tag{137}$$

$$L_1 = \frac{V_{in} T_s}{2\Delta i_1} \tag{138}$$

$$\frac{2\Delta i_{L2}}{T_s} = \frac{V_{C_s}}{L_2} \tag{139}$$

$$L_2 = \frac{V_{C_s} T_s}{2\Delta i_{L2}} \tag{140}$$

$$\frac{2\Delta V_{C_s}}{T_s} = \frac{i_{L_1}}{C_s} \tag{141}$$

$$C_s = \frac{i_{L_1} T_s}{2\Delta V_{C_s}} \tag{142}$$

$$\frac{2\Delta V_{C_o}}{T_s} = \frac{V_{out}}{RC_o} \tag{143}$$

$$C_o = (\frac{V_{out}}{R}) \frac{T_s}{2\Delta V_{C_o}} \tag{144}$$

9 RESULTS

In this chapter we will evaluate the results obtained during the thesis process. All the simulations made and the I and V graphics obtained will be included in the development of this chapter.

9.1 BIDIRECTIONAL BUCK-BOOST CONVERTER

First we will evaluate the simulation obtained from the components using the Simulink tool from Matlab. The values of simulation were estimated in this part to compare the response of the circuits.
The first simulation shows the process of the elevator phase.

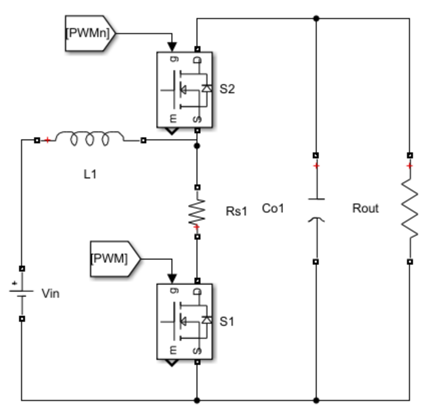
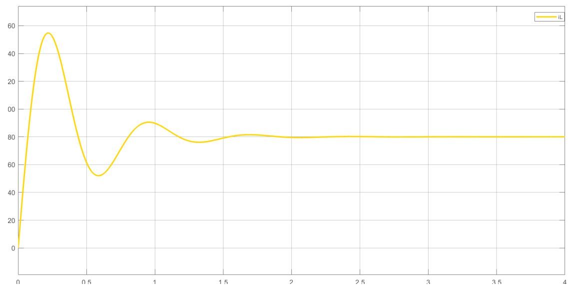
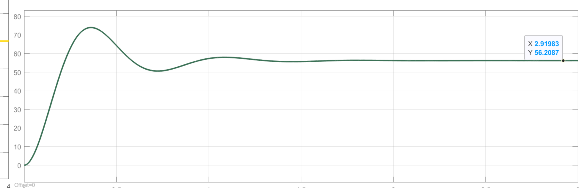


Figure 23: Buck-Boost Circuit in simulink without Soft-switching

The graphics shown in the *Figure 24* present both of the waveforms that compose the simulations without soft-switching. This simulations intend to show the difference between the application of soft-switching and a regular converter.



(**a**) Buck-Boost Inductors current waveforms from circuit



(**b**) Buck-Boost capacitor voltage waveforms from circuit

Figure 24: Buck-Boost current and voltage waveforms without soft-switching

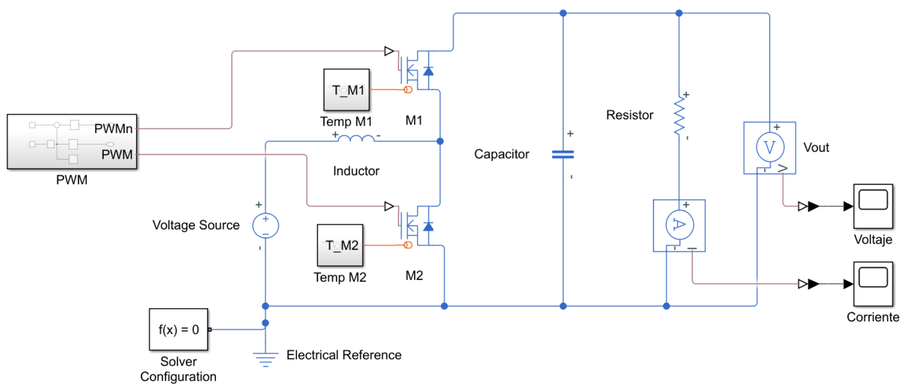
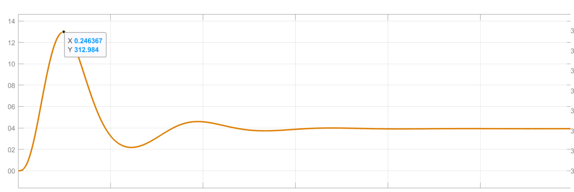
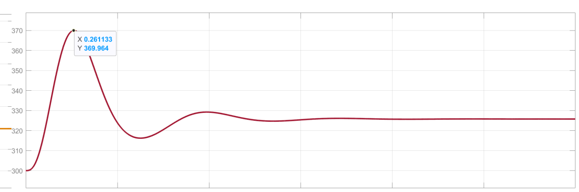


Figure 25: Buck-Boost Circuit in Simulink, using the Simscape Electrical library.



(**a**) Temperature in M1 MOSFET



(**b**) Temperature in M2 MOSFET

Figure 26: Temperature in MOSFETs M1 and M2 for Regular Buck-Boost

The schematic shown in *Figure 25* is used to verify the temperature on each MOSFET at their functioning time, and on the *Figure 26* it is shown the respective temperatures for each one in the regular configuration for the Buck Boost.

9.2 BIDIRECTIONAL BUCK-BOOST CONVERTER USING SOFT SWITCHING

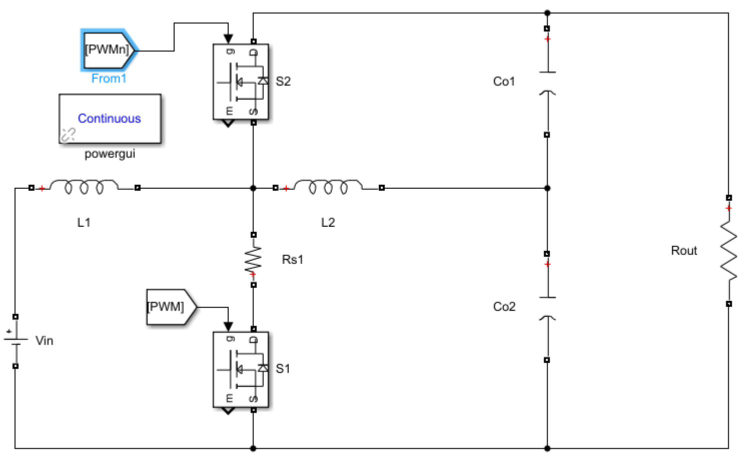


Figure 27: Buck-Boost Circuit in Simulink, using the powergui block.

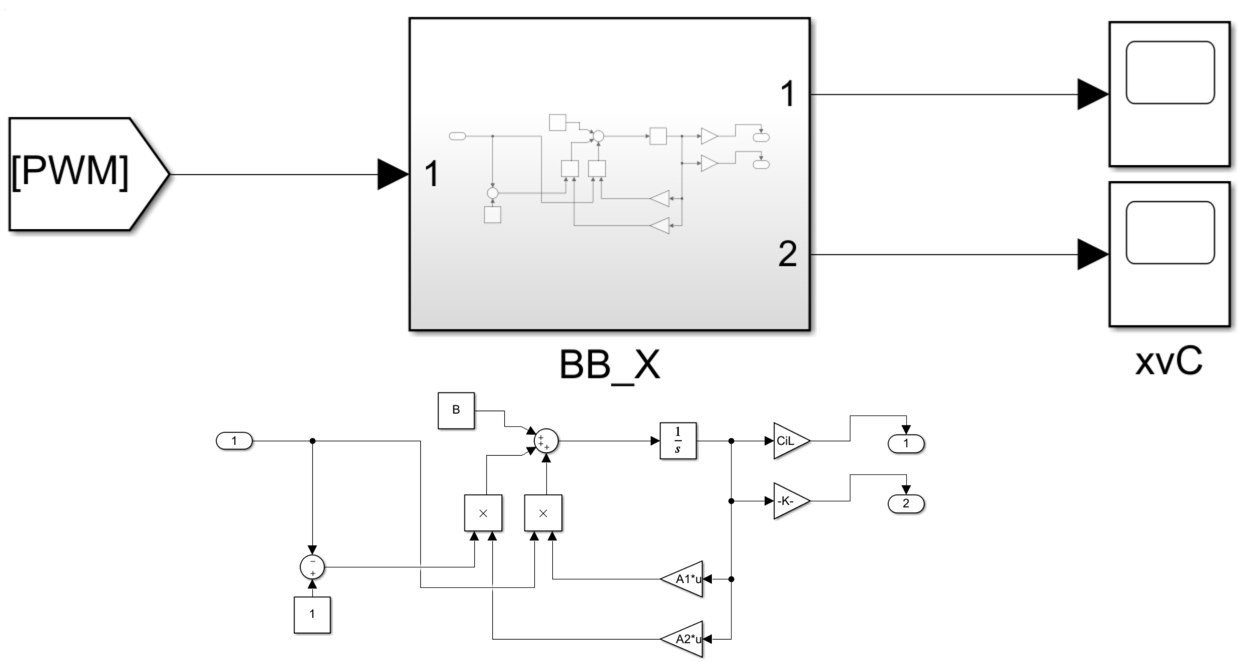
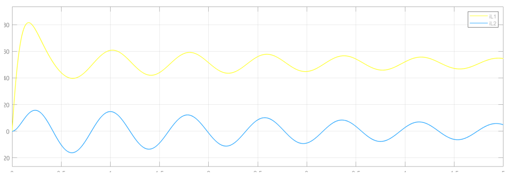
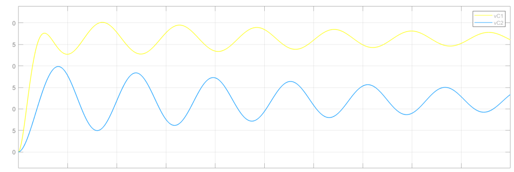


Figure 28: Buck-Boost Model in Simulink.

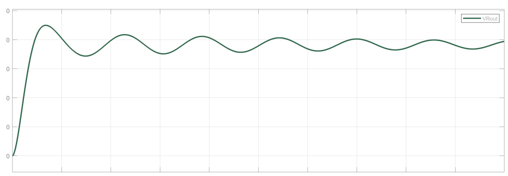


(a) Buck Boost Inductors current waveforms from circuit

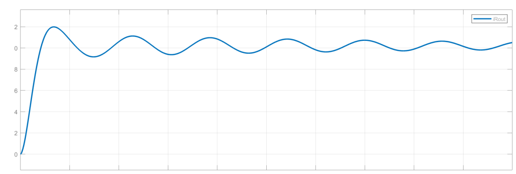


(b) Buck Boost Capacitor voltage waveforms from circuit

Figure 29: Buck Boost Inductors current and Capacitors voltage



(a) Buck Boost output voltage waveform



(b) Buck Boost output current waveform

Figure 30: Buck-Boost output voltage and current

The diagrams and responses obtained in the *Figure 28*, *Figure 29* and *Figure 30* correspond to the graphics obtained while modelating the proposed converter applying the soft-switching technique.

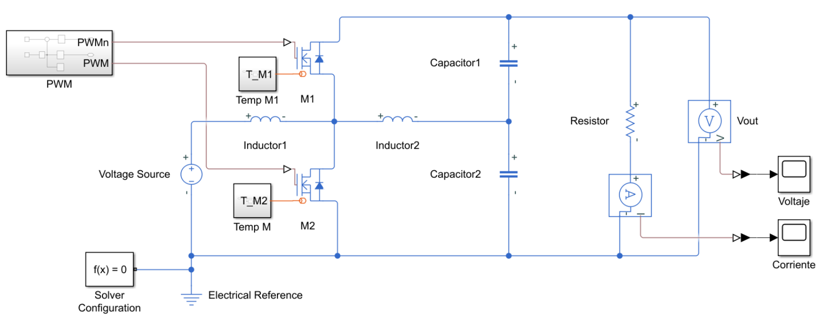
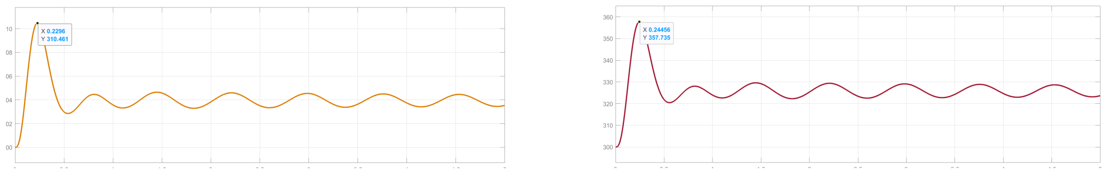


Figure 31: Buck-Boost Circuit using soft switching in Simulink, using the Simscape Electrical library.



(a) Temperature in M1 MOSFET

(b) Temperature in M2 MOSFET

Figure 32: Temperature in MOSFETs M1 and M2 for Buck-Boost using soft switching

9.2.1 Comparison Bidirectional Buck Boost converter

Compared to the first obtained images, it is shown a significant difference in the answer, which presents a better establishment time since on the first set of circuits we can see it takes a long time to stop oscillating, another divergence was that in the first set of results it appears clear that there is a peak current and a peak voltage, in the second set of images there is an improvement in the waveforms, this means that even when there is still a peak and a ripple it is much softer and subtle, and can be improved in an easier way. Lastly there is a change between the temperature in each of the MOSFETs, in the first images obtained we have a higher peak, but almost no fluctuation after it, on the second set which correspond to the soft switching topology, there is an improvement on the peak value, but it also shows an oscillation of temperature after said peak.
Also it must be taken into account that the circuits where modeled using the equations found during the development of the conceptual framework and the design section.

9.3 SEPIC-ZETA NON ISOLATED BIDIRECTIONAL CONVERTER

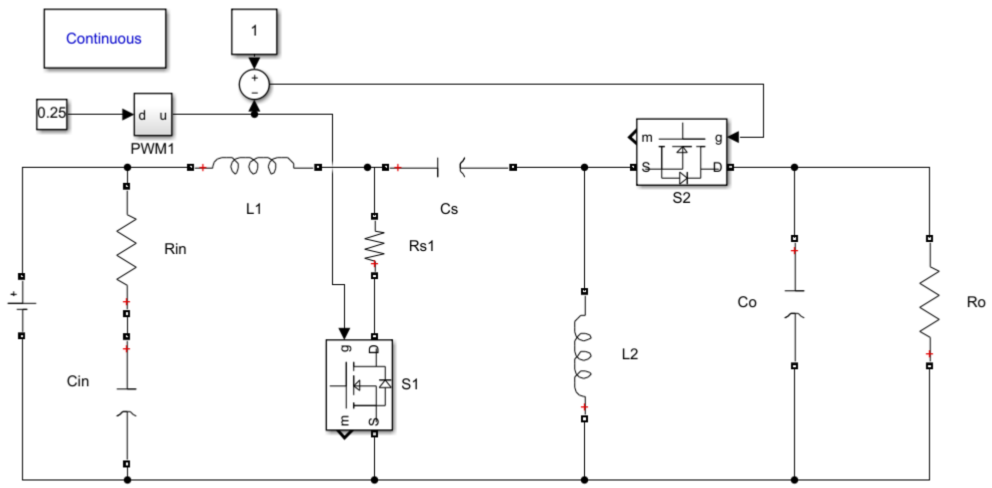


Figure 33: Sepic-Zeta Circuit in Simulink, using the powergui block.

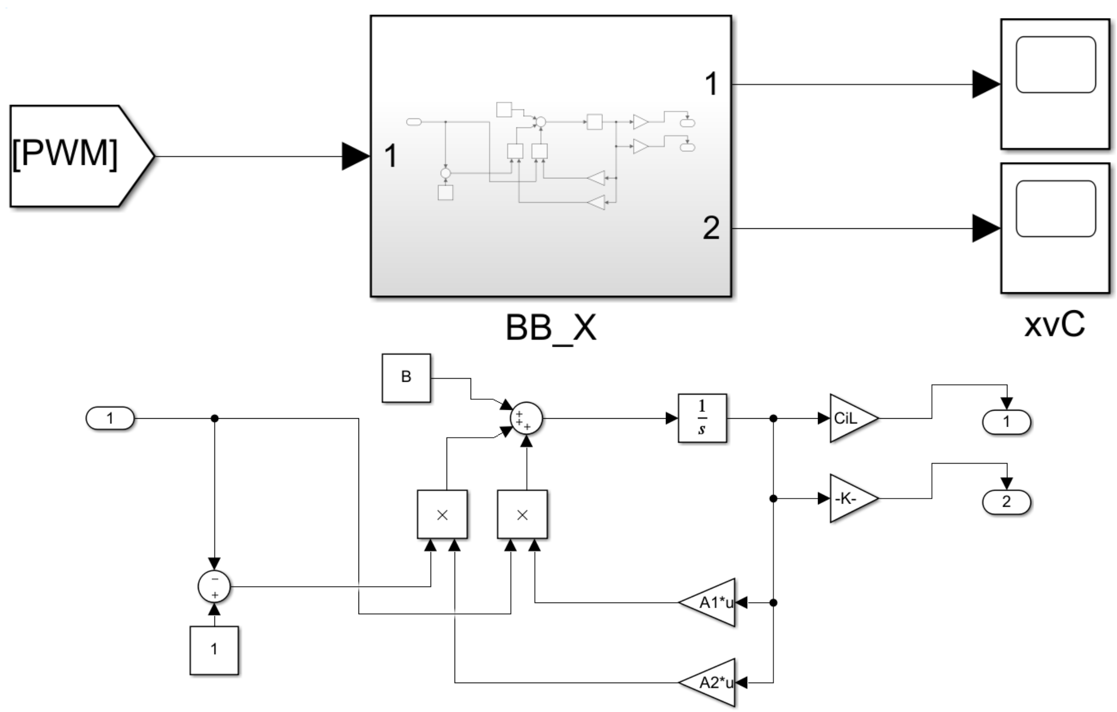
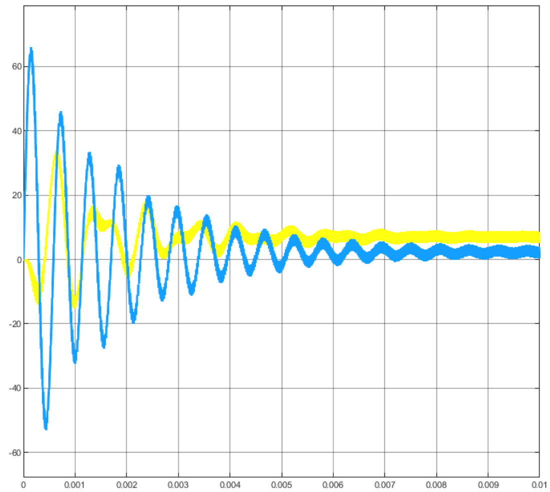
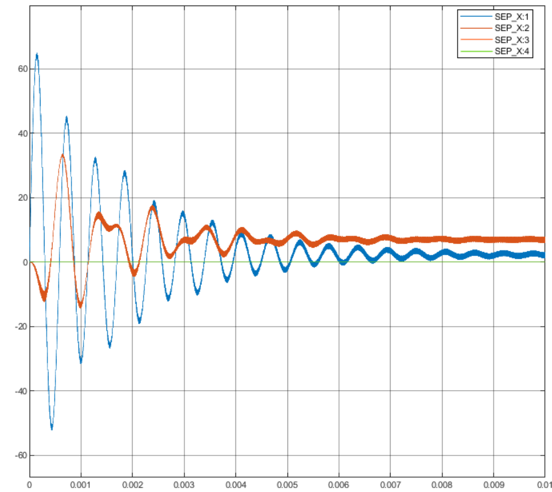


Figure 34: Sepic-Zeta Model in Simulink.

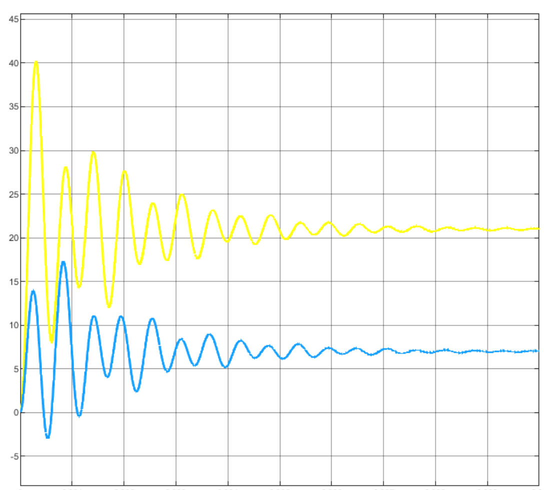


(a) Sepic-Zeta Inductors current waveforms from circuit

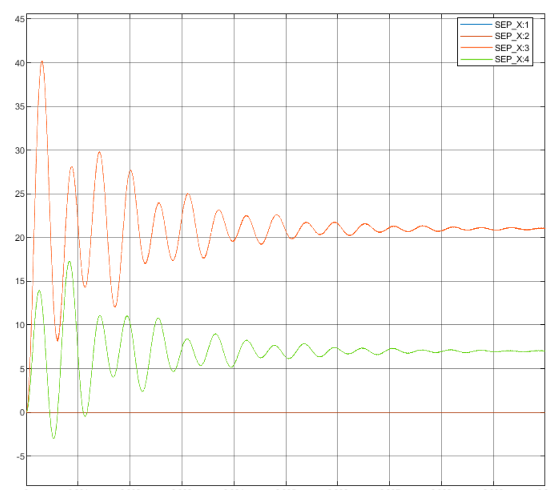


(b) Sepic-Zeta Inductors current waveforms from switched model

Figure 35: Sepic-Zeta Inductor Current Waveform



(a) Sepic-Zeta Capacitors voltage waveforms from circuit



(b) Sepic-Zeta Capacitors voltage waveforms from switched model

Figure 36: Sepic-Zeta Capacitor Voltage Waveform

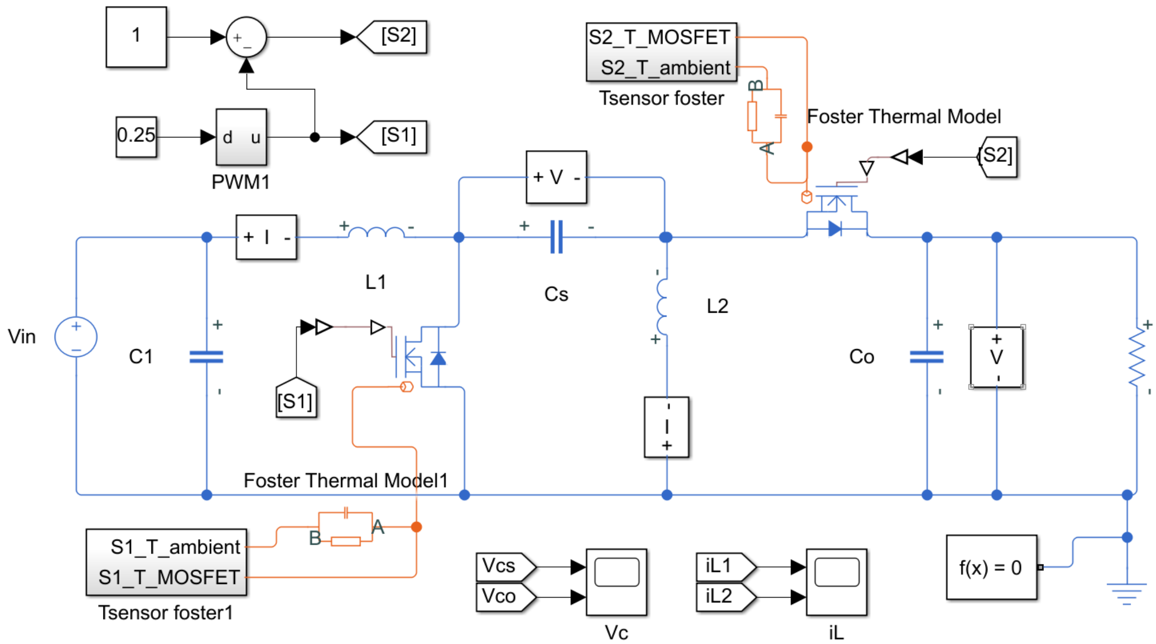
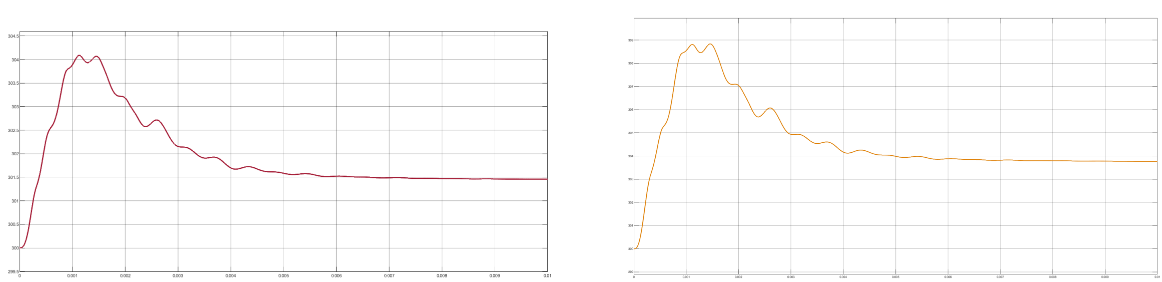


Figure 37: Sepic-Zeta Model in Simulink using the Simscape Electrical library



(a) Temperature in S1 MOSFET

(b) Temperature in S2 MOSFET

Figure 38: Temperature in MOSFETs S1 and S2 for Sepic-Zeta

9.4 SOFT SWITCHING SEPIC-ZETA NON ISOLATED BIDIRECTIONAL CONVERTER

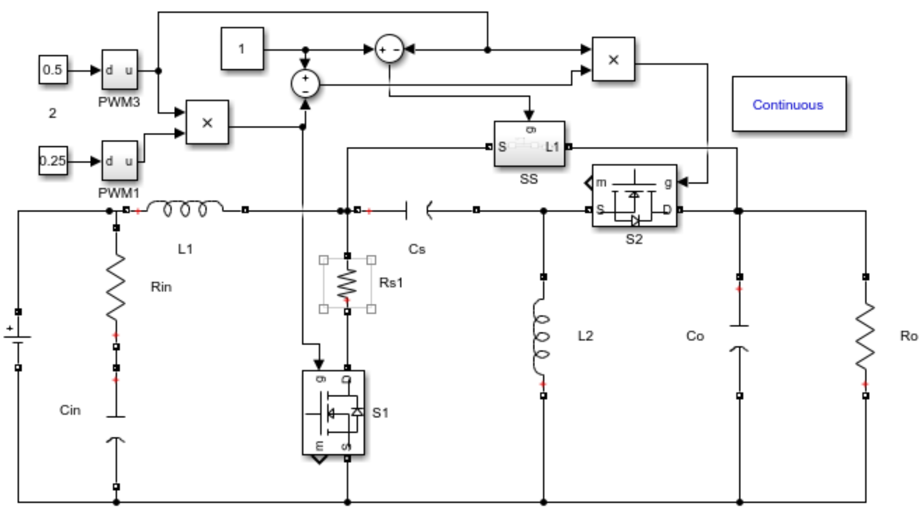


Figure 39: Soft Switching Sepic-Zeta Circuit in Simulink, using the powergui block.

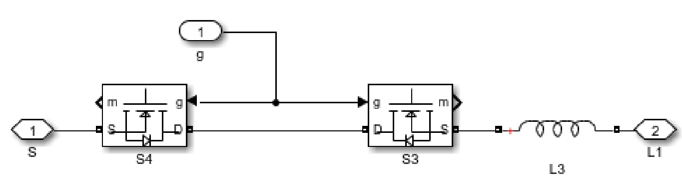


Figure 40: Auxiliary path with the resonant element.

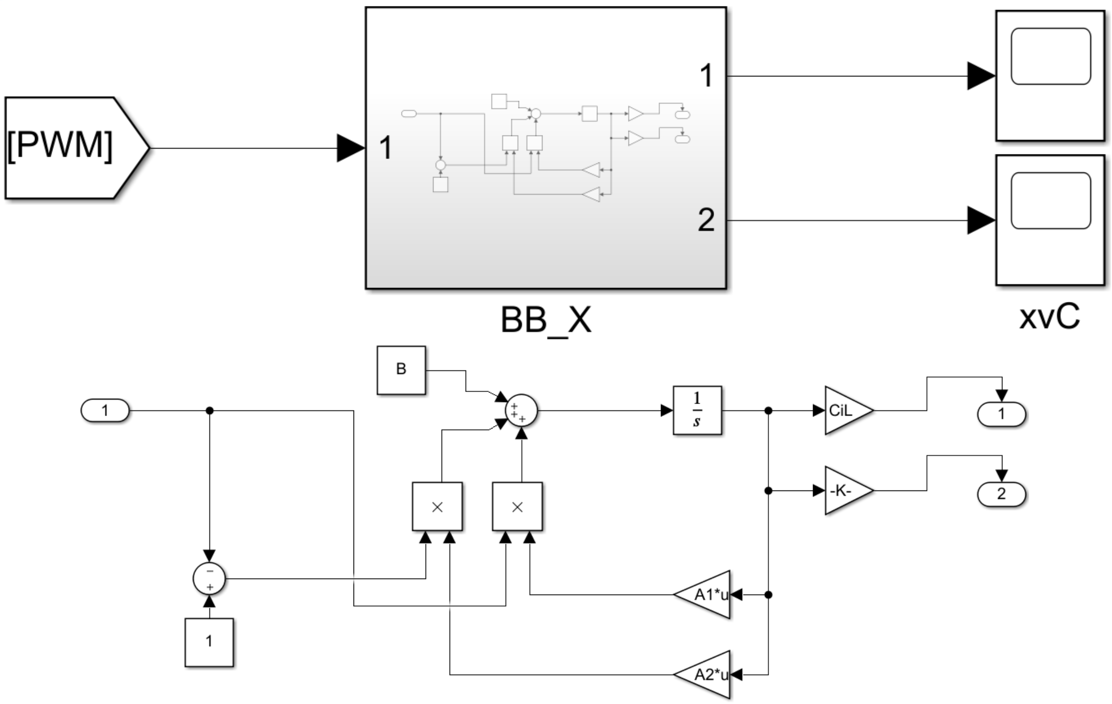


Figure 41: Sepic-Zeta Model in Simulink.

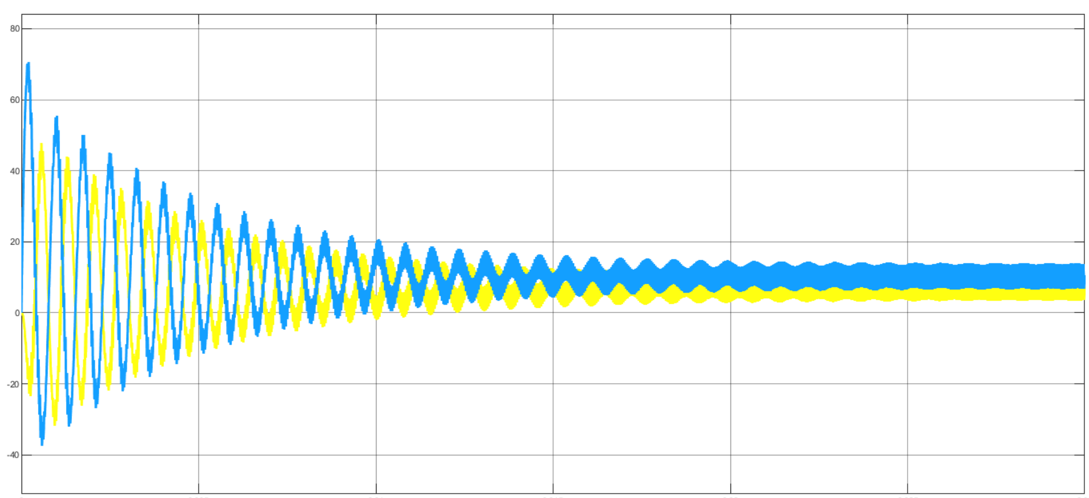


Figure 42: Soft Switching Sepic-Zeta Inductor Current Waveform

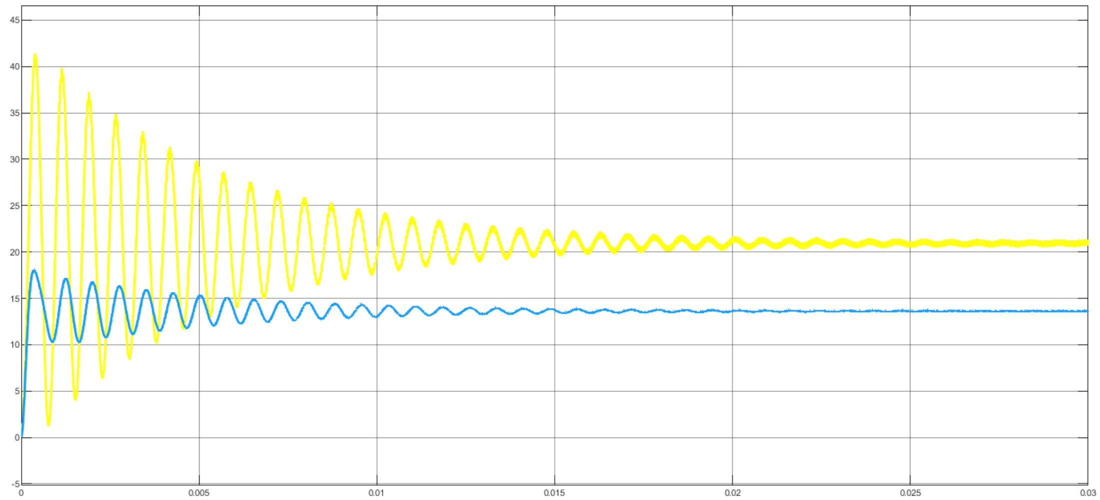


Figure 43: Soft Switching Sepic-Zeta Capacitor Voltage Waveform

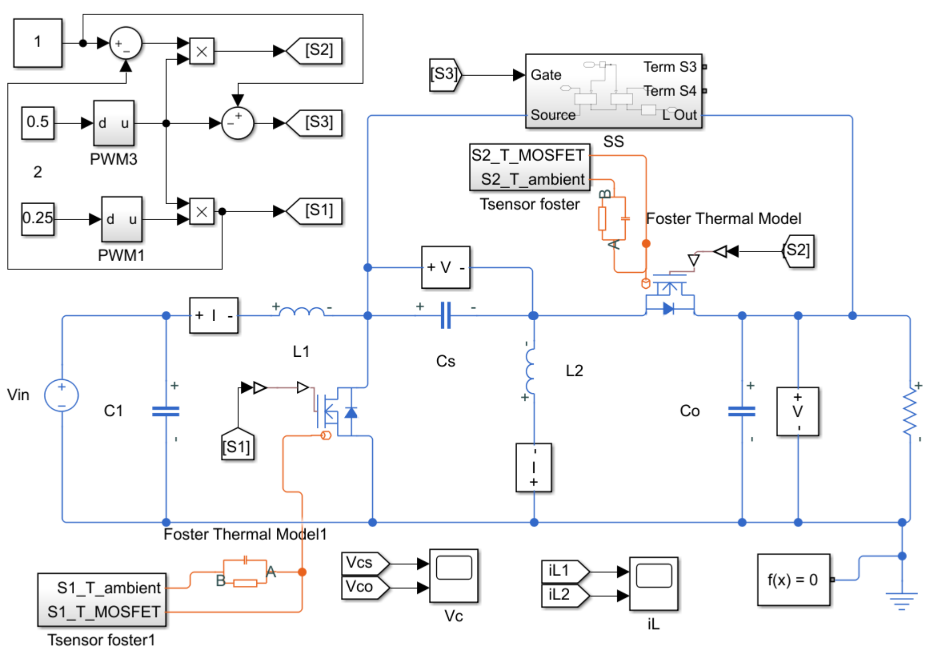
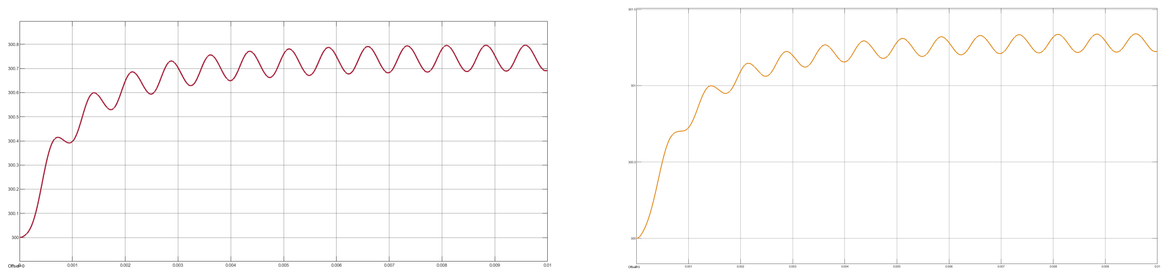


Figure 44: Sepic-Zeta Model with Soft Switching in Simulink using the Simscape Electrical library.



(a) Temperature in S1 MOSFET

(b) Temperature in S2 MOSFET

Figure 45: Temperature in MOSFETs S1 and S2 for Sepic-Zeta with Soft Switching

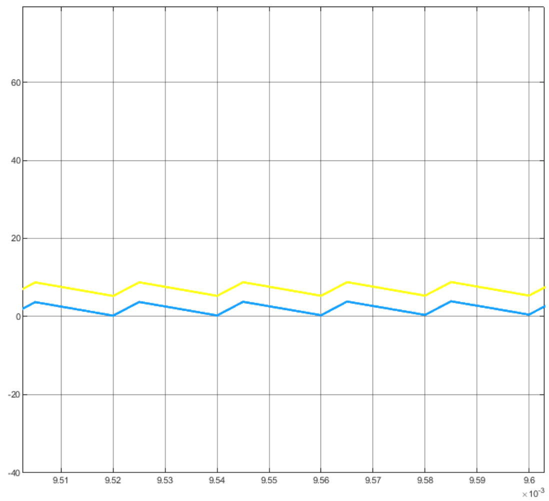
9.4.1 Comparison Sepic Zeta Bidirectional converter

Giving the closer look into the current and the voltage wave forms, could be found the changes mentioned before, just with the addition of one resonant element.

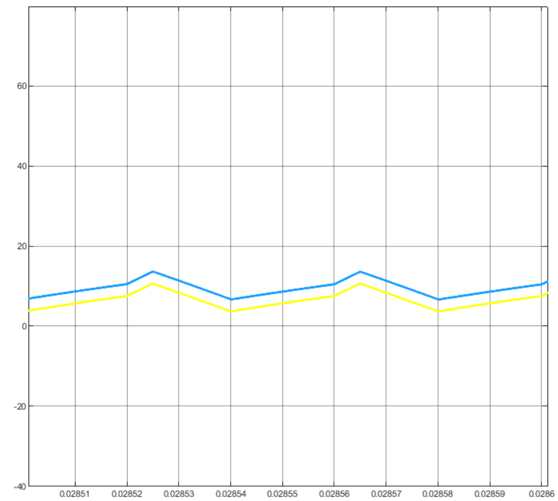
Taking a closer look to the current waveform, there can be found a difference in the waveform firstly, due to the switching states, it is because in order to apply the resonant element in the system is needed a new state. Thus, the number of peaks in the same time window, differs.

Equally important, there's a change in the waveform, what it shows is how the switching began to transform in one more escalated. Now, in the charging process of the elements can be seen a 'preparation' of the current to finally go to the peak. This section of time is when the auxiliary path is open and the inductor L_a is functioning.

In addition, if the thermal responses are compared between hard switching and the converter with the soft switching technique, there could be found some changes. Related with the thermal oscillation and the average level maintained in each case. In the hard switching the thermal response comes to a peak to stabilize in a lower level after, it can be seen in *Figure 38*. In comparison, when the SS is applied in the *Figure 45* could be seen that the warming is escalated gradually and do not have a pronounced peak, when arrives to the stable level it is true that it keeps oscillation but this is due to the additional path and resonant element, even with the oscillations, the average level of the temperature with SS is a bit lower than in the hard switching.



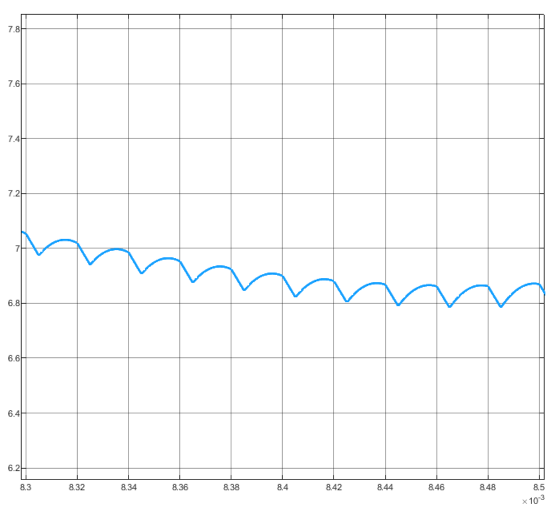
(a) Sepic Zeta Hard Switching Current



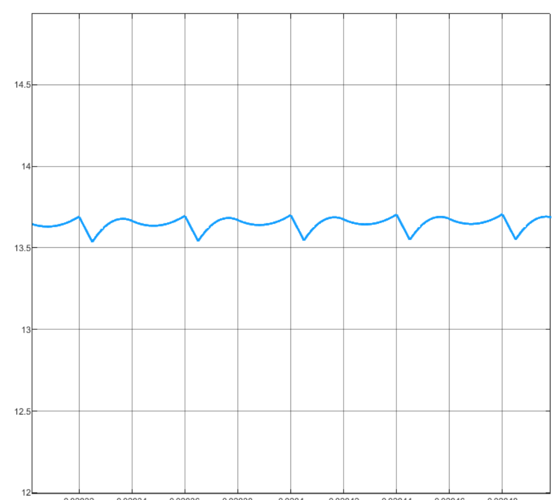
(b) Sepic Zeta Soft Switching Current

Figure 46: Sepic-Zeta current comparison $L_1 L_2$

Also, seeing the voltage waveform as well, maybe is in which the influence of the soft switching is more evident, because from a 'mountain signal' that has more low peaks, now there's a signal who keep its voltage level with the help that the auxiliary inductor gives period to period when it activates.



(a) Sepic Zeta Hard Switching Voltage



(b) Sepic Zeta Soft Switching Voltage

Figure 47: Sepic-Zeta voltage comparison $v_{Cs} v_{Co}$

10 CONCLUSIONS

- The circuit matrix model gives the facility to have a deep analysis of the circuit, this way the design and evaluation could be involved not just in terms of circuits and electronic but also in a mathematical analysis.
- The application of a bidirectional converter to the system in this case, brings the opportunity to provide and recover energy from different sources.
- Through the analysis of the circuits, it can be concluded that the Sepic-Zeta configuration is more appropriate in a real application, because of its properties that allow the circuit to have a step up/down configuration in both directions and because of the stability seen in the simulations.
- As an evidence presented during the development of this project the simulation conditions (initial state or values, circuit stages, etc.) are a key part to be able to obtain the results in non-ideal conditions.
- The design process and its complexity varies according to the detail sought in the circuit. The more real the simulation is expected to be, the more analysis and design stages will be necessary to retrieve.
- The temperature on the MOSFETs using soft switching is close or under the regular topology, the main difference is that using the soft switching technique, the temperature oscillates instead of keeping a steady behavior, this might be due to the additional resonant stage on the design presented.

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