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05 TRABAJO FIN DE GRADO

INDUSTRIALES

TRABAJO FIN DE GRADO

DYNAMIC CONTROL OF CASCADED BOOST AND BUCK CONVERTERS FOR BATTERY MANAGEMENT

TRABAJO FIN DE GRADO PARA LA OBTENCIÓN DEL TÍTULO DE **GRADUADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES**

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DEDICATION

This thesis is dedicated to the memory of my late grandfather Francisco. Although he did not have the opportunity to pursue higher education, he was a bright and kind person who always stood by me giving me his best pieces of advice. His encouragement was a constant wellspring of motivation and I know he would have been happy and proud to see me reach this milestone.

« The key to learning is feedback. It is nearly impossible to learn anything without it »

Steven D. Levitt, American economist and professor at the University of Chicago

« Energy conservation is the foundation of energy independence »

Thomas H. Allen, American author and former politician who served as a US Representative for Maine.

« Efficiency is doing things right. Effectiveness is doing the right things »

Peter F. Drucker, Austrian consultant and author widely regarded as the "father of modern management".

ACKNOWLEDGEMENTS

First and foremost, I thank my family and my close friends, who have been there for me every step of the way. Specifically, my parents, Ana and Roberto, and my brother, Eduardo, as they have been an unwavering source of support and strength, enduring the difficult times alongside me and consistently encouraging me to persevere. I am also deeply grateful for the fresh air and light my girlfriend, Rebeca, has brought me and how she has listened to my doubts and problems throughout this last year.

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I would also like to thank the other professors who have guided me the most during my studies: Pablo Garrido, Antonio Barrientos, Guido Matrella, Roberto Menozzi and Paolo Cova.

I am grateful to the people I shared my life with in Parma. Their companionship helped me through one of my most challenging, yet rewarding, years.

This journey has taught me the importance of self-kindness, a lesson I have struggled with throughout my life. Living up to others' expectations, or what we perceive them to be, can be a heavy burden. I believe we all deserve to stop for a moment and recognize our own accomplishments, which is why I want to acknowledge my personal growth and resilience throughout this difficult process. I am proud of the person I have become.

Finally, thank you to everyone who reads this thesis, and especially to those who have read these acknowledgements all the way to the end.

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ABSTRACT

The energy transition towards renewable sources and the constant urge for sustainable solutions demands increasingly sophisticated and efficient energy management systems. In this context, this bachelor's thesis addresses a fundamental challenge: the dynamic control of a hybrid energy storage system, more specifically a cascaded configuration of Buck and Boost converters.

This arrangement, which is crucial for managing multiple batteries with different voltages, presents inherent complexity, particularly due to the nonlinearity of the Boost converter.

The primary objective was to design and implement a control strategy for this system, demonstrating that a linearization-based approach is a viable and effective method for robust operation, given certain hypothesis and considerations. To achieve this, the problem was divided into two stages.

First, a rigorous theoretical analysis of each subsystem (Buck and Boost) was conducted in continuous conduction mode (CCM). The most critical step was the linearization of the Boost converter, which allowed for the derivation of its transfer functions and simplification of the control design.

Subsequently, Proportional-Integral-Derivative (PID) controllers were designed to regulate both the output voltage and the inductor current.

The implementation and verification of the complete system were carried out using advanced simulations in MATLAB and PLECS, which proved the efficacy of the controllers in realistic scenarios.

The simulation results confirmed that the designed control is effective and robust within a defined operational range. However, they also revealed the inherent limitations of PID control when faced with the complex, nonlinear dynamics of such a system, especially under low-resistance conditions which are not representative of real-world applications.

These conclusions not only validate the linearization approach for a first approximation but also highlight the need for more advanced explorations.

The project's findings pave the way for future research, suggesting the use of nonlinear controls, analysis in other operational modes and exploration of bidirectional power flux conversion systems. All efforts focused on overcoming difficulties in order to develop physical prototypes, improving the architectural capabilities, and both efficiency and efficacy, as the final step.

This project, therefore, not only demonstrates a viable and accessible technical solution but also underscores the importance of simulation tools for the development of control systems in engineering, offering an engineering and general knowledge base and vision for both actual and future advancements in the field of power electronics.

KEY WORDS

- Control Systems
- Power Electronics
- Converters
- Linearization
- PID Control
- Circuit Design
- Modeling
- Battery Management
- Energy Efficiency
- Simulation
- Analysis
- PLECS by Plexim
- MATLAB by MathWorks

UNESCO CODES[1]

- 12 Mathematics
  - 1203 Computer Science
    - 1203.26 Simulation
- 22 Physics
  - 2203 Electronics
- 33 Technological Sciences
  - 3306 Electrical Technology and Engineering
    - 3306.02 Electrical Applications
  - 3310 Industrial Technology
    - 3310.03 Industrial Processes
  - 3311 Instrumentation Technology
    - 3311.02 Control Engineering

[1] Based on the **UNESCO** publication, "*Proposed international standard nomenclature for fields of science and technology (6-digit classification)*" and the revised web version by the "**Universidad de Murcia**" (UM), "UNESCO nomenclature for fields of science and technology."

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1. INTRODUCTION

1.1 Context and Motivation

The global energy landscape is undergoing a deep transformation, driven by an urgent need to address climate change, enhance energy security, and transition towards sustainable solutions. This paradigm shift urges the development of new and advanced technologies capable of efficiently managing and integrating renewable energy sources.

Within this context, battery energy storage systems and power electronics play a critical role. This thesis presents a comprehensive investigation into an electrical system designed for precise battery management, employing cascaded Buck and Boost converters regulated by Proportional-Integral-Derivative (PID) controllers, alongside essential active and passive elements that facilitate switching inside said converters, such as Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) and diodes.

The aim is to contribute to the realization of sustainable energy solutions, particularly for applications such as electric vehicles, portable electronics and renewable energy storage systems, as well as many others.

This introduction will highlight the global imperative for sustainable energy, underscore the pivotal role of power electronics and battery management systems, articulate the specific problem addressed by this research, its objectives and contributions.

1.2 Global Energy Transition: Need for Sustainable Solutions

The world stands at a critical juncture in its energy journey. Due to escalating climate change concerns regarding transition to sustainable energy sources, a fundamental sway away from traditional fossil fuels and into cleaner, renewable alternatives urges.

The demand for renewable energies is experiencing unprecedented growth, with sources such as solar and wind power becoming increasingly competitive, projected and striving to dominate future electricity generation.

Not only that, but demand for energy in general has risen and will yet grow. Due to the acceleration of global electricity demand, electrification will contribute to an average annual growth of 3.7% approximately in 2026, as forecasted by the International Energy Agency (IEA).

Predictions from the IEA indicate that renewable energy is expected to crown an 80% of the growth in global electricity generation by 2030. Furthermore, solar energy is expected to become the largest source globally by 2050 (see *Figure 1*).

Similarly, the main common goal is for renewable sources to achieve almost 50% of global generation by 2030. This expansion embodies a critical transformation in the energy landscape, moving towards a more decarbonized future.

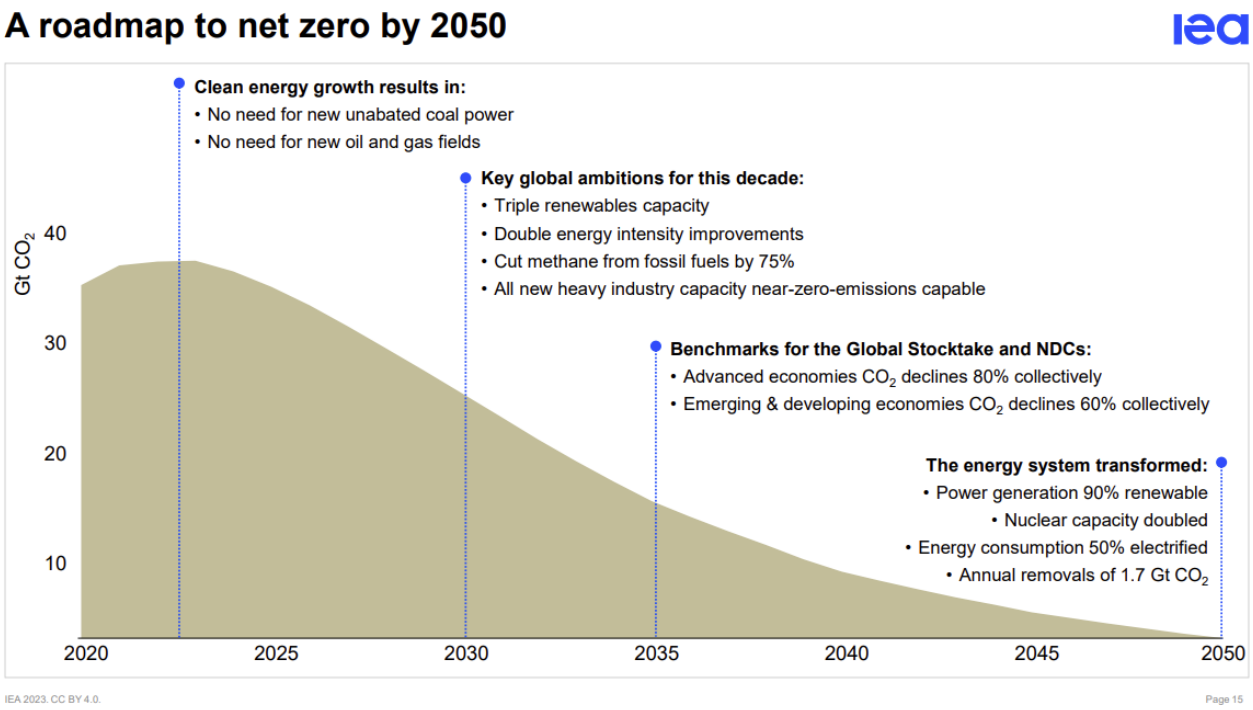


Figure 1: IEA's Net Zero Emissions Roadmap

Despite the actual significant progress in renewable energy generation, noticeable challenges persist, particularly concerning system stability and the adequacy of infrastructure investment.

For instance, even in regions demonstrating high renewable penetration, such as Spain -where 56% of electricity was generated from renewable sources in 2024, according to Red Eléctrica Española (REE)-, issues like insufficient grid infrastructure, bureaucratic hurdles, miscommunication and misunderstandings and a lack of demand integration remain considerable obstacles. An example of Spain's generation mix can be seen in *Figure 2*.

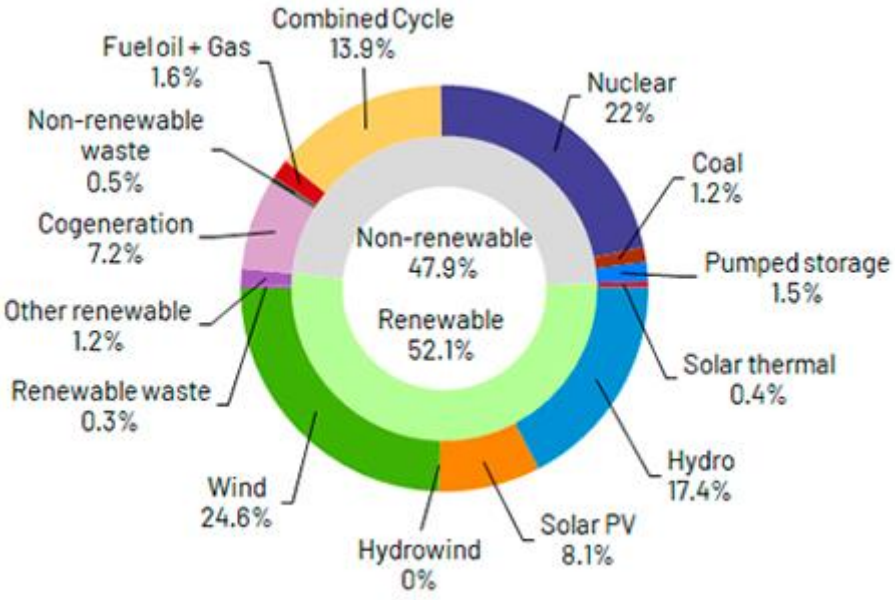


Figure 2: Spain's Energy Generation Mix, January 2024, according to REE

Politics aside, the big shutdown suffered in the whole Iberic Peninsula (April 2025) is a reliable proof and a sad demonstration that proves worrying about these concerns is far more important than anticipated.

The widespread adoption of power electronics converters, while enabling large-scale renewable energy generation, has also introduced complexities to conventional power grids, including reduced system inertia and potential stability issues.

The non-stop increase of renewables, while crucial for global sustainability, introduces inherent challenges related to grid stability and infrastructure deficits. Their inherent unpredictability, driven by weather, makes it tough to constantly balance electricity supply and demand. Unlike traditional power plants, they also lack the inherent "momentum" that helps keep the grid steady.

This calls for major upgrades to the power lines and distribution networks, which were not built for power flowing in multiple direction or for coping with big frequency changes, demanding smarter solutions for managing unpredictable loads and undesirable behavior.

This creates a direct and urgent need for advanced power electronics and battery management solutions that can ensure reliable, efficient, and stable integration of these inherently variable energy sources into existing power systems and emerging applications.

Grid-attached batteries, for example, can grant “momentum” and improve stability, when properly controlled. Traditional power grids are powered by large rotating generators, such as those in coal, gas and nuclear power plants, which have a lot of kinetic energy. This stored energy acts as a natural "shock absorber", or inertia, which helps to slow down sudden frequency changes when there is a mismatch between electricity supply and demand.

Summarizing, in most cases, renewable power grids do not include these large generators (usually they connect to the grid through inverters), which makes this one of the biggest inconveniences of renewables massive penetration without proper control.

The effective management of these fluctuations is an absolute must to unlock the full potential of the sustainable energy transition.

1.3 Problem Statement and Research Gap

This thesis addresses the critical need for efficient and sustainable battery management by developing an electrical system consisting of two batteries connected via a Buck and a Boost converter, sharing a common capacitor and resistor.

The main goal is to regulate power flux and efficiency through the application of control strategies. This objective, however, presents significant control challenges. Specifically, due to the Boost converter subsystem exhibiting inherent non-linear behavior. The easiest solution chosen for this thesis was linearization for effective control design.

While individual Buck and Boost converters are well-characterized components in power electronics, the precise and stable control of a mixed/cascaded system, particularly when dealing with said non-linearity of the Boost subsystem and the interactions introduced by shared passive elements, poses a way more complex engineering problem. Reaching optimal power flux and efficiency across varying input and load conditions demands robust and adaptable control mechanisms.

Initial design and simulation efforts, while demonstrating basic functionality, reveal notable limitations of conventional control approaches. The Boost converter's non-linearity makes its Proportional-Integral-Derivative (PID) tuning particularly challenging, and its dynamic stiffness significantly impacts the overall system behavior, effectively dominating the control dynamics.

This previous observation suggests that conventional PID approaches, while widely used for their simplicity in DC-DC converters, may not fully optimize performance across the wide operational ranges required for real-world sustainable energy applications.

Furthermore, the chosen physical parameters in this thesis, such as a low resistance value in the simulation, while enabling controller stability in a theoretical environment, would lead to significant power loss in a physical implementation. This highlights a practical trade-off between theoretical control stability and real-world efficiency, a critical consideration for sustainable systems.

Existing research often focuses on the control of individual converters or on simplified cascaded systems. A comprehensive analysis of a dual-battery system with cascaded Buck and Boost converters, specifically addressing the non-linear control challenges of the Boost stage and evaluating the system's performance and working intervals through detailed simulations with PID controllers, represents a critical gap in current literature.

This exact gap is approached by as many ways as a researcher can think of, as well as with more complex control strategies and devices that allow these ideas to be considered and thoroughly investigated in an extensive depth.

In this case, regarding the knowledge possessed by an average undergraduate student, the focus will be on PID’s and simple specifications, trying to obtain a basis from which to attain a general idea of the project’s scope and expand or improve in the future.

The need to balance control stability with practical efficiency considerations, such as minimizing resistive losses, is a challenge that requires time, effort and more professional knowledge regarding the subject.

The integrated control of a cascaded system with shared passive elements, particularly when dealing with non-linearities, presents a significant control challenge that conventional PID controllers, as demonstrated in this thesis, may not fully address for optimal sustainability and real-world efficiency.

All this highlights the need for exploring more advanced control strategies to unlock the full potential of such systems in dynamic energy environments.

1.4 Thesis Objectives and Contributions

This thesis aims to address the aforementioned challenges by developing and analyzing step-by-step a regulated electrical system for sustainable energy applications. The project provides a foundational “first” step towards more robust and efficient battery management.

The main objective of this research is to develop an electrical system consisting of two batteries interconnected via Buck and Boost converters, sharing a capacitor and a resistor, with the primary goal of regulating power flux and efficiency through the application of PID controllers for sustainable energy solutions, such as electric vehicles.

The specific objectives and contributions of this thesis are:

- **System Design and Theoretical Modeling:** The project wants to detail the design of the integrated Buck-Boost converter system, including the derivation of transfer functions for both converter subsystems. Looking for the successful linearization of the non-linear Boost converter's subsystem, a crucial step to enable the application of classical control design methodologies.

- **Simulation-Based Implementation and Analysis:** Search for the entire system to be implemented and simulated using industry-standard software tools, such as PLECS and MATLAB, allowing for an analysis of its behavior under various operating conditions.

- **PID Controller Selection and Tuning:** Focuses on establishing a systematic selection and precise tuning of individual PID controllers for both Boost and Buck converters. The thorough analysis of the controllers' responses, including stabilization time and overshoot, is vital to reaching an understanding of their performance within this system.

- **Performance Evaluation and Working Interval Determination:** Through extensive simulations via PLECS, the thesis will try to identify and analyze the system's working intervals, precisely defining, if possible, the ranges of input voltage and output current reference within which the system maintains acceptable control and behavior. This practical characterization would provide valuable insights into the system's operational limits and robustness.

- **Identification of Control System Limitations:** A significant objective of this work is the explicit identification of limitations given by the Boost converter's non-linearity and inherent stiffness, as well as possible flaws in the project’s design. This way future research and improvements to the original planning or design could be made, for the project to evolve and take steps forward.

The thesis's contribution lies not only in demonstrating a functional control scheme but also in systematically identifying the limitations of conventional PID control for complex, non-linear power electronic systems. This explicitly paves the way for future research into more adaptive and robust control strategies within this specific design, such as other non-linear control methods, that can overcome these challenges and induce broader and more efficient operation in real-world sustainable energy applications.

A concise summary will be shown next in *Table 1*.

1.4.1 Objectives and Findings Overview

Aspect	Objectives/Contributions	Main Findings
System Design	Development of an electrical system with two batteries, Buck and Boost converters, shared capacitor and resistor for power flux and efficiency control.	Novel cascaded architecture for battery management in sustainable energy applications.
Theoretical Analysis	Derivation of transfer functions for Buck and Boost subsystems; successful linearization of the non-linear Boost converter.	Confirmed the inherent non-linearity of Boost converters and the necessity of linearization for classical control.
Control Strategy	Implementation and tuning of cascaded PID controllers for voltage (Boost) and current (Buck) regulation.	Demonstrated effective control within specific working intervals; identified the Boost converter's dominant dynamic stiffness.
Simulation & Validation	Comprehensive simulation in PLECS and MATLAB to analyze system behavior and determine operational working points.	Defined practical operating ranges for the system, highlighting its susceptibility to variations in input voltage and output current.
Sustainability Focus	Designed for sustainable energy sources, with a plausible application in electric vehicles.	Contributes to efficient power management, crucial for extending battery life and optimizing renewable energy utilization.
Future Research Direction	Identified limitations of conventional PID control for non-linear systems and proposed advanced control strategies (e.g., adaptive PID) and system scalability.	Laid groundwork for future physical layer development and more complex, robust control solutions for real-world applications.

Table 1: Thesis's Findings and Objectives Summary

1.5 Thesis Applications

There are many useful applications for this thesis and its future aim, as it starts paving the way, regarding the sustainable energies landscape described earlier.

Some of the most interesting examples will be shown and explained next:

- **Renewable Energy Integration:** The converters could manage the connection between a variable renewable source (like solar panels) and a battery bank, ensuring a stable energy supply.

- **Grid Stabilization:** The circuit could be part of a larger system that helps out by providing inertia. It can rapidly inject or absorb power to counteract small-scale, instantaneous frequency fluctuations, helping to maintain grid stability.

- **Second-Life Battery Applications:** The system could manage multiple repurposed batteries with varying capacities and states of health. The converters could balance the charge and discharge cycles among the different batteries, extending their collective useful life.

- **Hybrid Energy Storage Systems:** The converters could regulate power flow between different battery purposes, such as a high-power battery for quick bursts of energy and a high-capacity battery for long-term storage. This system then would manage the charging and discharging of each battery to optimize performance and lifespan.

- **Electric Vehicles:** The ability to simultaneously manage the charging and discharging of two separate battery packs would be highly favorable. For instance, one battery could be dedicated to the main power, while the other powers other purposes (such as regenerative breaking). The converters would ensure that power is efficiently transferred and managed between the two packs, optimizing range and battery life. This application could make electric vehicles more efficient and secure.

1.6 Thesis Structure

- **Chapter 1: Introduction**

This chapter sets the stage by discussing the global imperative for sustainable energy, the role of power electronics and battery management systems, the actual market and techniques availability and the challenges and problems that the actual paradigm comply, inducing into the problem addressed by this research and the thesis's objectives and contributions.

- **Chapter 2: Background**

The background provides the technical and market context necessary for understanding the system design and its components, as well as the analysis techniques and software options to be used. It's where the foundational knowledge is detailed. Plus, where the different techniques and options for future development are mentioned and explained.

Even though most of them will not be used, it is interesting and important to gather up and clear out the general knowledge regarding the investigation’s current environment and landscape. This is of high importance to really know what is being done and how deep the project will be digging.

- **Chapter 3: Theoretical Approach**

Once the desired outcome and project’s path has been underlined, this section delves into the fundamental theory and step-by-step reasoning behind the developed system. It includes the division into subsystems, analysis in Continuous Conduction Mode (C.C.M.), derivation of general laws, linearization of the Boost subsystem and the obtention of the transfer functions for both converters.

- **Chapter 4: Design of Controllers**

The methodology for selecting and tuning PID controllers for both converters, including the chosen working point, physical parameters through the chosen software (MATLAB) will be the focus in this part of the thesis.

- **Chapter 5: Circuit Implementation**

Here the practical design of the circuit in PLECS for the C.C.M. will be detailed, explaining the control strategies for both Boost and Buck, the cascaded control approach, the three distinct operational periods and the implementation of realistic simulation features like rate limiters and anti-windup methods.

- **Chapter 6: Simulation Results**

Next, a detailed analysis of the simulation results obtained from PLECS, evaluating the system's performance under various working points and determining the optimal operational intervals for the designed controllers will be presented.

- **Chapter 7: Conclusions**

Giving closure, the key findings of the research will be synthesized, discussed the effectiveness of the chosen controllers, addressed the practical implications of the results, and reflected on the overall validity and potential of the system. Likewise, the possible ethical, social, professional and legal repercussions (as well as the responsibilities derived from them) will be addressed.

- **Chapter 8: Future Research**

This chapter acts as an epilogue and outlines potential directions for further development (considering the inconveniences noted in the previous chapter) including transitioning to physical layer development, exploring more complex and adaptive control strategies, and considering system expansion and alternative operating modes.

- **Bibliography**
- **Timeline and Budget**
- **Table of Figures**
- **List of Tables**
- **List of Mathematical Expressions**
- **Abbreviations and Acronyms**
- **Units**

2. BACKGROUND

2.1 The Major Role of Power Electronics in Modern Energy Systems

Power electronics is an essential asset for the successful implementation and operation of modern renewable energy systems. Said systems are of vital importance for improving energy conversion efficiency, minimizing energy losses, and enhancing the overall reliability of the entire energy infrastructure.

DC-DC converters play a crucial role in optimizing energy outputs from diverse renewable sources. They ease the conversion of fluctuating direct current (DC) voltages, originating from sources like solar panels and wind turbines, into stable power. Thereby, turning suitable for storage or direct distribution, and after all accelerating the energy transition.

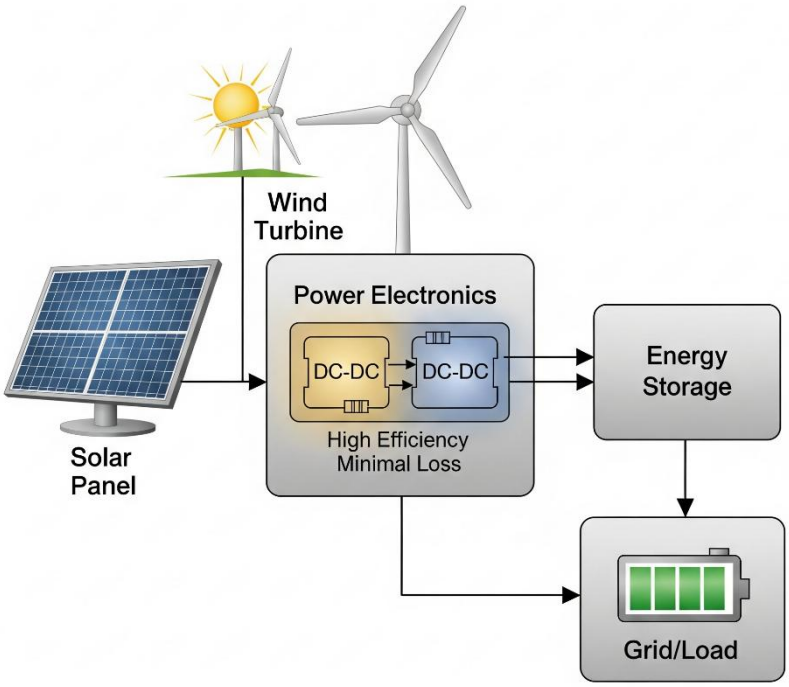


Figure 3: Renewable Sources Energy Flow Simplified System Diagram

Furthermore, converters are also a nexus, connecting energy storage devices to the broader power grid, synchronizing alternating current (AC) output, precisely controlling power flow. As a result, granting essential grid support functions such as frequency regulation and voltage stability.

Energy efficiency is a critical and foremost consideration in the design of power electronics, as it directly minimizes power losses and reduces unwanted energy consumption.

Modern power electronic devices materials, such as Silicon Carbide (SiC) and Gallium Nitride (GaN), offer exceptionally high efficiency, with improved reliability.

These advanced materials enable operation at higher frequencies and temperatures, which translates into reducing energy losses and thus allowing for more compact designs. Some examples of the most recent applications are SiC integrated circuits (ICs) or GaN high-electron-mobility transistors (HEMTs).

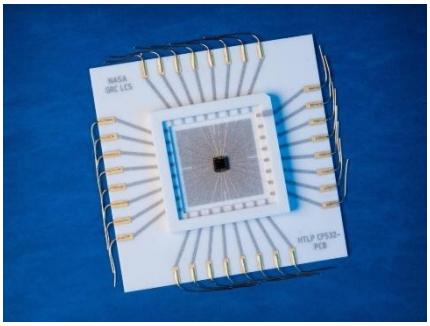


Figure 4: NASA's SiC Integrated Circuit

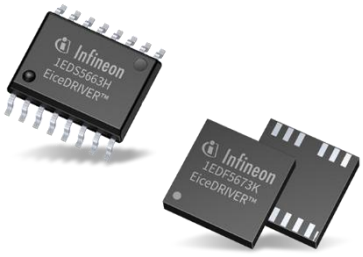


Figure 5: Infineon's GaN Gate Drivers

Such technological advancements are implemented into high-power applications like electric vehicles (EVs) and large-scale grid systems. The efficiency gains offered by these advancements in power electronics, particularly through the newest semiconductor materials and optimized switching techniques, are not merely incremental improvements but represent a fundamental enabler for the practical viability and economic competitiveness of sustainable energy systems.

Without these top efficiencies, the environmental benefits derived from renewable generation would be significantly compromised by unwanted and detrimental energy waste during the conversion and distribution processes.

The continuous pursuit of higher efficiency in power electronics is not just an engineering challenge but even more so a critical economic and environmental necessity, establishing it as a threshold of the global energy transition.

2.2 State of the Art: BMSs and DC-DC Converters

The global markets for both DC-DC converters and Battery Management Systems (BMS) are experiencing robust and sustained growth, driven by key technological and societal shifts in needs and trends.

The DC-DC converter market, valued at approximately USD 13.44 billion in 2025[2], is projected to reach USD 30.92 billion by 2034, exhibiting a Compound Annual Growth Rate (CAGR) of 9.70%, according to Precedence Research (a "leading market intelligence and consulting firm based in Canada and India").

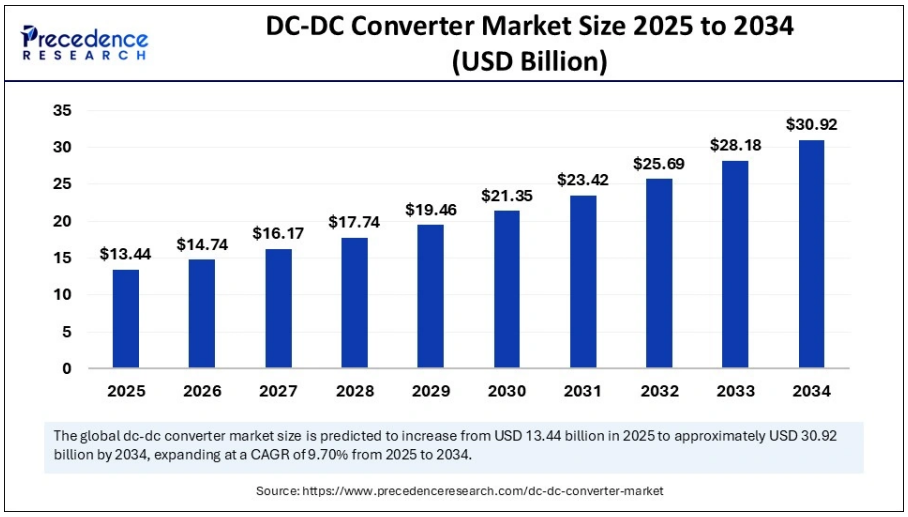


Figure 6: DC-DC Converter Market Size Projection via Precedence Research

Similarly, the BMS market, estimated at USD 14.24 billion in 2025, is forecast to grow at a robust CAGR of 19.83% to USD 72.05 billion by 2030.

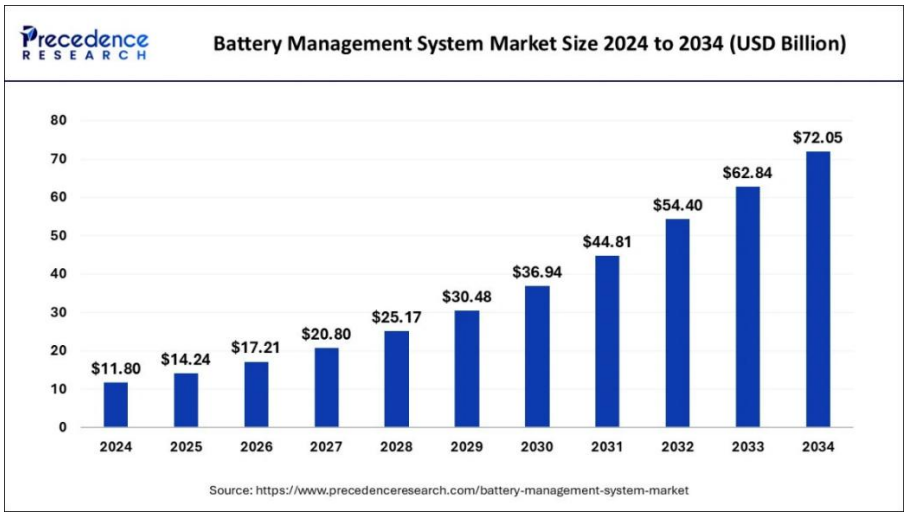


Figure 7: BMS Market Size Projection via Precedence Research

[2] This next monetary information will be given in United States Dollars (USD), being coherent with the found data. However, due to residing in Europe, the actual exchange rate of USD to € will be given: 1 USD = 0.8551€.

This expansion is mainly fueled by the rapid growth of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs), the expansion of consumer electronics and the increasing integration of renewable energy systems. A summary can be found in *Table 2*.

Market Segment	Value (2025)	Projected Value (2034)	CAGR (2025-2034)	Key Drivers
DC-DC Converters	USD 13.44 Billion	USD 30.92 Billion	9.70%	Electric Vehicles (EVs/HEVs), Consumer Electronics, Renewable Energy Integration, Industrial Automation, Data Centers
Battery Management Systems	USD 11.8 Billion	USD 72.05 Billion	19.83%	Electric Vehicles (EVs/HEVs), Consumer Electronics, Renewable Energy Systems

Table 2: Market Segmentation for DC-DC Converters and BMSs

Battery Management Systems (BMS) are decisive for ensuring the optimal performance, longevity, and safety of rechargeable batteries. Functioning as the "brain" of the battery pack, a BMS keeps track and monitors parameters such as voltage, current, and temperature.

Beyond fundamental protection against overcharging, deep discharge and overheating, modern BMS offer advanced functionalities including active/passive cell equalization, online estimation of battery states (e.g., State-of-Charge (SOC), State-of-Health (SOH), and State-of-Power (SOP)) and thermal management. These functions are critical for maximizing battery lifespan and ensuring safety, particularly in high-power applications like electric vehicles.

DC-DC converters are essential for adjusting DC voltage levels to meet specific application requirements. Buck converters, also known as step-down converters, reduce a higher DC input voltage to a lower output voltage while simultaneously increasing the output current.

Their operation regards controlled energy transfer through switches (typically MOSFETs), an inductor, and a capacitor, with the output voltage regulated by adjusting the duty cycle of the switch.

Alternatively, Boost converters, or step-up converters, efficiently increase an input voltage to a higher output voltage. This is achieved by storing energy in an inductor during a switch-on phase and subsequently releasing it to the load at an elevated voltage during the switch-off phase.

The efficacy of these converters heavily relies on their active and passive components. As a matter of fact, Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) serve as key active components in DC-DC converters, providing the high-speed switching and current-handling capabilities necessary for high-efficiency, pulse-width-modulation (PWM) based control strategies. Their superior switching characteristics, low on-state resistance (RDS(on)), and minimal gate drive requirements make them vital.

Advancements in MOSFET technology, including the adoption of soft-switching techniques, further reduce losses and electromagnetic interference (EMI), paving the way for higher frequency operation and more compact designs.

Passive elements, including inductors, capacitors, and resistors, are basic to the stability and correct functionality of electronic systems, operating without requiring an external power source.

The impending rise of complexity and demand for higher performance in battery systems, exemplified by requirements such as fast charging and the adoption of 800V structures in electric vehicles, need sophisticated integrated power electronics and BMS solutions. These solutions must extend way beyond basic protection to encompass real-time, predictive, and highly efficient energy management.

The combination of Buck and Boost converters, as explored in this thesis, enables bidirectional power flow and flexible voltage regulation, which is crucial for optimizing battery charging and discharging cycles and integrating diverse energy sources, such as regenerative braking in electric vehicles.

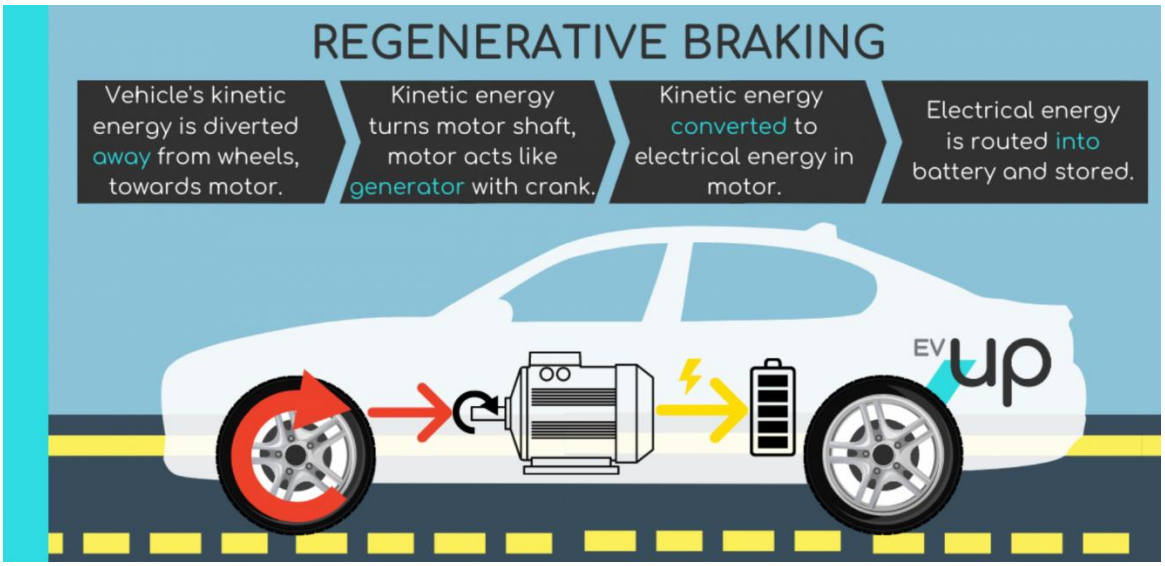


Figure 8: Regenerative Braking Functional Scheme

2.3 Component and Controller Market Analysis

Correct implementation of battery management systems relies, most importantly, on the selection and integration of appropriate power electronic components and control strategies.

In this section an overview of the current market landscape and important considerations for Buck and Boost converters will be provided. As well as passive elements, DC batteries, and various controller types, noticing and naming their functionalities, typical applications, costs[3], and the expertise required for their deployment.

In this way, a global understanding of the possibilities and current market can be reached.

[3] These costs are a market average approximation given in €, since most complex market components are marketed in USD. The € currency was chosen as a display price due to the research being conducted in Europe.

2.3.1 Buck and Boost DC-DC Converters

Buck and Boost converters are fundamental building blocks in power electronics, regulating DC voltage levels in diverse applications, such as electric vehicles and renewable energy systems.

- **Buck Converters (Step-Down):** They reduce a higher DC input voltage to a lower output voltage while increasing the output current.
    - **Functionality:** They operate by controlled energy transfer through switches (typically MOSFETs), an inductor and a capacitor. The output voltage is regulated by adjusting the duty cycle. Advantages include high efficiency, wide input voltage range, compact design, and flexible output voltage.
    - **Typical Usage:** Battery-powered devices, computer systems, and applications requiring local voltage conversion.
    - **Limitations:** Can exhibit slow response to sudden load changes (especially current mode at low duty cycles), output voltage fluctuations with fast load changes, and challenges with noise filtering due to pulsed input current.

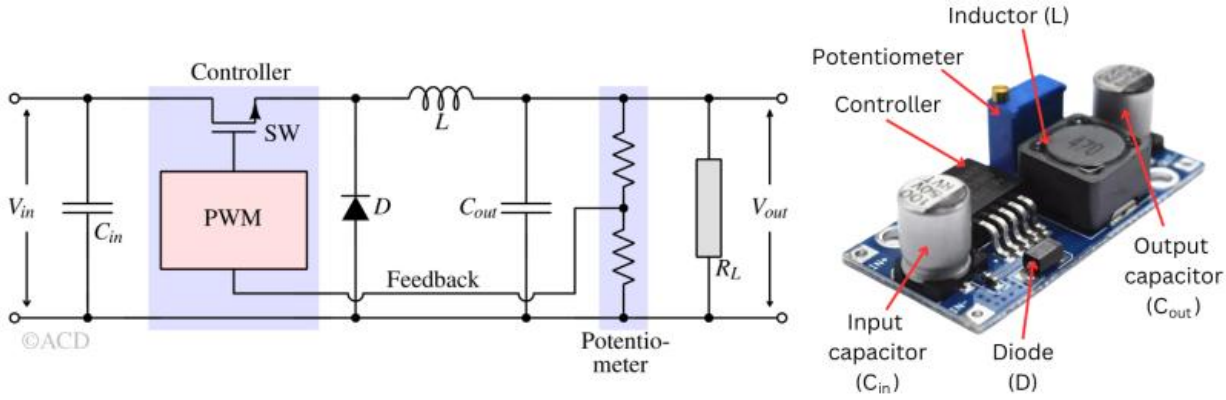


Figure 9: Buck Converter Schematics & Design

- **Boost Converters (Step-Up):** They efficiently increase input voltage to a higher output voltage while decreasing the output current.
    - **Functionality:** Energy is stored in an inductor during a switch-on phase and then released to the load at an elevated voltage during the switch-off phase.
    - **Typical Usage:** Power LED drivers, voltage Boosting for portable devices and hybrid electric vehicles where a higher output voltage than input is required.
    - **Limitations:** Due to high output ripples and discontinuous input currents, they require robust filtering. They have a Right Half-Plane Zero, complicating stable control loop design. Also, the switch and diode must bear high output voltage stress and, usually, lack inherent short-circuit protection, risking component damage.

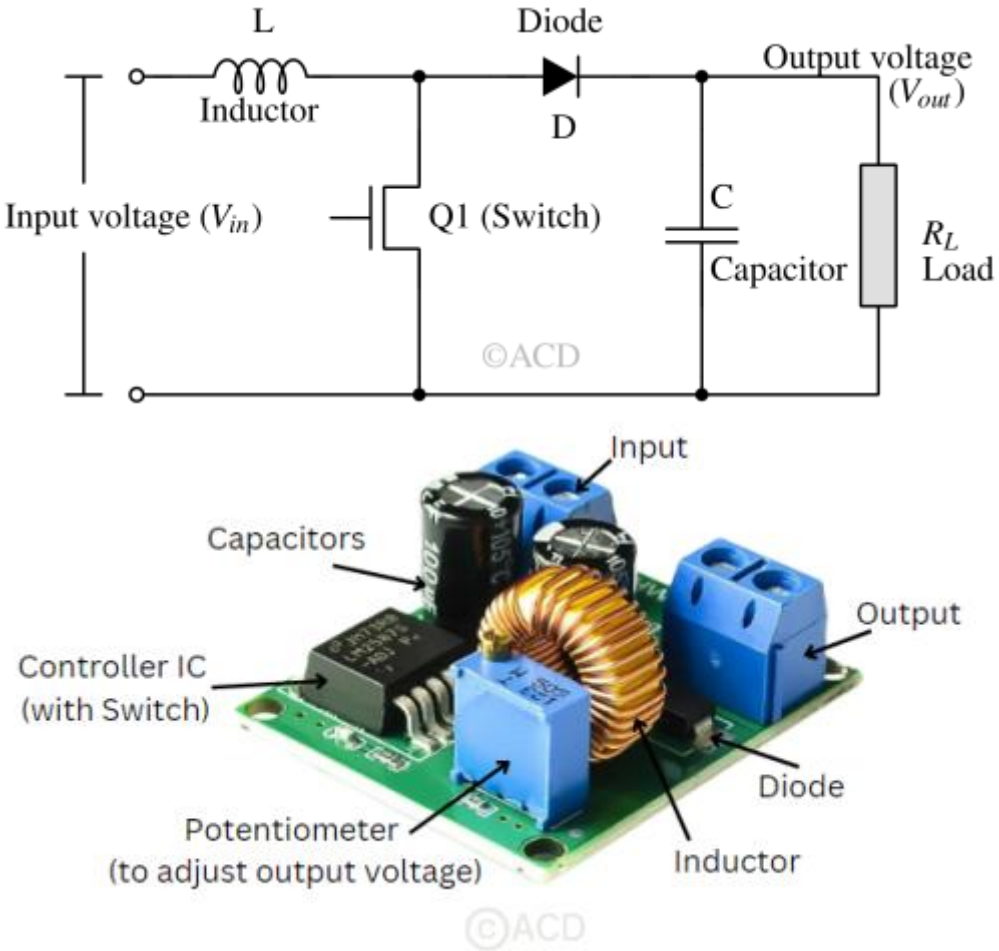


Figure 10: Boost Converter Schematics & Design

- **Buck-Boost Converters:** A versatile array of mixes of both that can either step up or step down the input voltage depending on the duty cycle. Functionalities vary as well. Cuk converters, which use the capacitor instead of the inductor as the main energy-storage component, are an example.

    - **Typical Usage:** Suitable for applications with varying input voltages or when both step-up and step-down conversions are needed, such as in solar power systems and battery-powered devices with fluctuating voltage levels.

    - **Limitations:** They have higher ripple currents (both input and output), and lower efficiency compared to dedicated Buck or Boost converters. This is due to their series connection of inductor and switch. They also lack inherent short-circuit protection and require components rated for the sum of input and output voltages, increasing component stress and cost.

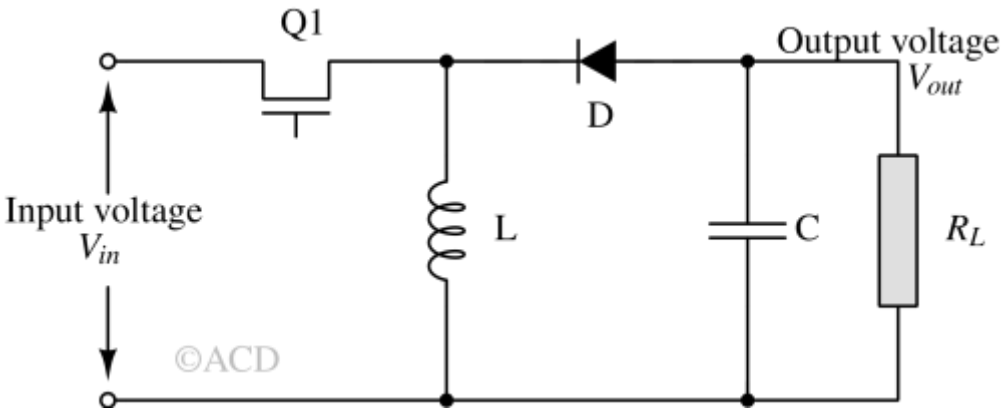


Figure 11: Buck-Boost Basic Example Schematics

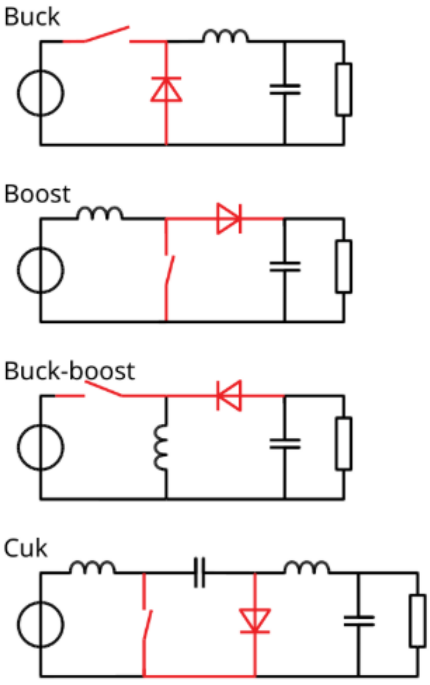


Figure 12: Comparison of Main Converter Types

- **Cost:** Individual Buck-Boost converter modules can range from approximately 1€ to thousands of them. Many common modules are available in the 10-30€ range for smaller power applications. Higher-end or specialized modules, such as those with advanced features or higher power ratings, command significantly higher prices.

- **Expertise:** Utilizing day-to-day modules simplifies integration, requiring less specialized design expertise. However, designing custom converters for specific applications demands significant expertise in power electronics, control theory and simulation tools like PLECS and MATLAB.

2.3.2 Passive Elements: Resistors, Capacitors, and Inductors

Passive electronic components help with the stability, functionality and filtering capabilities of power electronic circuits. They operate without requiring an external power source.

- **Resistors:**

    - **Functionality:** Limit current flow, divide voltages and dissipate power as heat. Major actor in setting operating conditions, filtering signals and protecting other components from excessive current.

    - **Types and Cost:** Common types include carbon composition (cheap and for general purpose with higher tolerances) and film type (more precise, higher ohmic values, tighter tolerances of 1% or less). They usually have very low cost, often available in kits of hundreds for 8-20€.

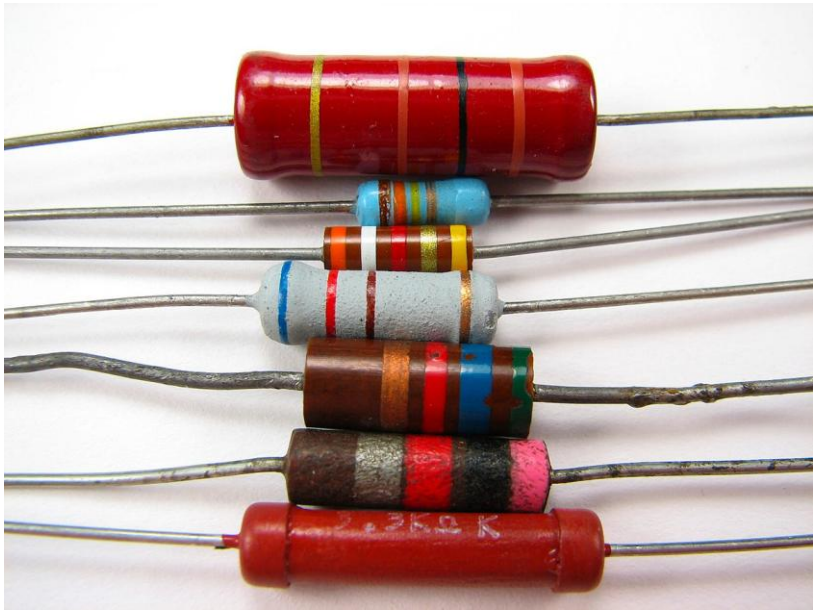


Figure 13: Array of Basic Resistors

- **Capacitors:**

  - **Functionality:** Store and release electrical energy, essential for filtering, buffering and dealing with voltage fluctuations by resisting its changes. They give aid to provide stable DC voltage to circuits and supply transient current during load changes.

  - **Types and Cost:** Common types include ceramic, electrolytic, supercapacitors, film and mica capacitors, AC capacitors… As well as many others more specialized. Supercapacitors offer exceptionally high capacitance, low internal resistance, and high efficiency charge/discharge cycles. Nevertheless, they have a high self-discharge rate. Film capacitors are suitable for frequency filtering and coupling, while mica capacitors are known for high accuracy and stability in RF and resonant circuits. Capacitors are generally low cost (a few or hundreds of dollars in general, sometimes sold in bulks) often included in basic electronics kits. Low ESR (Equivalent Series Resistance) capacitors are recommended for minimizing output ripple voltage. There are also High-Voltage/High-Power capacitors and other specialized ones that can cost up to thousands of dollars.

Figure 14: Display of Diverse Capacitors

- **Inductors:**
    - **Functionality:** Store energy in a magnetic field, filter unwanted frequencies, and resist changes in current. Used for energy management and granting CCM in converters. Small inductors generally result in a higher output current slew rate (maximum rate of change per unit of time) but higher output voltage ripple, while large inductors lower ripple current.
    - **Types and Cost:** Various types exist, including wire-wound, laminated core, ferrite core and toroidal core inductors. Each one of them is suited for different applications like power supplies, filters, and switching circuits. Inductor costs vary significantly based on inductance, current rating and type, ranging from under 1€ to over 100€ per unit.

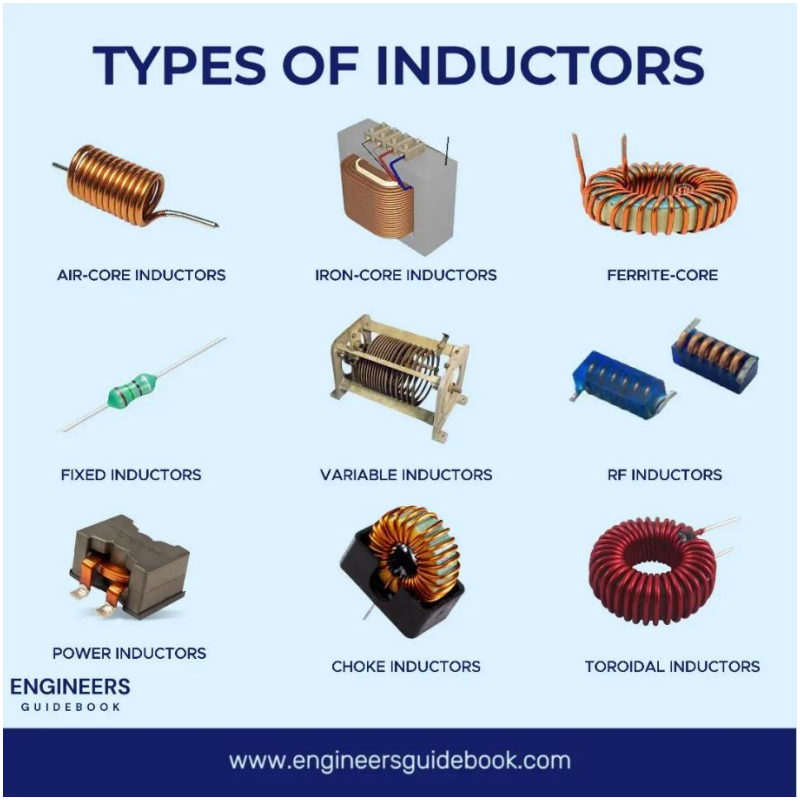


Figure 15: Some Types of Inductors

2.3.3 DC Batteries

Choosing the appropriate DC battery technology can be differential for the performance, longevity and sustainability of energy storage systems.

- **Lithium-ion (Li-ion):**
    - **Functionality:** High energy density, longer lifespan.
    - **Cost:** Pricier than lead-acid or NiMH initially, but often more cost-effective over their lifespan. Average cost around 115€ per kWh in 2025, though specific chemistries like Nickel Manganese Cobalt (NMC) can be more expensive than Lithium Iron Phosphate (LFP).
    - **Safety:** While some safety concerns have been historically noted, modern Battery Management Systems (BMS) are designed to mitigate risks like overcharging, deep discharge and overheating.
    - **Typical Usage:** Widely used in consumer electronics, electric vehicles (EVs) and hybrid electric vehicles (HEVs).

Figure 16: Li-ion Battery Example

    - **Lithium Iron Phosphate (LiFePO4 - LFP): Li-ion family member**
        - **Functionality:** Known for high efficiency, superior safety, and environmental friendliness. Offer excellent cycle life, outperforming other Li-ion batteries in longevity. Charges quickly.
        - **Cost:** More expensive upfront than the other batteries in the family, but its long cycle life and efficiency can lead to lower total cost in the long-term. LFP batteries are preferred for Vehicle-to-Grid (V2G) applications due to their lower Levelized Cost of Storage (LCOS) compared to commercial Battery Energy Storage Systems (BESS) and ternary lithium-ion batteries.
        - **Typical Usage:** Ideal for renewable energy setups and as replacements for lead-acid batteries.

Figure 17: LFP Battery Example

- **Nickel-Metal Hydride (NiMH):**
    - **Functionality:** Cost-effective and more environmentally friendly than Li-ion. Offers good temperature tolerance and is considered safer in certain contexts.
    - **Cost:** Typically, half the cost of a lithium battery.
    - **Limitations:** Hold less power and generally wears out faster than Li-ion in full discharge applications and tend to be prone to the memory effect (appear to "remember" a reduced capacity if they are repeatedly recharged after being only partially discharged).
    - **Typical Usage:** Suitable for toys, basic gadgets and some hybrid electric vehicles where their safety and reliability are prioritized.

Figure 18: NiMH battery Example

- **Lead-Acid:**
    - **Functionality:** Common and robust, but with lower energy density and shorter cycle life compared to lithium-ion batteries.
    - **Cost:** Cheapest initial investment, but higher long-term cost due to frequent replacements and higher transportation/installation costs per usable kWh.
    - **Limitations:** Present notable constraints including a low energy-to-weight ratio and minor usable capacity, often requiring discharge limits to extend their lifespan. Their relatively short cycle endurance and susceptibility to performance degradation from sulfation, particularly after deep discharges, further constrain their application in demanding or long-life scenarios.
    - **Typical Usage:** Primarily employed for automotive functions, extensively used in providing backup power for UPS systems and storing energy for renewable installations. Their cost-effectiveness makes them a reliable choice for many static and motive power applications.

Figure 19: Lead Acid Battery Design

- **Expertise:** Selecting the appropriate battery type requires a thorough understanding of the application's specific requirements for power, energy capacity, cycle life, safety, budget and others. Integrating batteries into a system calls for a robust Battery Management System (BMS) to monitor and control their state, assuring an optimal performance and safety.

2.3.4 Types of Controllers

The choice of control strategy significantly impacts the performance, stability, and complexity of power electronic systems.

- **Proportional-Integral-Derivative (PID) Controllers:**
    - **Functionality:** Widely adopted due to their simplicity and reliability. A PID controller calculates an error signal (difference between desired and actual output) and applies proportional (P), integral (I), and derivative (D) terms to generate a control action. The P-term provides immediate response, the I-term eliminates steady-state error, and the D-term anticipates future error.
    - **Typical Usage:** Effective for simple systems with stable and predictable behavior, such as regulating temperature in a furnace or speed of a motor. Commonly used in DC-DC converters for maintaining stable output voltage despite dynamic load changes.
    - **Tuning Methods**: Manual trial and error, Ziegler-Nichols[4] method and software-based automatic tuning tools (highlighting MATLAB's PIDTuner which was used in this thesis). Manual tuning is intuitive but time-consuming. Meanwhile, Ziegler-Nichols is a classic empirical simple method but can lead to oscillatory responses. It determines the controller parameters by observing the system's response to a step input or by finding the ultimate gain and oscillation period at the edge of instability.
    - **Limitations:** Struggles with complex systems, inherent delays, non-linear behavior or systems with many variables. Can lead to overshoot and windup issues in wide-range operations. Not flexible enough for changing system dynamics.
    - **Cost and Expertise:** Relatively low cost (simple PID modules/chips can cost from 5€ to 30€) and complexity for basic implementation. Requires experience and/or time for effective manual tuning, though software tools can ease the process.

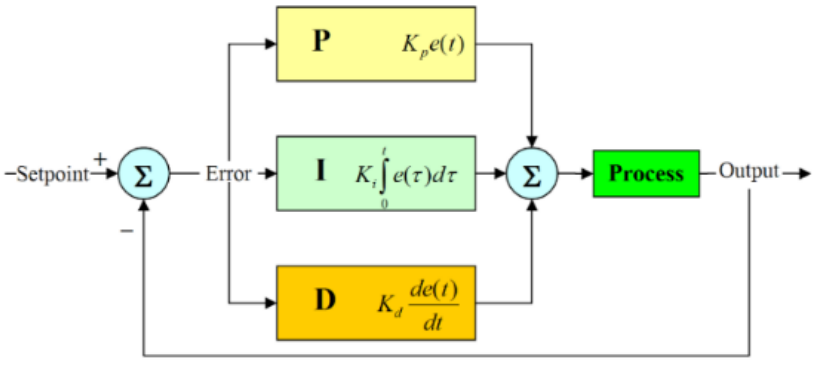


Figure 20: PID Control Block Diagram

- [4] Ziegler, J. G., & Nichols, N. B. (1942). "Optimum settings for automatic controllers." *Transactions of the American Society of Mechanical Engineers*, 64(8), 759-768.

- **Adaptive PID Control:**
    - **Functionality:** An enhancement to conventional PID where the controller parameters are adjusted online based on real time system signals. This way it strives to overcome the limitations of fixed gain PIDs in dynamic or non-linear environments. Can incorporate machine learning techniques, such as genetic algorithms, for real time adaptation.
    - **Typical Usage:** Suitable for systems with frequent parameter variations or environmental changes. It can improve performance metrics like anti-windup, overshoot reduction, and tracking acceleration.
    - **Complexity and Expertise:** More complex to design and implement than a standard PID controller. Requires a deeper understanding of control theory and potentially advanced programming skills for online adaptation, that is why it will not be trialed in this thesis.

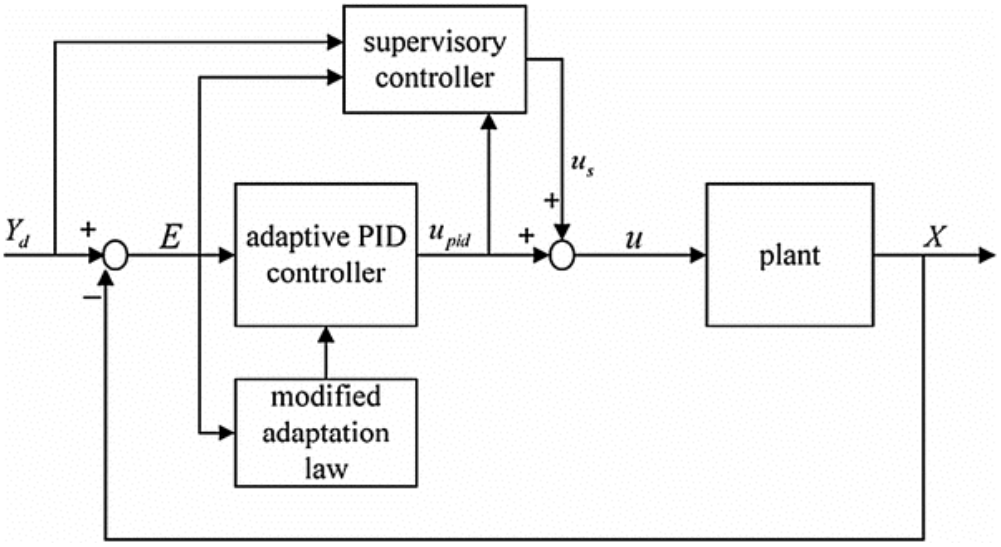


Figure 21: Adaptive PID Controller Block Diagram

- **Fuzzy Logic Control (FLC):**
    - **Functionality:** A rule-based control strategy that mimics human reasoning, operating with linguistic terms rather than precise mathematical models. It offers adaptive control capabilities and can manage system uncertainties effectively. Can be combined with PID for "Fuzzy Adaptive PID".
    - **Typical Usage:** Perfect for complex, non-linear or uncertain systems where precise mathematical models are difficult to obtain, such as fuel cells and wind turbine systems. Showcases faster dynamic response and robustness against parameter variations.
    - **Limitations:** May exhibit transient oscillations under rapidly changing environmental conditions.
    - **Complexity and Expertise:** Way more flexible and complex than PID, requiring more setup. However, its design can be easier than model-based controllers due to its customizable, rule-based nature. Can achieve good performance with less computational work if rules are well designed.

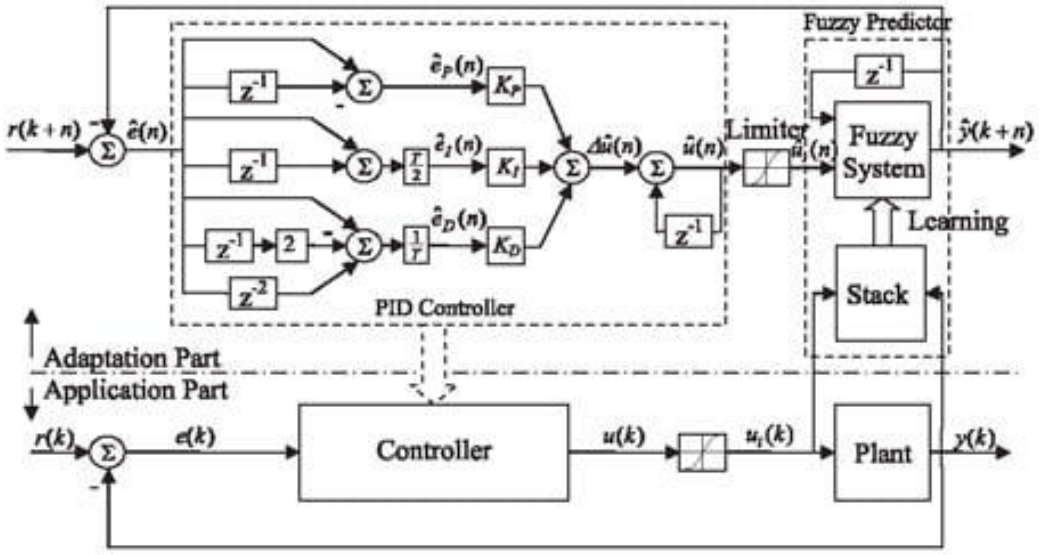


Figure 22: FLC Block Diagram Example

- **Model Predictive Control (MPC):**
    - **Functionality:** An advanced control strategy that uses a system model to predict future behavior over a finite time horizon. It optimizes control actions by minimizing a cost function while explicitly incorporating system constraints such as voltage, temperature, power limits and/or others.
    - **Typical Usage:** Highly effective for complex systems with delays, multiple variables, or strict operating limits. Applied in robotics, autonomous vehicles, and power converters. Offers superior transient and steady-state performance.
    - **Limitations:** Requires an accurate and effective system model. Demands significant computational resources, often requiring high-performance computing, which increases implementation difficulty and cost.
    - **Complexity and Expertise:** High implementation complexity due to the need for accurate modeling and real-time optimization algorithms. Requires great expertise in control theory, system identification, and computational optimization.

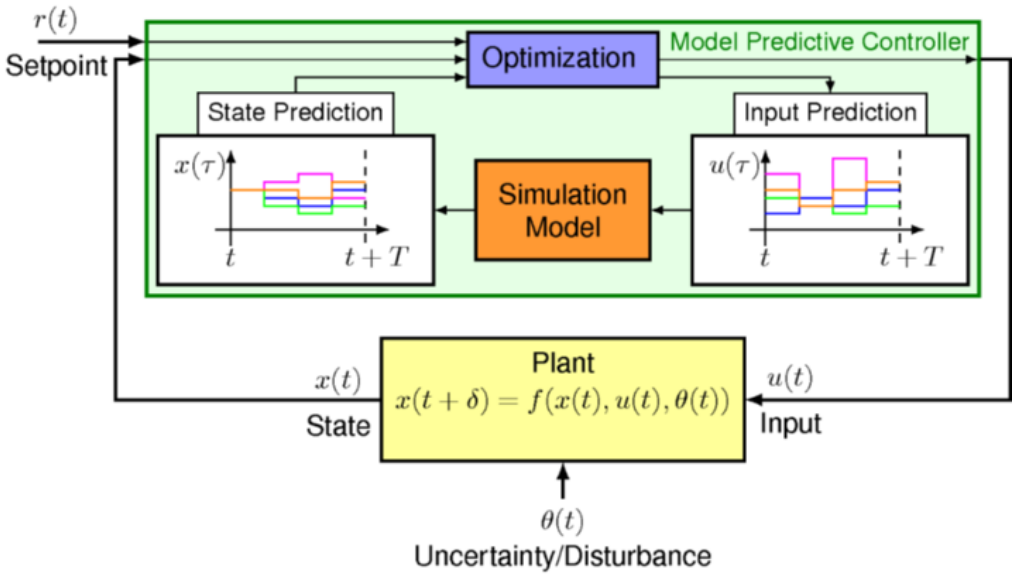


Figure 23: MPC Block Diagram Example

2.3.5 Pulse Width Modulators (PWMs)

Pulse Width Modulators refer to the integrated circuits (ICs) or digital algorithms that implement the PWM control technique. They are critical for efficiently controlling power delivery in converters. PWMs operate by rapidly switching power devices (such as MOSFETs) on and off. By varying the "duty cycle" (the ratio of ON time to the total period), they effectively control the average voltage or current delivered to a load, or the amount of power transferred, without significant energy loss. This way precise voltage regulation, power conversion and motor control are attainable more effortlessly. There are, likewise, some specific modulation schemes for different applications that do not limit to just controlling duty cycles.

- **Analog PWM Controllers:**
    - **Functionality:** These controllers are implemented using analog circuitry, typically involving a high-frequency oscillator and a comparator. The comparator compares a DC control voltage (representing the desired output) with a triangular or sawtooth waveform generated by the oscillator, producing a rectangular pulse whose width is proportional to the control voltage.
    - **Efficiency and Advancements:** Their efficiency is inherent to the switching nature of PWM. Advancements in analog PWMs primarily focus on improved accuracy, higher operating frequencies, integrated protection features (like overcurrent protection) and reduced external component count, leading to more compact and reliable solutions.
    - **Cost:** Generally, they present the most cost-effective solution for implementing basic PWM functionality, ranging from less than a dollar to a few dollars for single-channel ICs. Their simplicity contributes to lower manufacturing costs.
    - **Expertise:** Design and implementation require familiarity with analog circuit design, including careful selection of external timing components (resistors, capacitors) to set the switching frequency. Debugging can sometimes be more challenging due to the continuous nature of analog signals.

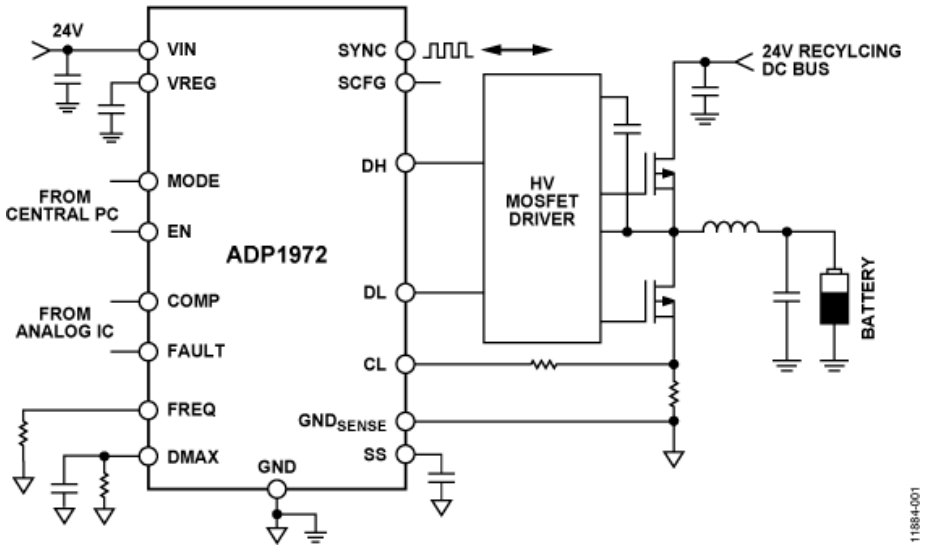


Figure 24: ADP1972 Analog PWM Controller by Analog Devices, Inc. (ADI)

- **Digital PWM Controllers:**

  - **Functionality:** These controllers implement PWM logic using digital processors such as microcontrollers (MCUs), Field-Programmable Gate Arrays (FPGAs), or Digital Signal Processors (DSPs). The duty cycle is calculated digitally based on control algorithms (e.g., PID), offering precise and programmable control over power delivery.

  - **Efficiency and Advancements:** Digital PWM offers superior precision, flexibility and immunity to noise compared to analog counterparts. Advancements include much higher switching frequencies, multi-channel control, advanced modulation schemes, adaptive control algorithms that optimize efficiency in real-time and sophisticated protection features. They can implement complex control laws that are not possible to produce with analog methods.

  - **Cost:** The cost varies widely from tens to hundreds of dollars for dedicated digital PWM ICs or MCUs with integrated PWM peripherals. For highly complex, high-performance or multi-channel applications, the solution might involve more expensive FPGAs or DSPs -which potentially reach thousands of dollars-.

  - **Expertise**: Designing and implementing digital PWM systems demands expertise in embedded programming, digital control theory and hardware-software co-design. This includes writing firmware for microcontrollers or programming FPGAs, alongside knowledge of power electronics topology and gate driver design.

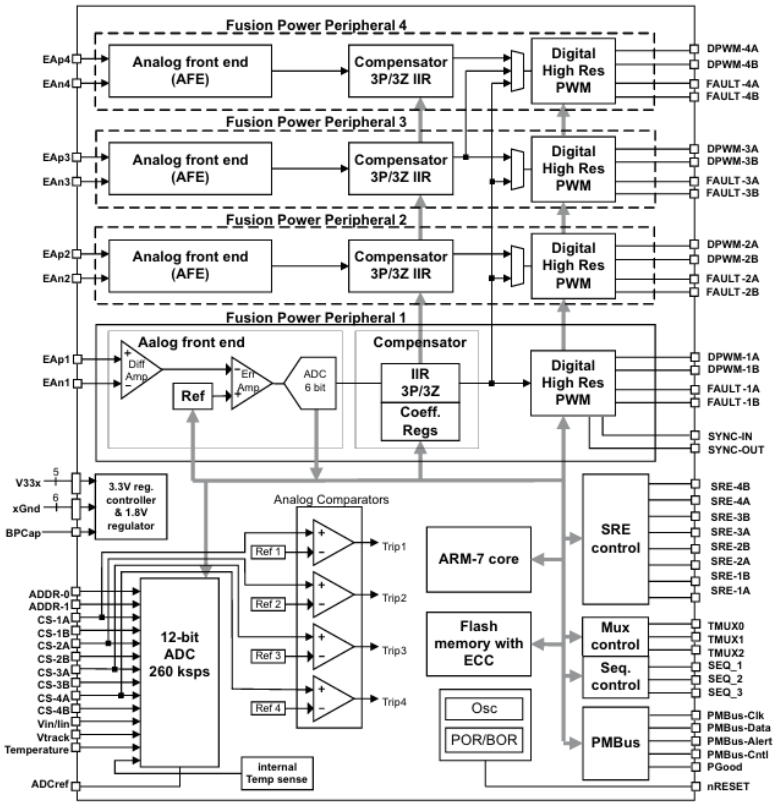


Figure 25: UCD9248 Synchronous Buck Digital PWM Controller by Texas Instruments

2.3.6 Diodes

Diodes are semiconductor devices that enable unidirectional current flow, serving as passive components in converters by steering current and providing rectification. They allow current to flow in one direction (acting like a closed switch under “forward bias”) and block it in the opposite direction (open switch under “reverse bias”).

In converters they help managing energy transfer by providing a low-impedance path during specific switching cycles.

- **Standard PN Junction Diodes (Rectifier Diodes):**
    - **Functionality:** These are the most common and basic diodes, converting alternating current (AC) to direct current (DC) by allowing current flow once a specific forward voltage is overcome. They are used in power supplies, simple rectifiers, and low-frequency applications.
    - **Efficiency and Advancements:** Their efficiency is primarily limited by their forward voltage drop (VF), leading to conduction losses, especially at higher currents. Advancements focus on reducing this VF and improving reverse recovery characteristics to minimize losses during switching transitions, though they remain slower than Schottky or SiC diodes.
    - **Cost:** Generally, the least expensive type of diode, available in a vast array of current and voltage ratings. Their low cost makes them acceptable for a wide range of general-purpose applications.
    - **Expertise:** Design is relatively straightforward, with main concerns being thermal management due to power dissipation from the forward voltage drop.

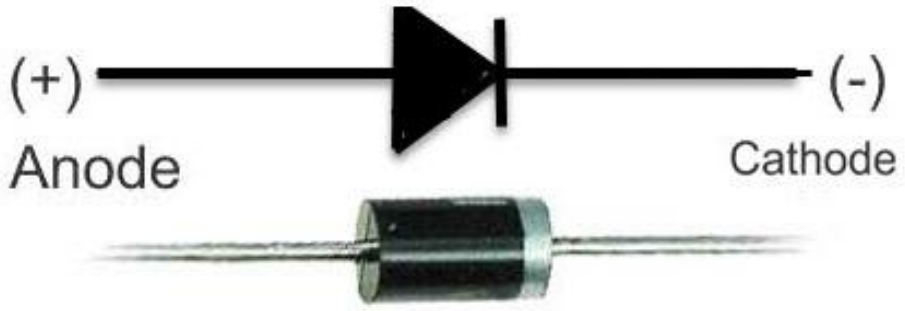


Figure 26: Rectifier Diode Example and Schematic

- **Freewheeling Diodes (Specific Application for Rectifier Diodes):**
    - **Functionality:** Usually employed in inductive circuits, such as in DC-DC converters, motor drives and relay coils. They provide a safe path for inductor current when the main switching element (e.g., a MOSFET) turns off. This prevents damaging inductive voltage spikes (flyback voltage) from occurring across the switch and allows the inductor current to decrease smoothly, ensuring continuous operation.
    - **Efficiency and Advancements:** For optimal converter efficiency, freewheeling diodes must have a low forward voltage drop to minimize conduction losses and a fast reverse recovery time to minimize switching losses. Research now focuses on developing diodes (often Schottky) with extremely fast recovery and very low forward voltage drop to enhance overall converter efficiency and reliability, especially in high-frequency applications.
    - **Cost:** Their costs vary significantly, reflecting their speed and efficiency capabilities.
    - **Expertise:** Proper selection requires careful matching of current and voltage ratings to the inductor and switching frequency. Minimizing lead inductance (wires, pins…) and confirming efficient thermal contact are crucial for effective operation, preventing overvoltage conditions and maintaining the reliability of the entire power stage.

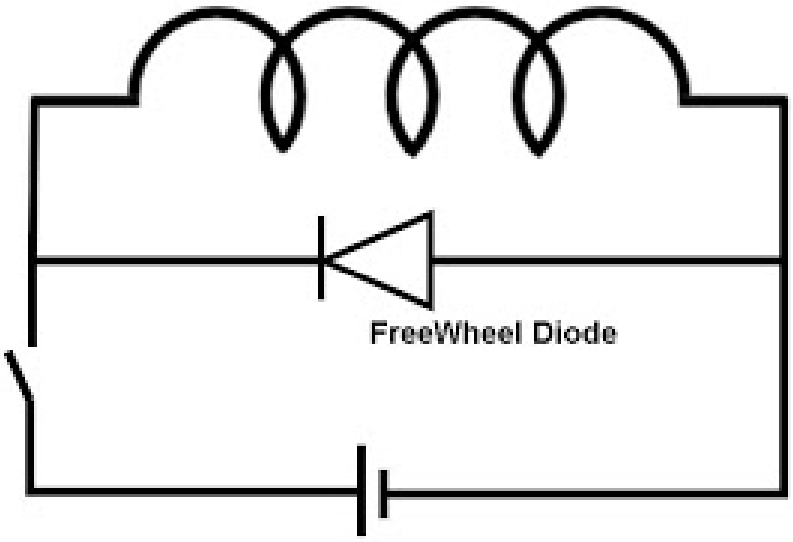


Figure 27: Freewheeling Diode Schematic

- **Schottky Diodes:**
    - **Functionality:** Characterized by a metal-semiconductor junction, Schottky diodes offer a very low forward voltage drop and extremely fast switching speeds. They are ideal for high-frequency rectification and the output rectification stage in many switch-mode power supplies.
    - **Efficiency and Advancements:** Their low forward voltage drop significantly reduces conduction losses, especially at low output voltages. Their major advantage is the almost non-existent reverse recovery time, which dramatically minimizes switching losses and reduces electromagnetic interference (EMI) at high switching frequencies. Advancements focus on improving breakdown voltage and reducing reverse leakage current, which can be higher than PN diodes.
    - **Cost:** More expensive than standard PN junction diodes due to their specialized construction and performance benefits in high-frequency applications. However, their efficiency gains can often justify the higher cost in terms of system energy savings.
    - **Expertise:** Selection requires careful consideration of their reverse voltage rating and managing their relatively higher reverse leakage current at elevated temperatures. Thermal management is critical due to their power dissipation.

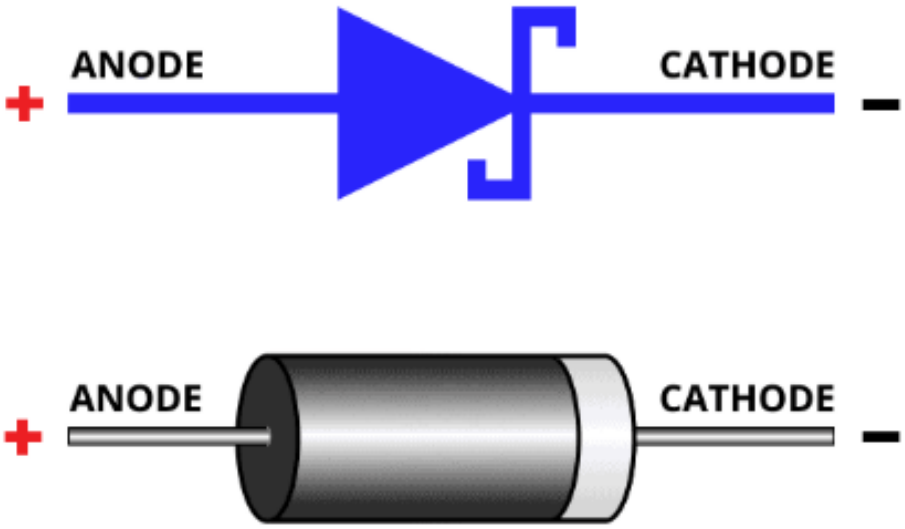


Figure 28: Schottky Diode Example and Schematic

- **Zener Diodes:**
    - **Functionality:** Designed to operate in a controlled reverse breakdown region, Zener diodes maintain a remarkably constant voltage across their terminals when reverse-biased above a specific threshold called the Zener voltage. Used for precise voltage regulation (creating reference voltages) and robust circuit protection against overvoltage transients.
    - **Efficiency and Advancements:** Zener diodes are not typically evaluated for "efficiency" in the same power conversion sense, as they regulate voltage by dissipating excess current as heat. Advancements focus on improving voltage stability over temperature and current, offering tighter voltage tolerances and enabling higher power dissipation capabilities for robust protection.
    - **Cost:** Generally cheap, often comparable to PN junction diodes.
    - **Expertise:** Selection involves choosing the correct Zener voltage and power dissipation rating for the specific regulation or protection task. Circuit design around them is usually simple, involving a series resistor to manage power dissipation within safe limits.

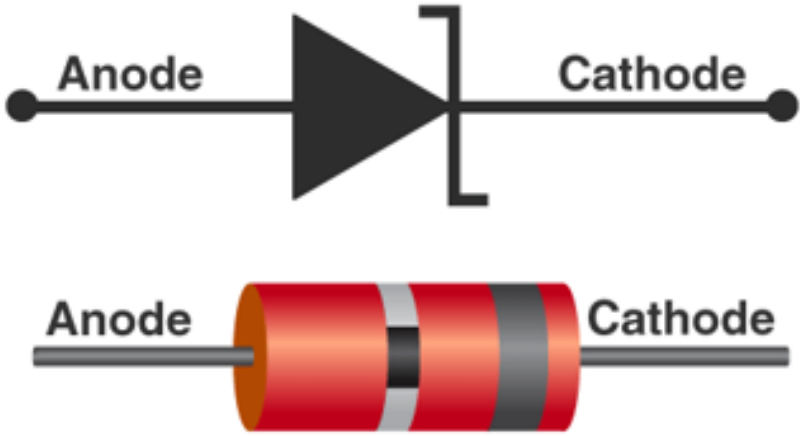


Figure 29: Zener Diode Example and Schematic

2.3.7 MOSFETs

Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) are active components in converters which provide means to achieve high-speed switching and efficient power conversion.

- **Functionality:** Grant high-speed switching and current-handling capabilities for Pulse Width Modulation (PWM) based control strategies. Important advantages include fast switching speeds, low on-state resistance (RDS(on)), minimal gate drive requirements, excellent thermal performance and high reliability.

- **Efficiency and Advancements:** Continuous advancements particularly with wide-bandgap (WBG) semiconductors like Silicon Carbide (SiC), have led to significantly improved efficiencies (superior to 90%), higher frequency operation and more compact designs. Soft-switching techniques further reduce losses and electromagnetic interference (EMI).

- **Cost:** Silicon MOSFETs are generally the most viable option. SiC MOSFETs are typically about three times more expensive than equivalent Silicon transistors but offer benefits like smaller form factors and improved efficiency.

- **Expertise:** Selection requires being aware of parameters such as RDS(on), gate charge, and switching losses to optimize efficiency for the desired application. Design and integration demand expertise in gate drive circuits, PCB layout (to minimize parasitic inductance and capacitance), and thermal management to make a reliable and efficient operation possible.

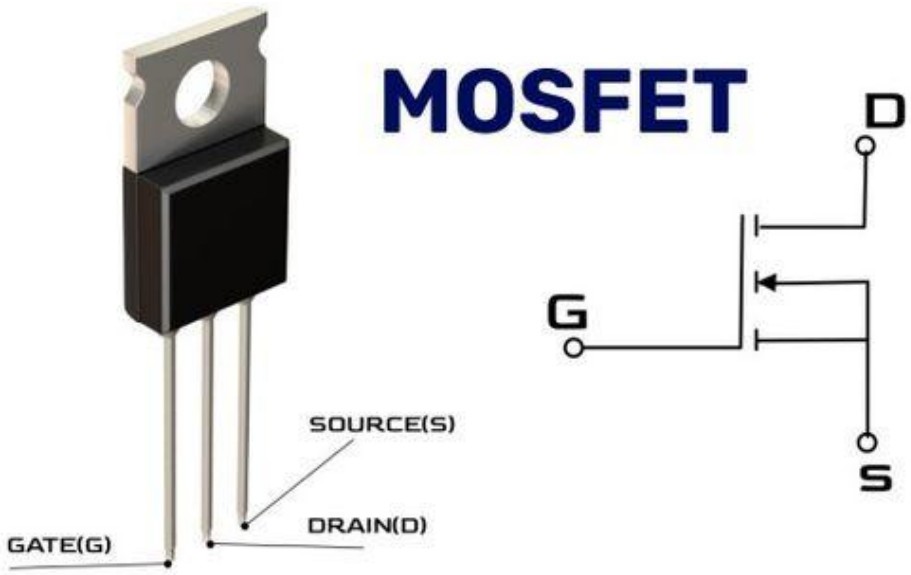


Figure 30: MOSFET Build-Up and Circuit Depiction

2.3.8 Components and Controllers Overview

Component / Controller	Functionality & Key Features	Typical Usage & Applications	Relative Cost	Expertise Needed
Buck Converter	Steps down DC voltage, increases current. High efficiency, compact.	Battery-powered devices, computer systems, local voltage regulation (e.g., 24V to 5V).	Low-Medium (modules 7-30€, custom higher)	Moderate (module integration) to High (custom design)
Boost Converter	Steps up DC voltage, decreases current. Stores energy in inductor.	Power LED drivers, portable devices, hybrid electric vehicles.	Low-Medium (modules 7-30€, custom higher)	Moderate (module integration) to High (custom design)
Resistors	Limits current, divides voltage, dissipates heat.	Setting operating conditions, filtering, protection.	Low (kits 8-20€)	Low (basic selection) to Moderate (precision/power applications)
Capacitors	Stores/releases energy, filters, smooths voltage.	Filtering, buffering, voltage stabilization, energy storage.	Low (kits 8-20€)	Low (basic selection) to Moderate (ESR, frequency considerations)
Inductors	Stores energy in magnetic field, filters frequencies, resists current changes.	Energy management, filtering, CCM in converters.	Low-High (0.30-100€+ per unit)	Moderate (basic selection) to High (core material, current rating, ripple)
Li-ion Batteries	High energy density, long-lasting.	Consumer electronics, EVs, HEVs.	High (139€/kWh average)	High (BMS)

Component / Controller	Functionality & Key Features	Typical Usage & Applications	Relative Cost	Expertise Needed
LiFePO4 (LFP) Batteries (Li-ion family)	Very efficient, safest, excellent cycle life, fast charging.	High-end EVs, renewable energy storage, V2G applications.	High (higher upfront, lower long term)	High (BMS integration, safety, thermal management)
NiMH Batteries	Cost-effective, eco-friendly, good temp tolerance.	Toys, basic gadgets, some hybrid vehicles.	Medium (half of Li-ion)	Moderate (BMS integration for longevity)
Lead-Acid Batteries	Low initial cost, robust.	Automotive starting, backup power, basic storage.	Low (highest long-term cost)	Low (basic usage) to Moderate (maintenance, lifespan management)
PID Controllers	Simple, robust for stable systems. P, I, D terms for error correction.	General industrial control, DC-DC voltage regulation.	Low (software/basic hardware)	Moderate (manual tuning) to Low (auto-tuning tools)
Adaptive PID Control	PID with online parameter adjustment.	Systems with changing dynamics, non-linearities.	Medium-High (software complexity)	High (advanced control theory, programming)
Fuzzy Logic Control (FLC)	Rule-based, mimics human reasoning, handles uncertainties.	Complex, non-linear, uncertain systems (e.g., fuel cells, wind turbines).	Medium (software complexity)	High (rule design, system understanding)
Model Predictive Control (MPC)	Model-based, predicts future behavior.	Complex systems (EVs, Robotics…)	High (Hardware, computing demands)	Very High (modeling, optimization…)

Component / Controller	Functionality & Key Features	Typical Usage & Applications	Relative Cost	Expertise Needed
Pulse Width Modulators (PWMs)	ICs or digital algorithms implementing PWM for efficient power delivery by rapidly switching devices.	Precise voltage regulation, power conversion, motor control.	Low (analog, < 1-few €) to High (complex digital, 10s-100s €, FPGAs & DSPs up to thousands)	High (embedded programming, control theory, hardware-software co-design, gate drive/layout)
MOSFETs	High-speed switching, current handling. Low RDS(on), high efficiency.	DC-DC converters, power supplies, motor drives.	Low (Silicon) to High (SiC,)	High (thermal management, gate drive, PCB layout)
Diodes	Semiconductor devices enabling unidirectional current flow by acting as switches, steering current and providing rectification.	Rectification, freewheeling, voltage regulation, circuit protection.	Very Low (PN Junction) to High (SiC Schottky)	Moderate (thermal management, reverse recovery, leakage current) to High (matching to frequency/inductor, lead inductance minimization)

Table 3: Background Controllers/Components Summary

2.4 Dynamic Control and Simulation Software Market

Regarding dynamic control there are several software and types that are used, each with its own strengths and main focuses. A summary of the best known is important and interesting due to understanding what sorts of possibilities there are and why and when to choose one or another.

This choice is more important than it can appear to be at first glance, since time differences in engineering processes end up being translated in costs. And the economical layer is one of the most crucial for any engineering feat.

2.4.1 Types of Simulation

- **SPICE based simulation**

  They specialize in circuit-level analysis of individual components, with high precision for analog behavior. Some examples are LTspice, QSPICE or PSpice.

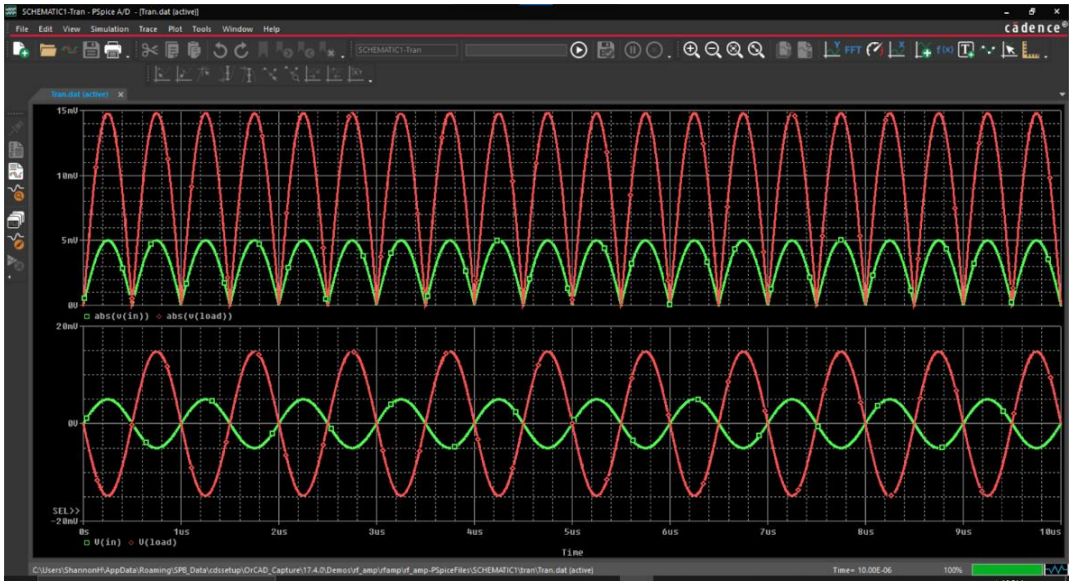


Figure 31: SPICE Simulation Example

- **Piecewise Linear (PWL) simulation**

One of the main examples is PLECS. It models devices using simplified, piecewise linear functions, prioritizing efficiency and robustness for circuits with rapid switching, common in power electronics. For this reason, when working with complex dynamic systems with converters, this is the best possible choice.

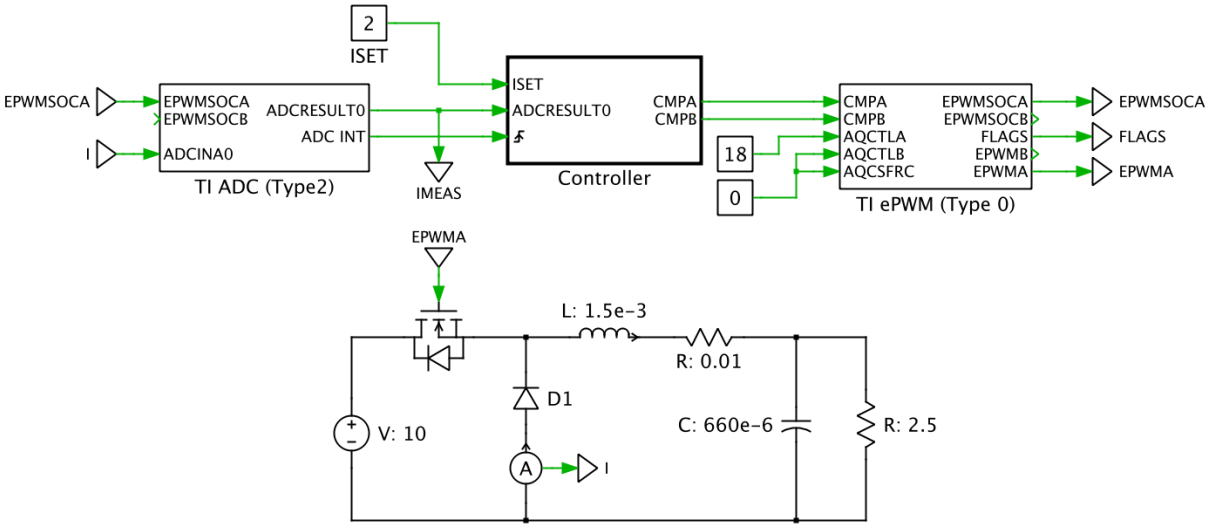


Figure 32: PWL PLECS Example: Efficient Microcontroller Peripheral Modeling

- **Block diagram simulation**

MATLAB's Simulink is one of the best-known examples. It provides a visual, intuitive approach for dynamic systems and modeling, connecting pre-defined blocks to build complex system models.

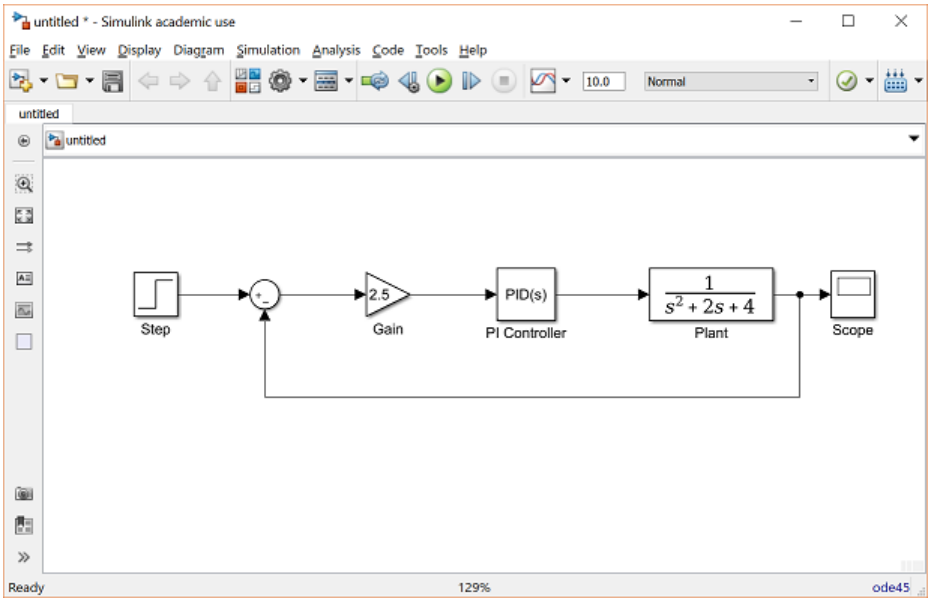


Figure 33: Block Diagram Simulation Example on MATLAB's Simulink

2.4.2 Main Software

- **MATLAB and Simulink**

  Developed by MathWorks, form a powerful computational and dynamic system modeling environment. MATLAB offers textual programming and computational, while Simulink (an add-on) offers an intuitive graphical block-diagram interface in real-time systems.

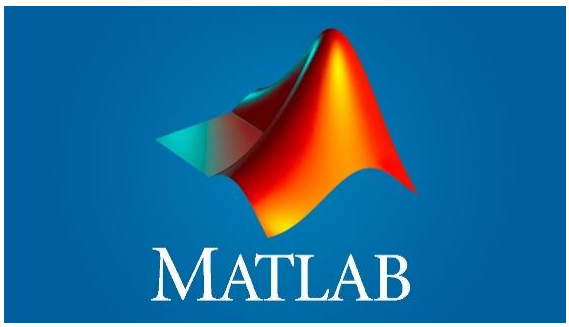


Figure 34: MATLAB's Logo

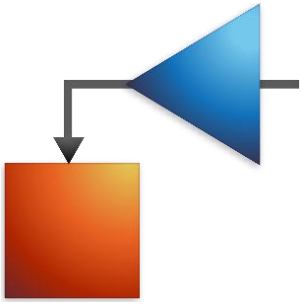


Figure 35: Simulink's Logo

- **PLECS**

  Acronym for Piecewise Linear Electrical Circuit Simulation, designed by Plexim, is used for system simulations of electrical circuits, with a particular emphasis on power electronics. It centers on an intuitive schematic editor and efficient algorithms for switched systems. There is a close relationship between PLECS block set and Simulink, as it is a possible add-on, it allows hybrid modeling which can be useful.

Figure 36: PLECS's Logo

- **Siemens EDA**

  Centered on Electronic Design Automation (EDA): IC design, system verification, industrial automation and Printed Circuit Boards (PCBs) are some of its goals. Focuses more on complex IC design, PCBs and digital twins. Currently they have launched an AI-driven EDA.

Figure 37: Siemens EDA AI Advertisement

- **Altium Designer**

  A strong EDA software with a much deep-rooted PCB design and verification focus. It combines schematic capture, PCB layout and manufacturing. Also simplifies the design process.

Figure 38: Altium Designer's Logo

- **Ansys**

  Specialized in engineering simulation across multiple physics domains. Ranging from mechanics, fluid dynamics, electromagnetics… Multiphysics coupling is one of its strengths. It helps to simulate, analyze and optimize designs before physical prototyping.

Figure 39: Ansys's Logo

- **LTspice**

  Free and fast SPICE-based analog electronic circuit simulator by Analog Devices. It implements schematic capture, SPICE simulator and a waveform viewer. It is widely used for simulating electronic circuits.

Figure 40: LTspice's Logo

- **QSpice**

  Developed by Qorvo, it is an advanced SPICE simulator designed for power, analog, and mixed-signal circuit designs. Makes a difference given its ability to incorporate massive quantities of digital logic. It also supports C++ and Verilog source code compilation for complex simulations.

Figure 41: QSpice's Logo

- **Cadence PSpice Designer**

  Circuit simulation and verification software with native analog/mixed-signal analysis. It has various analysis types (transient, bias point, DC sweep, AC sweep, noise, temperature, parametric…) and an extensive model library. Usually employed for simulating and optimizing circuit functionality.

Figure 42: Cadence PSpice Designer's Logo

2.4.3 Software Comparison Overview

Software	Primary Focus	Simulation Method	Key Strengths	Key Weaknesses	Typical Cost
MATLAB/Simulink	Multi-domain system modeling & control	Block-diagram, physical modeling	Comprehensive ecosystem, MBD, HIL	High cost, steep learning curve	Commercial (high)
PLECS	Power electronics, HIL, thermal	Piecewise linear	Speed/robustness for power electronics	High cost, ideal switch limitations	Commercial (high)
LTspice	Analog circuit simulation	SPICE-based	Free, fast, accurate, large library	Steep learning curve	Free
QSPICE	Next-gen SPICE, power, mixed-signal	Enhanced SPICE-based	Free, faster/more accurate SPICE	Convergence with stiff I-V curves	Free
Ansys	Multiphysics, high-freq EM	SPICE, multi-physics	Multiphysics, broad applications	Very high cost, steep learning curve	Very high (enterprise)
Cadence PSpice Designer	Analog/mixed-signal, PCB simulation	SPICE-based	High accuracy, integrated PCB flow	Convergence issues, high cost	Commercial (high)
Siemens EDA	IC/PCB design, AMS, reliability	SPICE-based (various)	Comprehensive EDA, high accuracy/speed	High cost, specific tool limitations	Commercial (high)
Altium Designer	Integrated PCB design, mixed-signal	Enhanced SPICE-based	Integrated PCB design, mixed-signal simulation	SPICE engine specifics, accuracy perception	Commercial (high)

Table 4: Software Comparison Summary

3. THEORETICAL APPROACH

3.1 Circuit Schematics and Division: First Steps of the Approach

The circuit's first designed schematic, in other words the one to be analyzed, consists of two batteries united by a Boost and a Buck converter, by using only a capacitor and a load in the middle of the system.

Since ideal switches are not realistic, it will be implemented with MOSFETs and diodes, obtaining unidirectional flow architecture. Given that the power flux is generally considered from left to right, the first DC battery, v_1, is followed by a Boost converter and the other one, v_2, is preceded by a Buck, as shown in *Figure 43*.

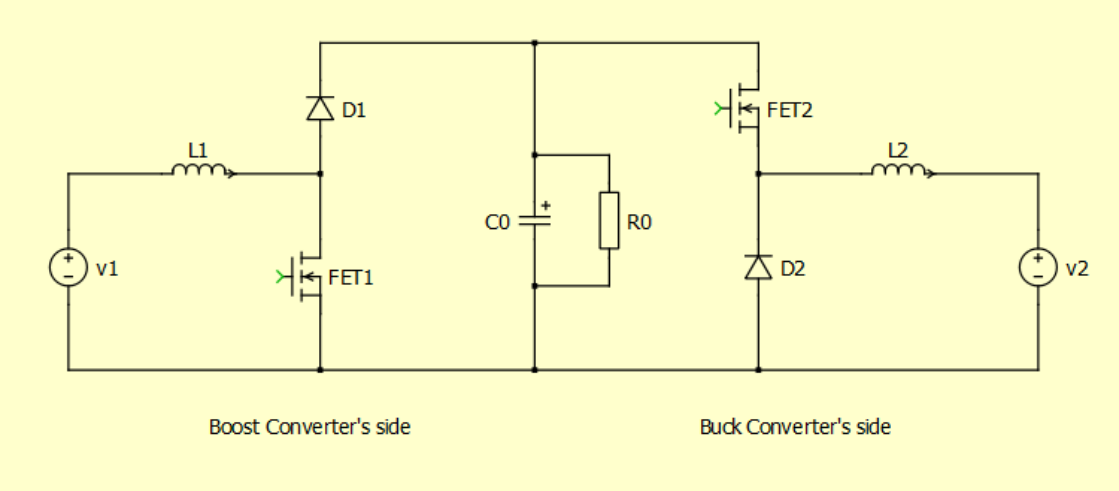


Figure 43: Circuit Design in PLECS

Since the system, as a whole, is complex to analyze, it will be divided into two subsystems through the Norton (*Figure 44*) and Thevenin (*Figure 45*) Equivalent Circuits, granting continuity.

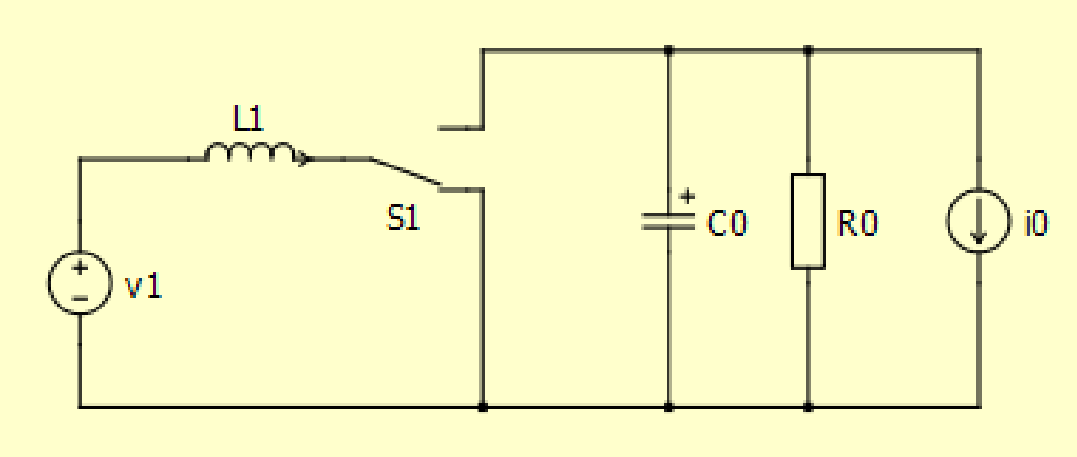


Figure 44: Simplified Boost's Subsystem in PLECS

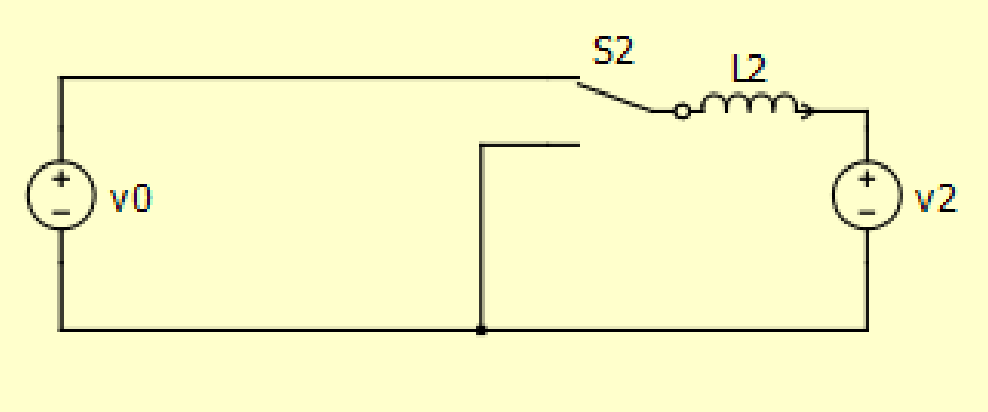


Figure 45: Simplified Buck's Subsystem in PLECS

The main design differences the Buck converter's side shows, in comparison to a traditional Buck converter's schematics, are that i_2 (L_2's current) is "flowing" in the opposite direction to the Boost's power flow (which would be from right to left, the considered system's power flux) and that the MOSFET and the diode are trading places between the two of them.

Therefore, since the flow is being studied from left to right, the effect and the switching behavior of this subsystem is the same as that of a Buck, reducing voltage from v_0 (capacitor's voltage, acts as Thevenin's voltage source) to v_2, but without inverting poles.

Also note that, while the Boost follows the traditional model with the R_0 load and Norton's i_0 active load, the Buck subsystem is not fully recognizable at first glance, due to the capacitor not being included in the subsystem's design. Nevertheless, it is of great importance to clarify that the approach taken requires controlling the Boost first, charge the capacitor and then stabilize v_0 for the Buck to start acting. By highlighting this, the subsystem can be finally regarded as a Buck converter for its role in the system's behavior.

3.2 CCM Analysis & Theoretical Approach Hypotheses

The analysis will be done in continuous conduction mode. In this mode, the current flowing through the inductor never drops to zero throughout the entire switching period. Energy is continuously transferred, whether it being stored in the inductor or delivered to the load.

Also, there is need to clarify that the analysis chosen will consist in applying voltage control mode in the Boost, afterwards "forcing" that voltage across the Buck through a Voltage source v_0. Keeping this in mind, it is possible to obtain a sense of continuity and independent action of both converters at the same time: The voltage v_0 will vary by action of the Boost whereas acting as a concise and known input in the Buck's analysis. Lastly, ending by applying current control mode in the Buck converter. This way the control will be based on v_0 (Boost) and i_2 (Buck).

The approach of the small ripple approximation and the small-signal assumption that are the base of converters' analysis are being considered. The AC fluctuations for the converter's non-ideal switching behavior in both the inductor current and capacitor voltage are considered negligibly small in comparison to the DC average values. Also, the combination or existence of the AC fluctuating terms is considered non-existent or close to zero.

Regarding realistic technicities, parasitical losses and non-ideal resistances in these switching elements are not being regarded, for the scope taken requires only a general and first-impression analysis to be done. That is also why diodes and MOSFETs are considered ideal switches throughout the theoretical development, following this simplified approach of Buck and Boost converters.

3.3 Final Objective of the Approach

The definitive focus is to obtain both transfer functions, one for each subsystem and control mode desired.

Having found the transfer functions, knowing how the system behaves and having cleared out the hypotheses, the process of determining controllers' parameters would be ready to be executed.

Furthermore, confirming reasonable theoretical behavior is key for taking further steps within the project and to start implementing the design in any kind of software.

3.4 Methodology for Obtaining Subsystem Transfer Functions

Due to the duty cycles, a division of each subsystem into two cases is required. Firstly, the MOSFET lets the current through and the diode does not, meanwhile, the next period succeeds in the opposite.

The switching period will be addressed as T_s and the duty cycles as D and D' $(D + D' = 1)$, which correspond to the fraction of the switching period that the MOSFET is ON and the diode OFF, and vice versa, respectively.

After this, by applying Kirchoff's Voltage and Current Laws, the differential equations for the capacitor's voltage and inductor's current will be sorted out. By doing this, the state-space model for each scenario can be designed.

Then the average state-space model for the whole switching period will be obtained by multiplying each case's equations for its switching period duty cycle, adding them and clearing out terms (averaging both cycles).

The Boost subsystem's state variables are the inductor's current $i1$ and the capacitor's voltage v_0 (also considered output), as they change with time and grant the internal "state" of the subsystem. The duty cycle D_1 is its control input, meanwhile, the battery's voltage v_1 and the active load's current i_0 are inputs that will be regarded as perturbances, thus, not being analyzed.

On the other hand, within the Buck subsystem, the state/output would just be the inductor's current i_2 and the control input the duty cycle D_2. Meanwhile the input regarded as a perturbance due to not being subject of analysis would be v_2. The voltage source v_0 is not regarded as a state due to being forced as a constant.

By this point, linearization is usually needed to be able to switch into the frequency domain through the Laplace transformation, since Laplace's principles of linearity and superposition are demanded for the transformation to be applied and, also, converters have an inherent non-linearity due to their switching behavior (usually a voltage multiplied by the duty cycle always appears).

Whereas the Buck converter's case is generally easily solved (and in this case is already linearized by forcing v_0), the Boost's scene takes a different approach to linearize.

The Laplace Transformation Definition for transfer functions analysis works as *Eq. 1* depicts.

$$F(s) = \mathcal{L}\{f(t)\} = \int_{-\infty}^{+\infty} e^{-st} f(t) dt$$

Eq. 1: Laplace Transformation Definition

After sorting out these steps, having a linear model and changing into frequencies, the transfer function of each control mode desired can be easily obtained by substituting steady-state values (if needed) and having a two equation with two indeterminates system, which is easily solved.

It is also worth mentioning that, after switching to frequencies, the other outputs are not considered in the equations, therefore they are disregarded and nullified. The resulting model would be, then again, a way too difficult approach. Looking just for one type of output control (voltage or current) also permits the desire to create a focused, simplified model that allows for the practical application that is being researched.

3.4.1 Boost Subsystem

- **First Duty Cycle State-Space Modeling: MOSFET ON & Diode OFF.**

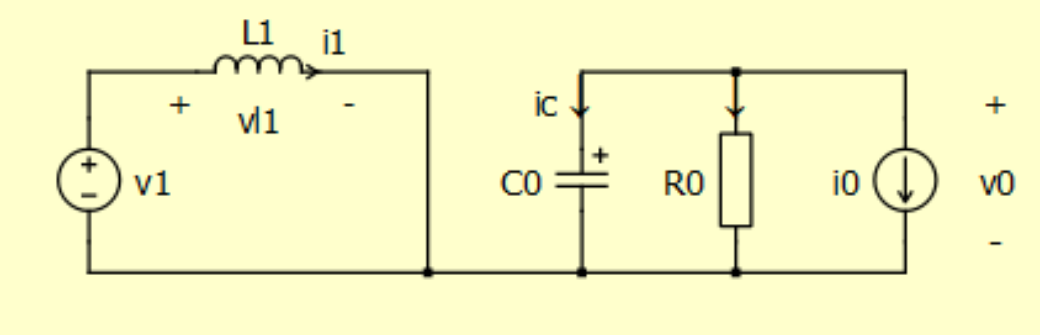


Figure 46: Boost's First Duty Cycle D_1 Scenario

Current flows from the input source v_1, through the inductor L_1,, and through the MOSFET to the ground. The inductor stores energy from the input. The output load is supplied by the output capacitor (if able).

The inductor's current and capacitor's voltage differential equations are described in *Eq. 2* and Kirchoff's laws applied in *Eq. 3*.

$$\begin{cases} \dot{i_1} = \dfrac{v_{L_1}}{L_1} \\ \dot{v_0} = \dfrac{i_c}{C_0} \end{cases}$$

Eq. 2: Inductor Current and Capacitor Voltage Differential Equations (D1)

$$\begin{cases} v_{L_1} = v_1 \\ i_c = -\left(i_0 + \dfrac{v_0}{R_0}\right) \end{cases}$$

Eq. 3: Kirchhoff's Laws (D1)

Thus, substituting *Eq. 3* in *Eq. 2*, the state-space model of D_1, cycle's scenario is obtained, as shown in *Table 5*.

$$\begin{cases} \dot{i_1} = \dfrac{v_1}{L_1} \\ \dot{v_0} = \dfrac{-\left(i_0 + \frac{v_0}{R_0}\right)}{C_0} \end{cases}$$ *Eq. 4: D1 State-Space System*
$$\begin{pmatrix} \dot{i_1} \\ \dot{v_0} \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & -\dfrac{1}{R_0 C_0} \end{pmatrix} \begin{pmatrix} i_1 \\ v_0 \end{pmatrix} + \begin{pmatrix} \dfrac{1}{L_1} & 0 \\ 0 & -\dfrac{1}{C_0} \end{pmatrix} \begin{pmatrix} v_1 \\ i_0 \end{pmatrix}$$ *M_1: D1 State-Space Simplified Matricial System*

Table 5: Boost's First Duty Cycle D_1 State-Space Model

- **Second Duty Cycle State-Space Modeling: Diode ON & MOSFET OFF**

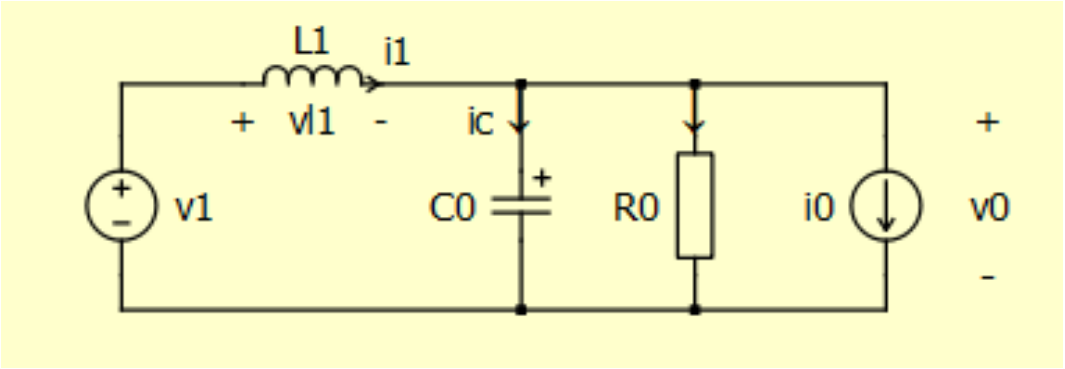


Figure 47: Boost's Second Duty Cycle D_1' Scenario

The inductor, charged, generates a voltage that adds to the input voltage, creating a higher voltage that activates the diode. The current then flows from the inductor and input source, through the diode, to charge the capacitor and supply the load.

The same procedure as with the previous cycle's scenario will be followed. Thus, the inductor's current and capacitor's voltage differential equations are obtained in *Eq. 5* and Kirchoff's laws are applied in *Eq. 6* to get the inductor's voltage and capacitor's current.

$$\begin{cases} \dot{i_1} = \frac{v_{L_1}}{L_1} \\ \dot{v_0} = \frac{i_c}{C_0} \end{cases}$$

Eq. 5: Inductor Current and Capacitor Voltage Differential Equations (D1')

$$\begin{cases} v_{L_1} = v_1 - v_0 \\ i_c = i_1 - \left(i_0 + \frac{v_0}{R_0} \right) \end{cases}$$

Eq. 6: Kirchhoff's Laws (D1')

Subsequently, by substitution of *Eq. 6* in *Eq. 5*, the state-space model of this second cycle's scenario is defined, as depicted in *Table 6.*

$$\begin{cases} \dot{i_1} = \dfrac{v_1 - v_0}{L_1} \\ \dot{v_0} = \dfrac{i_1 - \left(i_0 + \dfrac{v_0}{R_0}\right)}{C_0} \end{cases}$$

Eq. 7: D1' State-Space System

$$\begin{pmatrix} \dot{i_1} \\ \dot{v_0} \end{pmatrix} = \begin{pmatrix} 0 & -\dfrac{1}{L_1} \\ \dfrac{1}{C_0} & -\dfrac{1}{R_0 C_0} \end{pmatrix} \begin{pmatrix} i_1 \\ v_0 \end{pmatrix} + \begin{pmatrix} \dfrac{1}{L_1} & 0 \\ 0 & -\dfrac{1}{C_0} \end{pmatrix} \begin{pmatrix} v_1 \\ i_0 \end{pmatrix}$$

M_2: D1' State-Space Simplified Matricial System

Table 6: Boost's Second Duty Cycle D1' State-Space Model

- **State-Space Average Model**

By averaging both duty cycles' state-space models throughout the whole switching period, T_s, the joint model for the whole state will be obtained depending on the duty cycle D_1 (recalling that $D1' = 1 - D1$).

For clarifying purposes, the relation *R.1* is proposed.

$$(\text{Eq. } 4)D_1 T_s + (\text{Eq. } 7)(1 - D_1)T_s = (Eq. 8)$$

R. 1: System of Equations Averaging Relation: Eq. 8 Obtention

This state-space average model will simplify the non-linear system with both switching states into a single, time-invariant set of equations.

Also, by analyzing the steady state, their laws can be found and will be needed for linearization, and these laws can prove whether the behavior of the ideal Boost converter is recognizable or not.

In said state, the change over time of the average inductor's current and capacitor's voltage is zero, thus, the average steady state laws will be obtained, as *Eq. 9* show.

All these results are summarized in *Table 7*.

$$\begin{cases} \dot{i_1} = \dfrac{v1 - (1 - D_1)v0}{L_1} \\ \dot{v_0} = \dfrac{(1 - D_1)i_1 - \left(i0 + \dfrac{v_0}{R0}\right)}{C_0} \end{cases}$$

Eq. 8: Boost's State-Space Average System

$$\begin{pmatrix} \dot{i_1} \\ \dot{v_0} \end{pmatrix} = \begin{pmatrix} 0 & -\dfrac{1 - D_1}{L_1} \\ \dfrac{1 - D_1}{C_0} & -\dfrac{1}{R_0 C_0} \end{pmatrix} \begin{pmatrix} i_1 \\ v_0 \end{pmatrix} + \begin{pmatrix} \dfrac{1}{L_1} & 0 \\ 0 & -\dfrac{1}{C0} \end{pmatrix} \begin{pmatrix} v1 \\ i0 \end{pmatrix}$$

M_3: Boost's State-Space Average Simplified Matricial System

$$\begin{cases} \dfrac{V_0}{V_1} = \dfrac{1}{1 - D_1} \\ \dfrac{I_1}{I_0 + \dfrac{V_0}{R_0}} = \dfrac{1}{1 - D_1} \end{cases}$$

Eq. 9: Boost's Steady State Laws

Table 7: Boost's State-Space Average Model

Notice that the model fulfils the ideal Boost's conversion ratio and current gain description, demonstrated in *Dm. 1*. Given the proposed model, the output current would be the sum of the active load's current and the resistor's deviated current.

$$\begin{cases} M(D_1) = \frac{V_{out}}{V_{in}} = \frac{V_0}{V_1} = \frac{1}{1-D_1} \\ \frac{I_{out}}{I_{in}} = \frac{I_0 + \frac{V_0}{R_0}}{I_1} = 1 - D_1 \end{cases}$$

Dm. 1: Applied Boost's Ideal Conversion Ratio and Current Gain Description

- **Linearization**

As it has been previewed, the model needs to be linearized due to the requirements of Laplace's Principle of Superposition and transfer functions specs. Non-linear terms due to switching appear, such as $(1\text{-}D_1)\ v_0$ and $(1\text{-}D_1)\ i_1$.

To achieve this, each variable x will be divided into a steady state DC component ($\bar{x}$) and the small-signal AC fluctuation ($\tilde{x}$). All the variables' divisions are displayed in *Eq. 10.*

$$\begin{cases} i_1 = \overline{i_1} + \widetilde{i_1} \\ i_0 = \overline{i_0} + \widetilde{i_0} \\ v_1 = \overline{v_1} + \widetilde{v_1} \\ v_0 = \overline{v_0} + \widetilde{v_0} \\ D_1 = \overline{D_1} + \widetilde{D_1} \\ \dot{i_1} = \dot{\widetilde{i_1}} \\ \dot{v_0} = \dot{\widetilde{v_0}} \end{cases}$$

Eq. 10: Boost's Linearization: Division of Variables into DC and AC Components

Considering that the AC fluctuations are small, all the factors combining just small-signal AC values are considered zero. Plus, the steady state laws apply to the DC components.

Therefore, reapplying the steady-state laws in *Eq. 9* with the DC components, clearing out terms and substituting them in the average state-space system described in *Eq. 8*; as well as using the division of components just pictured in *Eq. 10*, will make some terms cancel each other.

In the model obtained, the terms multiplying the AC fluctuating components are now all constant (steady state DC components), solving the non-linearity problem.

The results are shown in *Table 8*.

$$\begin{cases} \dot{\widetilde{\imath_1}} = \dfrac{\widetilde{v_1} + \widetilde{D_1}\overline{v_0} - \widetilde{v_0}(1-\overline{D_1})}{L_1} \\ \dot{\widetilde{v_0}} = \dfrac{\widetilde{\imath_1}(1-\overline{D_1}) - \widetilde{D_1}\overline{\imath_1} - \dfrac{\widetilde{v_0}}{R_0} - \widetilde{\imath_0}}{C_0} \end{cases}$$

Eq. 11: Boost's Small-Signal Linear State-Space System

$$\begin{pmatrix} \dot{\widetilde{\imath_1}} \\ \dot{\widetilde{v_0}} \end{pmatrix} = \begin{pmatrix} 0 & -\frac{1-\overline{D_1}}{L_1} \\ \frac{1-\overline{D_1}}{C_0} & 0 \end{pmatrix} \begin{pmatrix} \widetilde{\imath_1} \\ \widetilde{v_0} \end{pmatrix} + \begin{pmatrix} \frac{1}{L_1} & 0 & \frac{\overline{v_0}}{L_1} \\ 0 & \frac{-1}{C_0} & \frac{-\overline{\imath_1}}{C_0} \end{pmatrix} \begin{pmatrix} \widetilde{v_1} \\ \widetilde{\imath_0} \\ \widetilde{D_1} \end{pmatrix}$$

M_4: Boost's Small-Signal Linear State-Space Simplified Matricial System

Table 8: Boost's Small-Signal Linear State-Space Model

- **Laplace Transformation**

As reasoned before; after obtaining a linear state-space system such as that of *Eq. 11*, the differential equations can now be turned into simple algebraic ones by changing from time to frequency domain through Laplace.

The AC time fluctuating components turn into proper s-domain variables since they do change and now will act accordingly with frequency. When differentiated over time an 's' factor appears.

Meanwhile, the DC components acting as factors are treated as numerical constants and remain the anchor points to which the system's values will have to be close to, for the dynamics to properly work (since the linearization is funded itself around the small variation of the AC fluctuations).

Therefore, keeping in mind *Eq. 1*, the component transformations will work as overviewed in *Table 9.*

AC	$\tilde{x}(t) \rightarrow X(s)$
DC × AC	$\bar{x}\tilde{y}(t) \rightarrow XY(s)$
Differential AC	$\tilde{z}(\dot{t}) \rightarrow sZ(s)$

Table 9: Boost's Laplace Transformation: Terms Linearization Summary

Finally, the transformation of the whole model into the frequency domain stands as *Eq. 12* system shows.

$$\begin{cases} sI_1(s) = \frac{V_1(s)+V_0D_1(s)-(1-D_1)V_0(s)}{L_1} \\ sV_0(s) = \frac{(1-D_1)I_1(s)-I_1D_1(s)-\frac{V0(s)}{R0}-I_0(s)}{C_0} \end{cases}$$

Eq. 12: Boost's Laplace Transformation into Frequency Domain

- **Transfer Function Obtention**

Since it is the output's voltage control the one researched, and as explained before due to the transfer function behavioral simplification through superposition, the rest of variables not desired to analyze (all those that are neither the states nor the duty cycle), will be neglected. That means that $I_0(s)$ and $V_1(s)$ will be considered zero.

Now the output voltage control transfer function $V_0(s)/D_1(s)$ can be obtained, since, *Eq. 12* has been transformed into a two-equation system with three variables: $V_0(s)$, $I_1(s)$ and $D_1(s)$ .Then again, by clearing out $I_1(s)$ in one of them and substituting said term in the other, and using and substituting I_1 through the steady-state laws, the transfer function can be, finally, determined.

After some easy simplification to leave the 's^2' term on its own, the Boost subsystem transfer function and the proper steady-state values are ready to be used for its output voltage control, as can be seen in *Table 10*.

$$\frac{V_0(s)}{D_1(s)} = \frac{-\frac{\frac{V_0}{R_0}+I_0}{C_0(1-D_1)}s + \frac{V_0(1-D_1)}{C_0L_1}}{s^2 + \frac{1}{C_0R_0}s + \frac{(1-D_1)^2}{C_0L_1}}$$

Eq. 13: Boost's Subsystem Voltage Control Transfer Function

$$\begin{cases} V_0 = \frac{V_1}{1-D_1} \\ I_1 = \frac{\frac{V_0}{R_0}+I_0}{1-D_1} \end{cases}$$

Eq. 14: Boost's Design Steady State DC Values

Table 10: Boost's Transfer Function Summary

As it is easily observed, the transfer function possesses a Right Half-Plane Zero (RHPZ). This means that the numerator's root, 's', is a positive real zero in this case.

This zero introduces a phase lag and a temporary "wrong way" response. A sudden increase in the duty cycle, which should cause the output voltage to rise, will instead initially cause the output voltage to dip before it starts rising. This is due to the capacitor having to supply on its own the load while the inductor is charging.

3.4.2 Buck Subsystem

Since this subsystem works as a simplification of the "Buck's behavior", to have a linear model a new voltage source must be considered and forced as a constant voltage source. That would be v_0, as explained before. It is obtained as $v_0 = D_1 v_1$, furthermore, being direct consequence of the Boost Subsystem procedure's steady-state results.

- **First Duty Cycle State-Space Modeling: MOSFET ON & Diode OFF**

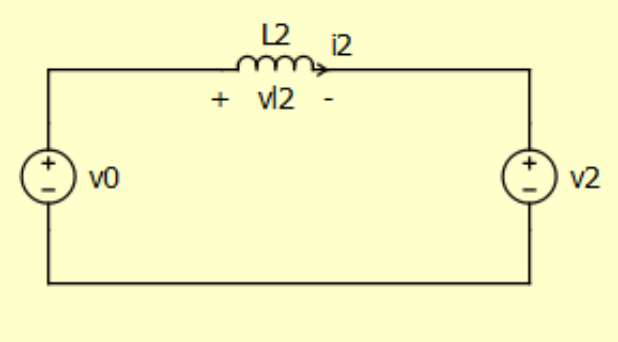


Figure 48: Buck's First Duty Cycle D_2 Scenario

In this first cycle, the input voltage v_0 charges the inductor L_2, which is the same as stating that, in the system, the capacitor would start discharging itself to charge the inductor (since it has been previously charged, the Buck converter does not act until then).

This sets the stage for the Buck converter's operation by charging the inductor, which acts as a temporary energy storage element, smoothing the current flow and enabling the voltage step-down function until reaching the desired v_2 and controlling the increased i_2.

Since the analysis is done the same way as in the Boost's subsystem analysis, but just with the inductor's current, only the important equations and results will be found in *Table 11*.

$$\dot{i_2} = \frac{v_{L_2}}{L_2}$$ *Eq. 15: Inductor's Current Definition (D2)*
$$v_{L_2} = v_0 - v_2$$ *Eq. 16: Kirchhoff's Voltage Law Application (D2)*
$$\dot{i_2} = \frac{v_0 - v_2}{L_2}$$ *Eq. 17: D2 State-Space Equation*

Table 11: Buck's First Duty Cycle D_2 State-Space Model

- **Second Duty Cycle State-Space Modeling: Diode ON & MOSFET OFF**

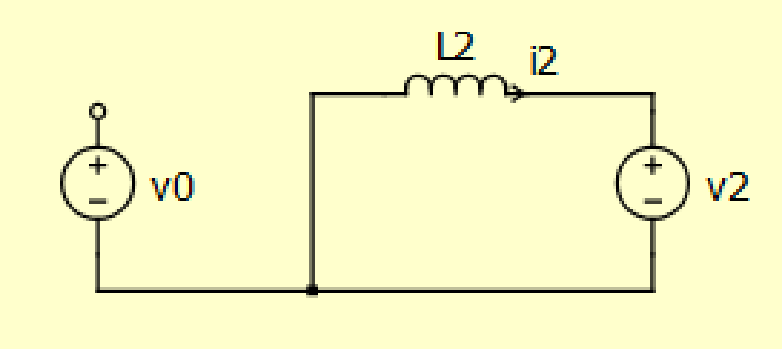


Figure 49: Buck's Second Duty Cycle D_2' Scenario

Here, the forced source v_0 does not transfer energy to the inductor, which in the system is the same as saying that the capacitor will not discharge its energy into the inductor L_2. That also means that the inductor will start to drop energy linearly, acting as the source for the load (the battery v_2).

This second duty cycle ensures that there is a continuous flow of power to the output load, even when the input is disconnected, allowing the converter to effectively step down the voltage.

The same analysis applied to the second duty cycle results in everything gathered in *Table 12*.

$$\dot{\imath_2} = \frac{v_{L_2}}{L_2}$$ *Eq. 18: Inductor's Current Definition (D2')*
$$v_{L_2} = -v_2$$ *Eq. 19: Kirchhoff's Voltage Law Application (D2')*
$$\dot{\imath_2} = \frac{-v_2}{L_2}$$ *Eq. 20: D2' Cycle State-Space System*

Table 12: Buck's Second Duty Cycle D_2' State-Space Model

- **State-Space Average Model**

Following the averaging process by doing the same as in the Boost subsystem analysis, the Average State-Space Model development results are shown in *Table 13*.

$$\dot{i_2} = \frac{-v_2 + D_2 v_0}{L_2}$$ *Eq. 21: Buck's State-Space Average Equation*
$$\frac{V_2}{V_0} = D_2$$ *Eq. 22: Buck's Steady State Law*

Table 13: Buck's State-Space Average Model

The same as during the Boost converter's average model analysis, the steady state law coincides with the ideal Buck converter's conversion ratio. In *Dm. 2* it is proven that the output voltage V_2 gets reduced by D_2 times the input voltage V_0.

$$M(D_2) = \frac{V_{out}}{V_{in}} = \frac{V_2}{V_0} = D_2$$

Dm. 2: Applied Buck's Ideal Conversion Ratio Description

- **Laplace Transformation**

As predicted the model is already linear, due to v_0 being imposed as a constant value. The only values that will change over time will be the duty cycle D_2, the "load" voltage v_2 and the desired control state/output, the inductor's current i_2.

Then the model is apt for the transformation into the frequency domain for the transfer function analysis.

The result is collected in *Eq. 23*.

$$sI_2(s) = \frac{-V_2(s) + V_0 D_2(s)}{L_2}$$

Eq. 23: Buck's Laplace Transformation into Frequency Domain

- **Transfer Function Obtention**

Due to having current control as the objective, the output/load voltage is considered a perturbation and ignored, again thanks to the superposition effect in transfer functions and the simplification it carries. Then again after applying this to *Eq. 23* the desired current control transfer function is easily obtained, also its design voltage DC value (obtained through the steady state law). All this is described next in *Table 14*.

$$\frac{I_2(s)}{D_2(s)} = \frac{V_0}{L_2 s}$$ *Eq. 24: Buck's Subsystem Current Control Transfer Function*
$$V_0 = \frac{V_2}{D_2}$$ *Eq. 25: Buck's Design Steady State DC Value*

Table 14: Buck's Transfer Function Summary

3.4.3 Transfer Functions Obtention: Conclusion & Overview

Now that both transfer functions have been obtained, the design of the PID Controllers for each converter can start.

Also, the fact that the Boost converter acts first becomes of great importance, as the Buck's control will have way less repercussion.

The bigger analysis complexity due to the sterner Boost converter's non-linear behavior is what really marks the path for the design layer.

Said step, after closing this chapter with the summary made in *Table 15*, is now ready to be taken.

Boost's Subsystem Voltage Control Transfer Function	$\frac{V_0(s)}{D_1(s)} = \frac{-\frac{\frac{V_0}{R_0}+I_0}{C_0(1-D_1)}s + \frac{V_0(1-D_1)}{C_0L_1}}{s^2 + \frac{1}{C_0R_0}s + \frac{(1-D_1)^2}{C_0L_1}}$
Boost's Design Steady State DC Values	$\begin{cases} V_0 = \frac{V_1}{1-D_1} \\ I_1 = \frac{\frac{V_0}{R_0}+I_0}{1-D_1} \end{cases}$
Buck's Subsystem Current Control Transfer Function	$\frac{I_2(s)}{D_2(s)} = \frac{V_0}{L_2 s}$
Buck's Design Steady State DC Value	$V_0 = \frac{V_2}{D_2}$

Table 15: Subsystems Transfer Functions Summary

4. DESIGN OF CONTROLLERS

4.1 Software Choice

To choose the controllers' parameters bound to be used, open and close-loop analysis are the options to work with. Within the open-loop it is possible to analyze the Bode diagram whereas in the closed-loop it is possible to try different techniques, manually or with diverse kinds of software.

In this case MATLAB was chosen due to possessing some of its own functions -which are destined exclusively for tuning- and being one of the programming software studied and promoted by many universities. The multi-domain system and its easy interface, added to the experience granted by this degree's studies, make it an easy choice. Plus, it is easy to link to Block Diagram Analysis, if required, via its own Simulink, or to the PLECS block diagram library add-on.

4.2 Controllers Development Working Point (WP)

To do this, a need arises to choose a Working point for the development of said controllers. In this case, $Vgen = 12\,V$ and $IL2ref = 10\,A$ have been chosen. Also, for the nominal average Boost duty cycle value, $D0 = 0.5$ was chosen. Consequently, $V0out$ and $I0out$ with the respective hypothetical values depending on a hypothetical Steady-State analysis with $D0$: $V0out = 24\,V$ and $I0out = 5\,A$.

L, C and R are the values chosen to set the physical circuit:

$$R = 1\,\Omega,\ L = 1\,mHr \text{ and } C = 0.1\,mF.$$

R should be higher to minimize the loss of power, but with PID controllers there is a lack of robustness if a better approximation than this one is studied. This will be better addressed in the respective section at the end of the report.

4.3 Boost Converter PID Controller Design

Given the nature of the Boost converter dynamic and the linearization bound to execute, it is already predictable that it will not be as smooth as the Buck's response.

The MATLAB code and its response for the Boost converter adjustments will be displayed in *Figure* 50. The response to its code is showcased in *Figure* 51, *Figure* 52 and *Figure* 53.

```
D0 = 0.5;         % Nominal duty cycle
Vout0 = 24;       % Hypothesis: Vout0----->(Vgen/D0) Vgen=12 V
Iout0 = 5;        % Hypothesis: Iout0----->(IL2ref*D0) IL2ref=10 A
L = 1e-3;
C = 1e-4;
R = 1;

num_boost = [-((Vout0/R) + Iout0) / (C * (1-D0)), Vout0 * (1 - D0) / (L * C)];
den_boost = [1, 1/(R * C), ((1 - D0)^2) / (L * C)];
G_boost = tf(num_boost, den_boost);

disp('Boost Converter transfer function');
G_boost
bode(G_boost)
rlocus(G_boost);
grid on;
title('Root Locus of the Transfer Function');

[PID_boost, info_boost] = pidtune(G_boost, 'PID');

disp('PID Controller Parameters');
Kp_boost = PID_boost.Kp
Ki_boost = PID_boost.Ki
Kd_boost = PID_boost.Kd

disp(info_boost);

T_boost = feedback(G_boost * PID_boost, 1);

t = 0:0.001:0.1;
step(T_boost, t);
title('Closed Loop step response with PID controller');
xlabel('Time (s)');
ylabel('Output Voltage (V)');

```

Figure 50: MATLAB's Boost Converter PID Controller Design Code

```
Boost Converter transfer function
G_boost =

    -580000 s + 1.2e08
  ----------------------
  s^2 + 10000 s + 2.5e06

Continuous-time transfer function.
Model Properties
```

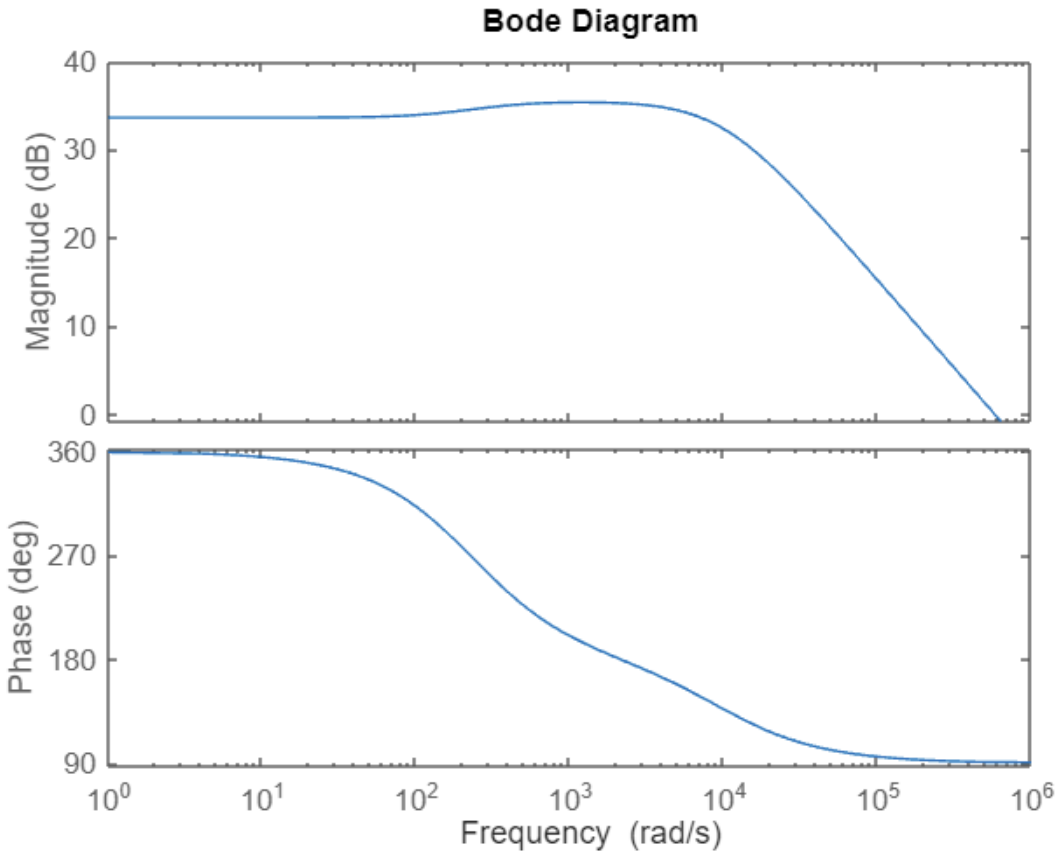
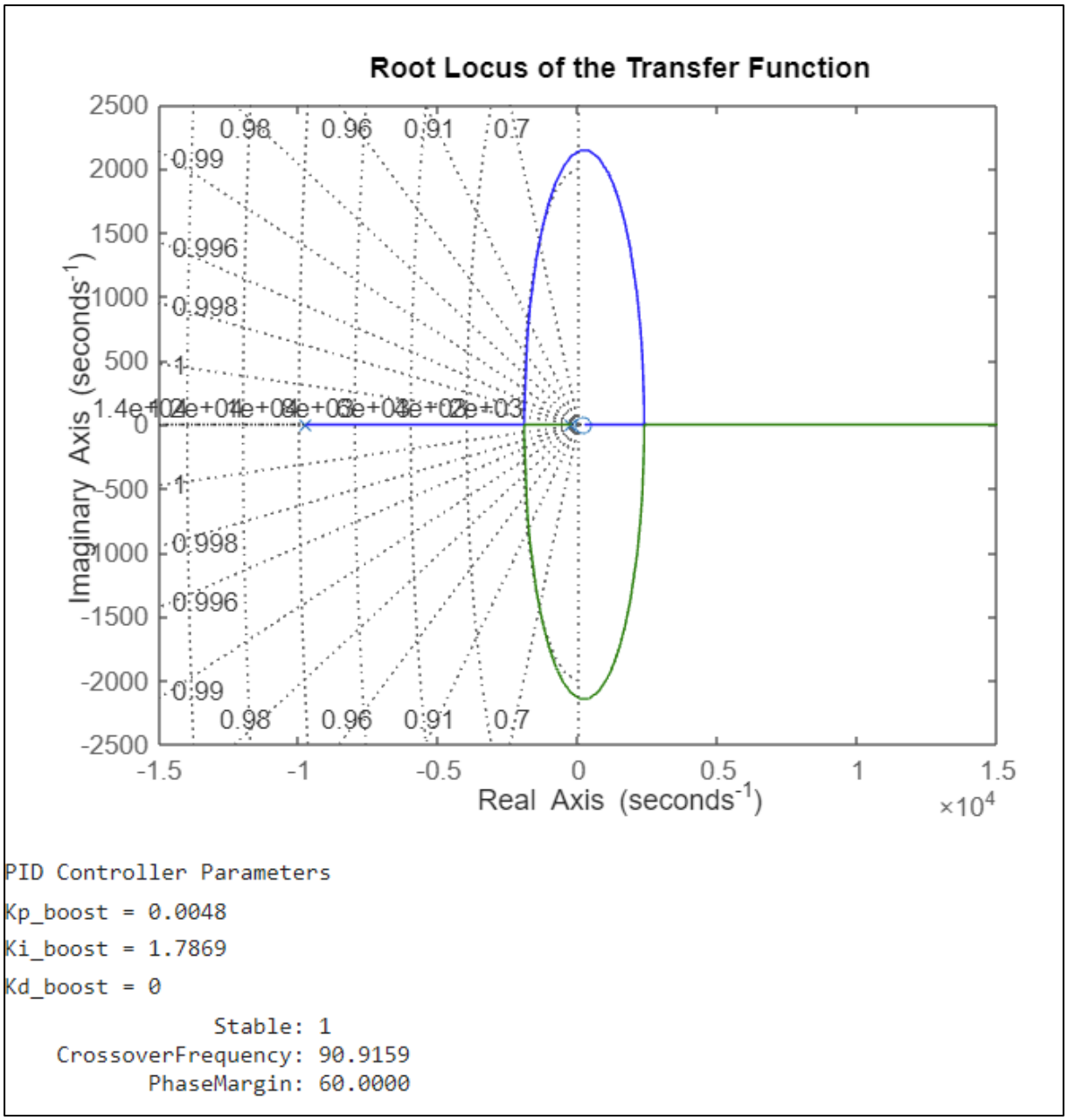


Figure 51: MATLAB's Boost Converter PID Controller Design Response (1)




```
PID Controller Parameters
Kp_boost = 0.0048
Ki_boost = 1.7869
Kd_boost = 0

               Stable: 1
   CrossoverFrequency: 90.9159
          PhaseMargin: 60.0000
```

Figure 52: MATLAB's Boost Converter PID Controller Design Response (2)

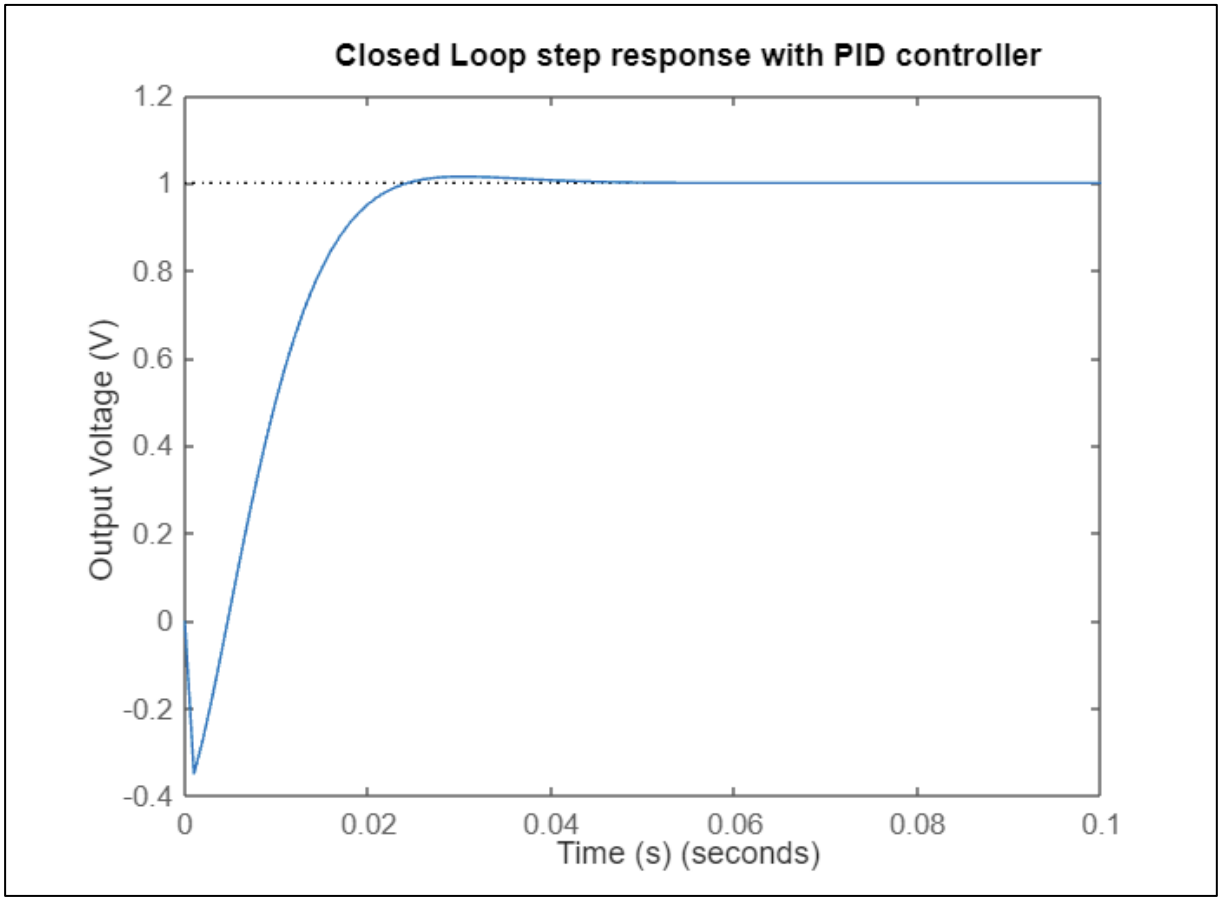


Figure 53: MATLAB's Boost Converter PID Controller Design Response (3)

By mere observation it is sure that the closed loop step response (seen in *Figure* 53) works just fine and takes just around 0.04 seconds to stabilize.

It is worth noticing that the mentioned infamous RHPZ effect is observed. At first, the response dips into negative voltage for an instant, but it is corrected soon enough.

The RHPZ can be appreciated as well in the root locus in *Figure* 52.

The Bode diagram in *Figure* 51 clearly reassures this zero's effect: The phase plot drops continuously, introducing a phase lag where the output signal V_0 reaches its peak after the input signal D_1. In essence, the output lags behind the input in time and that is the reason behind the drop of V_0 before increasing to the desired value.

Also notice the Phase Margin as high as 60º is considered ideal because it is large enough to ensure stability and provides a good transient response with minimal overshoot and ringing. A smaller phase margin (such as 30°) would lead to a system that is more oscillatory, while a larger one (close to 90°) might be too damped and slow.

Meanwhile the magnitude plot describes the system's gain across different frequencies. It reveals the DC gain, the system's bandwidth and any resonant peaks, which indicate how much the system amplifies or attenuates signals. For instance, between 10^3 and 10^4 $rad/_s$, the maximum gain of V_0 is obtained.

The bandwidth is the frequency at which the magnitude plot drops by 3 dB from its flat, low-frequency value and it indicates how fast the system responds. A higher bandwidth can end up with instability issues (specially with RHPZs). In this case it will be also between 10^3 and $10^4\ {rad}/{s}$.

This short analysis reaffirms the observational conclusion. The system Closed Loop step response is good enough. Then again, as shown in *Figure* 52, the Boost Converter's PID Controller Parameters chosen are:

Kp_Boost = 0.0049

Ki_Boost = 1.7956

Kd_Boost = 0

4.4 Buck Converter PID Controller Design

The Buck converter is designed after the Boost is already sorted out (since it uses $V0$ as a constant input, the Buck's adjustments depend on the work beforementioned). The values were obtained in a more effortless way, by trial and error (obtention of Ku and Tu) and implementing Ziegler-Nichols in MATLAB.

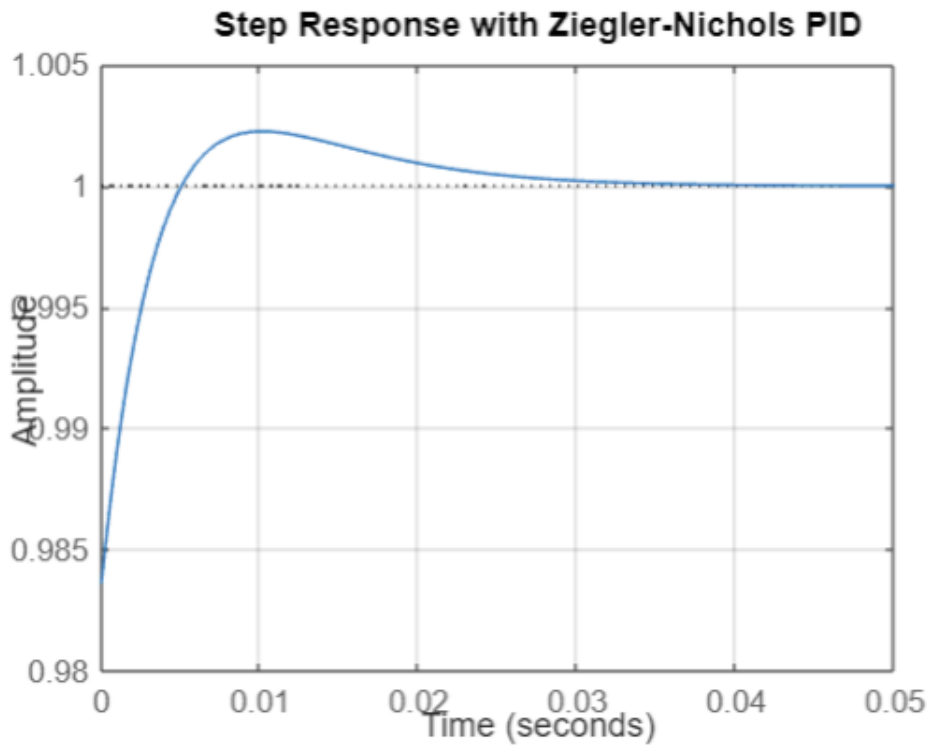
As a result of this, the values for Ku and Tu were chosen at will so the result was as fast, steady and stable as possible by trial and error. Resulting in the $Ku = 1.666666667$ and $Tu = 0.02$ assumptions.

After this choice, implementing the Ziegler-Nichols method is automatic and gives a decent solution for the Buck converter controller design, as shown in the next MATLAB code in *Figure* 54 and its response in *Figure* 55.

```
V0 = 24;  % Input voltage
L2 = 1e-3; % Inductor (H)

% Define transfer function G(s)
s = tf('s');
G = V0/(L2*s);

% Assume Ku and Tu
Ku = 1.666666667;
Tu = 0.02;

% Compute PID gains using Ziegler-Nichols
Kp = 0.6 * Ku
Ki = 2 * Kp / Tu
Kd = Kp * Tu / 8

% Define the PID controller
C = Kp + Ki/s + Kd * s;

% Closed-loop system
T = feedback(C * G, 1);

% Step response of tuned PID controller
figure;
step(T), grid on, title('Step Response with Ziegler-Nichols PID')

% Performance metrics
info = stepinfo(T);
disp(info)

```

Figure 54: MATLAB's Buck Converter PID Controller Design Code

```
Kp = 1.0000
Ki = 100.0002
Kd = 0.0025
```




```
     RiseTime: 0
TransientTime: 0.0271
 SettlingTime: 0
  SettlingMin: 0.9836
  SettlingMax: 1.0022
    Overshoot: 0.2243
   Undershoot: 0
         Peak: 1.0022
     PeakTime: 0.0101
```

Figure 55: MATLAB's Buck Converter PID Controller Design Response

By simple observation, what was predicted is now confirmed: The control works swiftly, without the RHPZ's dip, and stabilizes the response without much problem - and way faster than the Boost does -.

In conclusion, the Buck Converter's PID Controller Parameters chosen are:

Kp_Buck = 1

Ki_Buck = 100

Kd_Buck = 0.0025

4.5 Design of Controllers: Conclusion and Overview

With the controllers' parameters already determined and confirming the preemptive suspicion of the Boost being the most difficult to control, the assumption of it being as well the main factor of change in this system is basically confirmed.

The next layer of development, the system's circuit implementation, is finally ready to start. With all the parameters finally determined, it will also be ready for simulations and analysis.

The summary of the parameters is shown in *Table 16*.

Controller Parameter	Boost Converter	Buck Converter
Kp	***0.0049***	***1***
Ki	***1.7956***	***100***
Kd	***0***	***0.0025***

Table 16: PID Controllers Parameters Summary

5. CIRCUIT IMPLEMENTATION

5.1 Software Choice

After the theoretical design, the whole circuit's general design implementation was translated into a PLECS implementation.

This software by Plexim was chosen because of its high focus on power electronics and easy to learn PWL simulation, which is optimal for circuits with converters since it grants robustness and speed.

Plus, the wide range of blocks and options and the interface make the program easy to use and make the learning curve way less pronounced for undergraduate engineers with basic knowledge. This way the latter simulation will be as well easier.

5.2 Whole Circuit General Design

The resulting implementation for both the mere design and the subsequent analysis stands as *Figure 56* shows.

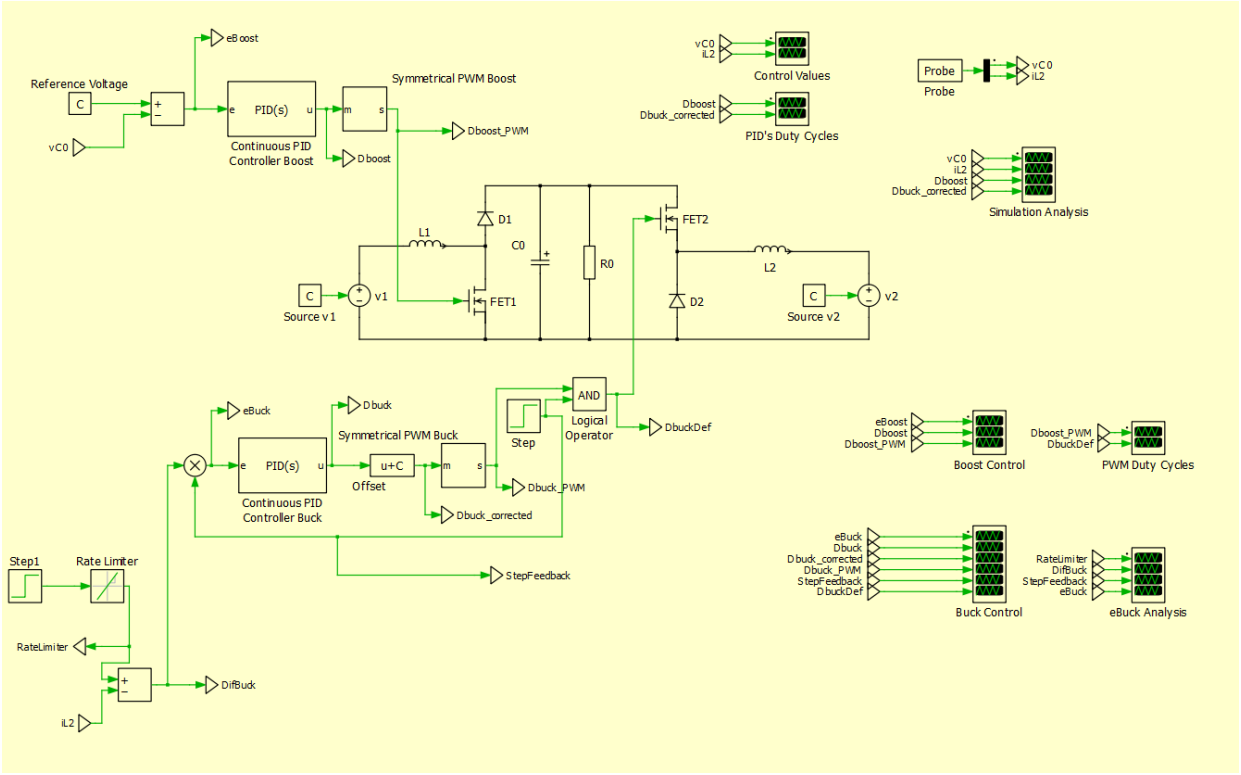


Figure 56: PLECS Whole Circuit General Design

5.3 Boost Subsystem Control

Please note that indexation is not used going forward to be consistent with the design variables in PLECS and MATLAB. This was necessary as PLECS does not seem to support this feature.

The *Boost converter* is controlled by the output voltage *V0* in *C0*. This way the reference voltage *V0ref* is the only one needed to be introduced.

Since at the start the analysis power flux is read from left to right, the *Boost converter*'s *PID controller* just needs to act accordingly. The rest of the flags via "*Goto"* (*eBoost*, *DBoost* and *DBoost_PWM*) are used for the analysis of the *Boost*'s behavior and to keep track of how each element acts to see If the desired effect takes place or not. This remains effective during and after design (implementation and simulation stage).

Said design can be seen in *Figure* 57.

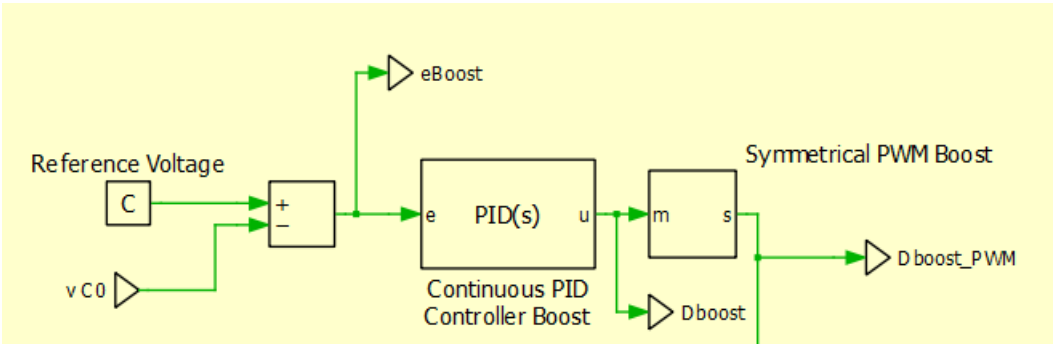


Figure 57: PLECS Boost's Side Design

vC0 (which holds said value in real time) comes through a "*From"* that originates from the Probe keeping check at the capacitor's voltage. It connects through a "*Goto"*. The "*Goto/From"* linking has been widely used as seen in the design to keep things at check, flagging and debugging purposes and clarity of design.

DBoost_PWM is the designed final duty cycle that acts as control input in the *MOSFET FET1*. Being already compensated by the Boost's action to follow *V0* and generate the average value by "pulsating" and turning on or off that segment of the circuit (acting as a switch combined with the *Diode D1*).

The *MOSFETs* and *Diodes*, as stated earlier, work as ideal control elements with no internal resistance whatsoever.

5.4 Buck Subsystem Control

The *iL2* control value for the Buck's current control mode has also been designed this way in the exact same Probe as the Boost's *vC0* (*Figure* 58).

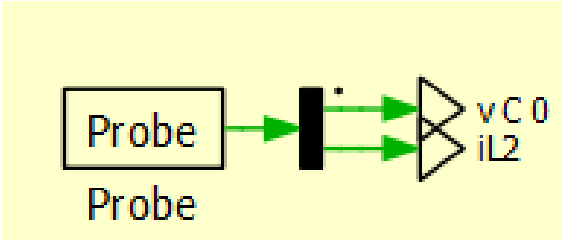


Figure 58: PLECS Control Probe

On the other hand, *the Buck converter* control design (*Figure* 59) will be of higher complexity, given the fact that the transfer function already depends on the Steady-State average of the value controlled by the Boost (vC0). Since the control is, then, cascaded, the real implementation analysis is not exactly just assigning the Buck transfer function obtained beforehand. For it to work there is an imperative wait (a lapse in the time of action) to be forced, which ensures the capacitor is fully charged before control of the Buck converter begins.

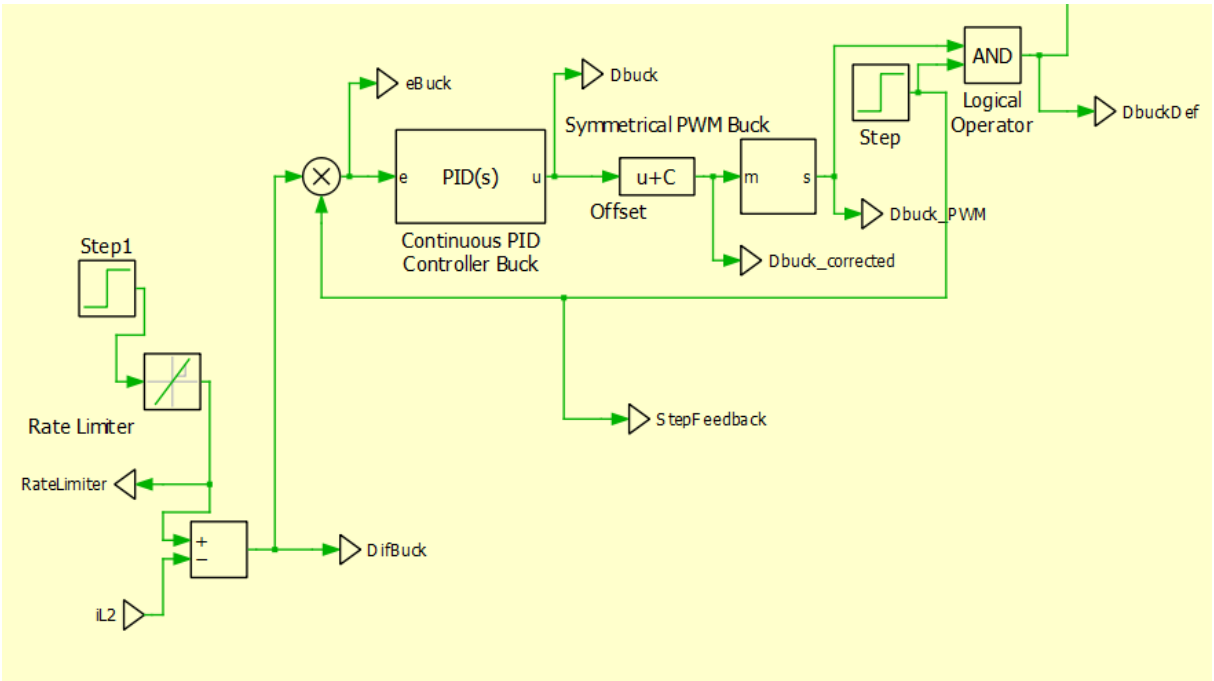


Figure 59: PLECS Buck's Side Design

5.5 Systems' Working Periods

Because of the *Buck converter*'s design, a division of the analysis and functionality of the circuit in 3 periods has been made. They stand as follows in *Table 17*.

Period	Time Interval	Functionality Description
First Period	0 - 0.1 s	The charge of *C0* until *vC0* reaches *V0ref*.
Second Period	0.1 - 0.2 s	The subsequent control of *iL2* until *I2Ref* is achieved.
Third Period	0.2 s onwards	*iL2* is forced to increase to twice the value of *IL2ref*.

Table 17: Working Periods Definition

This was all implemented by using *Step1* and *Step* with different time triggers.

With *Step*'s time trigger being 0.1 s and with help of the '*AND'* logical operator it is ensured that until the time trigger is not activated, the duty cycle of the Buck's *MOSFET* (the signal *DBuckDef*) will be zero.

Simultaneously, *Step* ensures -in the same lapse of 0.1 seconds- that the signal *eBuck* will be null through action of the *Product1* block (*Figure 61*). This means the entry to the *Buck's PID controller* will be null until the first period is finished, understandably so, when the capacitor *C0* is fully charged. These blocks' parameters can be seen in *Figure 60* and *Figure 62*

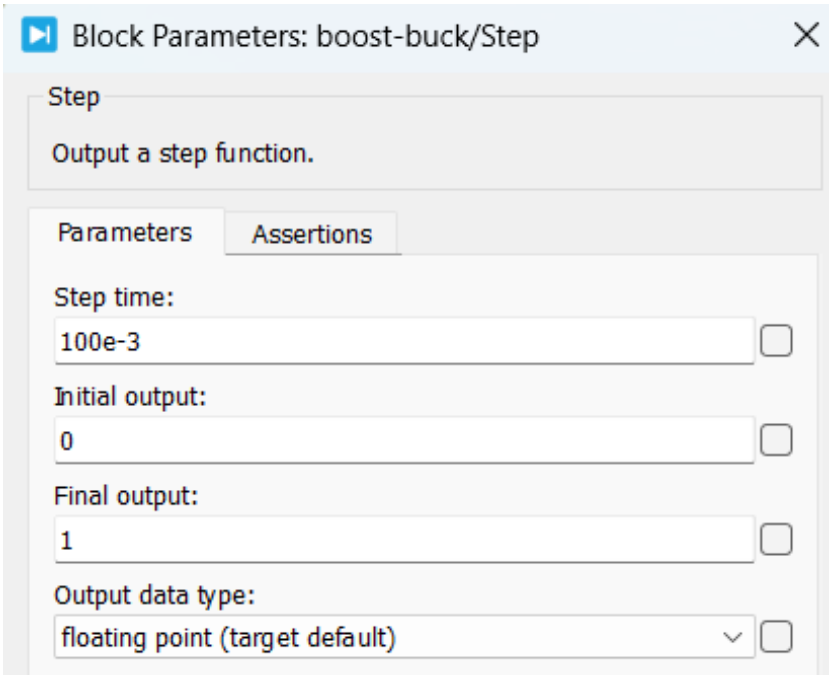


Figure 60: Step's Block Parameters

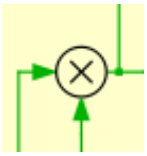


Figure 61: Product1's Block Diagram

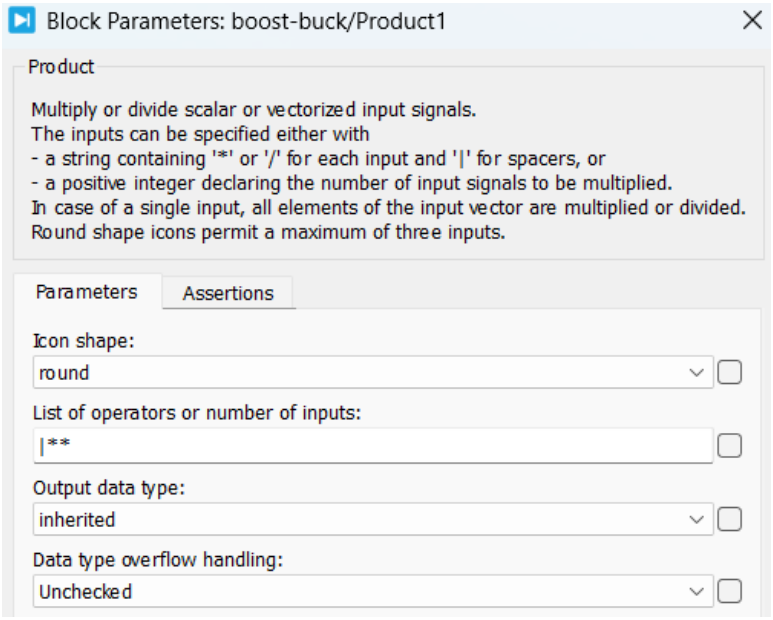


Figure 62: Product1's Block Parameters

Meanwhile *Step1* acts as a differentiator between the second and third periods, with 0.2 seconds being the *Step* time trigger and changing between the desired values *iL2* has to follow (*IL2Ref* in the second period and twice the same value in the third period). It is compared since the beginning of the simulation with *iL2*, but thanks to the *Step* block (as explained before) it only influences the PID from 0.1 seconds onwards. Its parameters are shown in *Figure 63*.

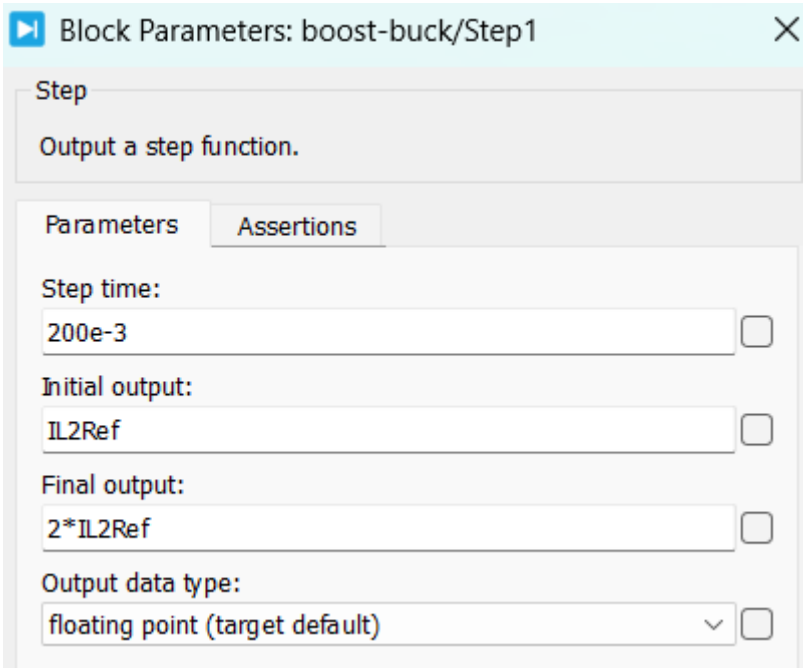


Figure 63: Step1's Block Parameters

The *Rate Limiter* following *Step1* makes the simulation more realistic, since it makes the step act progressively instead of being an abrupt and instant jump of values, with a rising rate limit of one thousand (*Figure 64*).

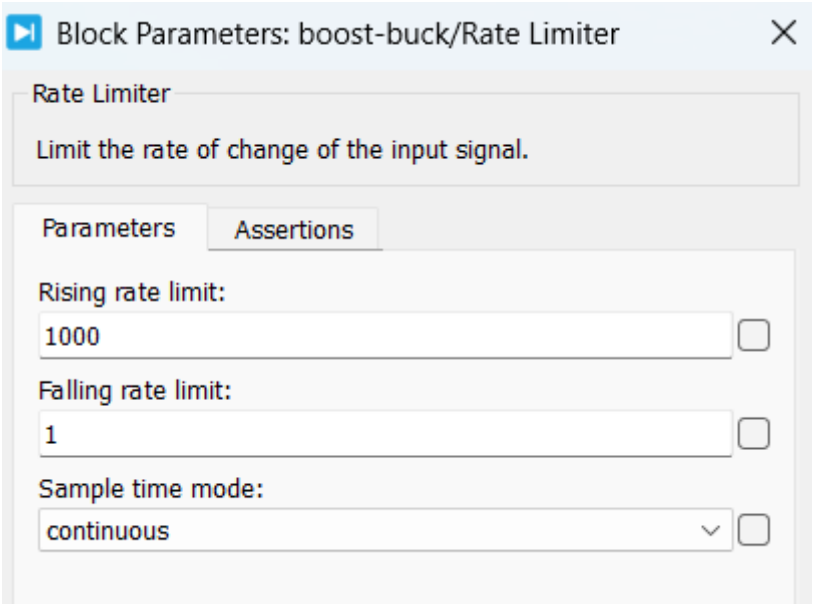


Figure 64: Rate Limiter's Block Parameters

In this way, a more accurate view of how the system would react has been achieved and comparing it to working ranges of potential batteries for a hypothetical prototype has become possible.

5.6 Duty Cycles Adjustments

Meanwhile, the *Offset* block is always adding a constant value of $Vgen/V0$, which is the value of the Boost's steady-state duty cycle. Through this adjustment, seen in *Figure 65*, continuity between both duty cycles *PWMs* is guaranteed.

This is a must, since the *Buck converter*'s *PWM* needs to have a constant value close to that of the Boost's duty cycle when the capacitor is fully charged, if meant to work properly.

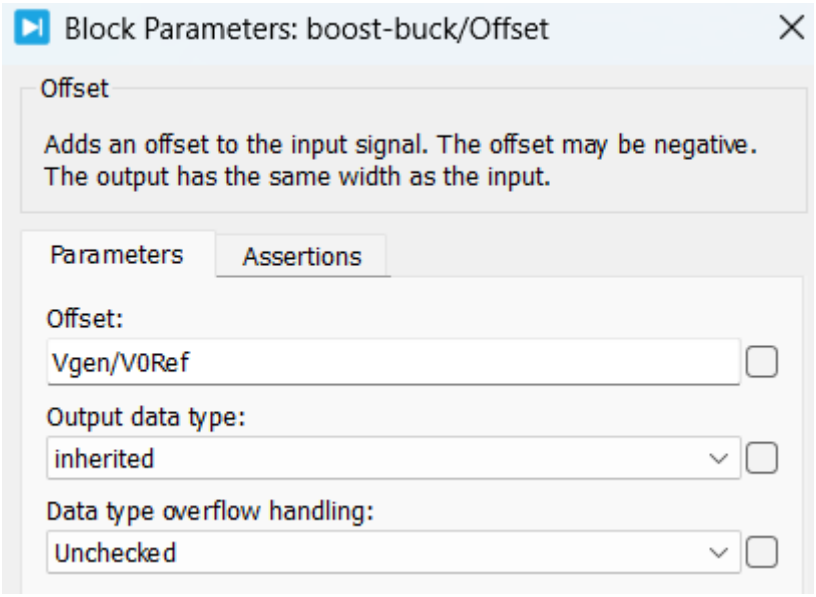


Figure 65: Offset's Block Parameters

To obtain it, the *saturation limits* of the *Buck*'s *PID controller* were set between -0.5 and 0.5. The motivating reasoning being that the maximum obtained would theoretically be 1.0 after adding the offset, since in this case in the Steady State value of the duty cycle when the capacitor is fully charged would be 0.5. Achieving a desirable working range of the *Buck*'s duty cycle between 0 and 1, approximately.

Also, an *Anti-Windup Method* (*Conditional Integration*) is added within each controller – check *Figure 66* -. As it stands, improving the dynamic of the controller, regulating the integrative function.

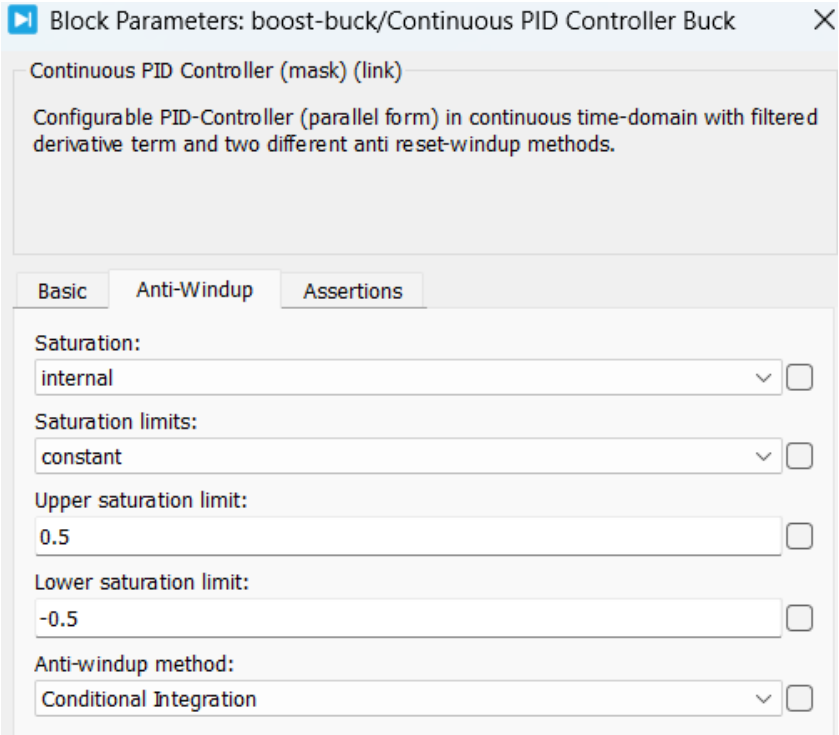


Figure 66: Buck's Anti-Windup Block Parameters

Having corrected the duty cycle for the *Buck converter's PWM* to act, it is also worth noting that its signal is not null during the first period, due to the offset being constant. This makes it imperative to ensure that the *PWM*'s exit during this first period turns zero before entering the *MOSFET*.

This way it will work as intended and make both duty cycles work with a similar average value, yet only acting when the capacitor is fully charged.

Then again, this is perfectly achieved by the combination of the *Step* block and the "*AND*" logical gate (as explained before).

Given that all the system's actions have been already explained, now some more technical details will be given. Most of them regarding the simulation, the flagging and debugging method approached to build and to understand the way the system acts and, finally, to test the working points and its influence afterwards.

The Scope named *Control Values* (*Figure 67*) will display the real time output voltage *v0* and *iL2* current and will be used to check the simulations' functioning and to compare the validity of the controllers and working points.

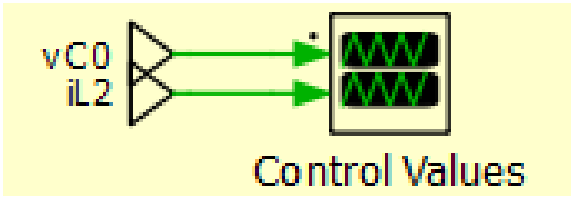


Figure 67: Control Values

The *PWMs*' frequencies are used to get a quicker simulation or a slower one, controlling the duty cycle and the saturation and managing to get the desired outcome, they are set like *Figure 68* and *Figure 69* show. The higher the frequency, the lower the passive elements needed to guarantee CCM. However, as they rise, the bandwidth can be surpassed easily, and instability can be reached.

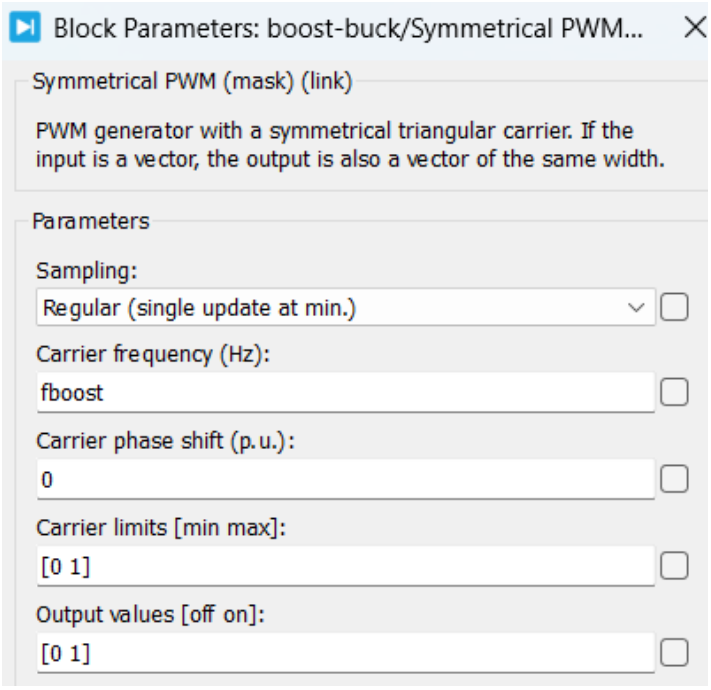


Figure 68: Boost Symmetrical PWM's Block Parameters

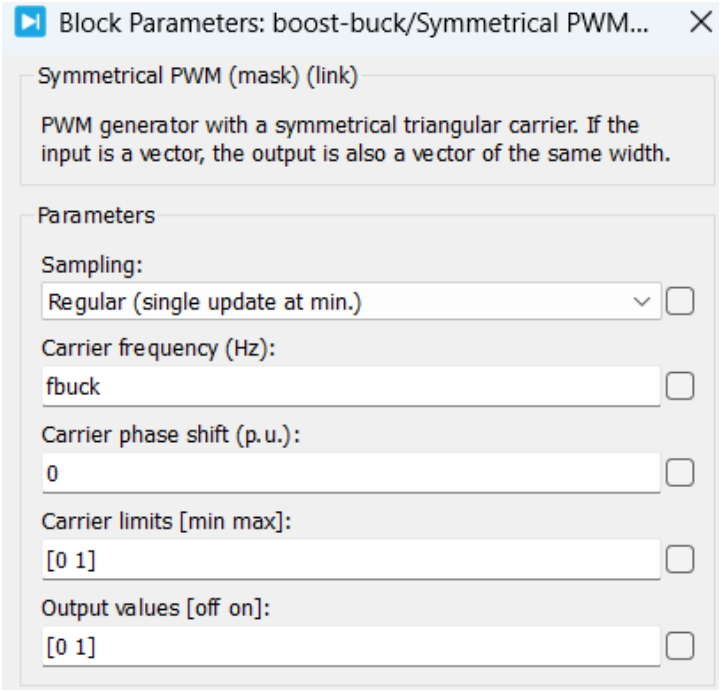


Figure 69: Buck Symmetrical PWM's Block Parameters

5.7 Initialization Parameters & Values

The physical parameters chosen to design the circuit are *R0*, *L1* and *L2* (values assigned to *L*), *C0*, *Source v1* and *Source v2* (assigned the value *Vgen*). The values are entered as *Simulation Parameters*, in the *Model Initialization Commands* section that can be seen in *Figure 70*. This way, each time a new working point or change in a simulation is needed, all of them are subject to control at the same time and are easily accessible and comfortably organized.

Model initialization commands

```
1  Vgen=12
2  IL2Ref=10
3  V0Ref=24
4  L=1e-3
5  C0=1e-4
6  R0=1
7  fbuck=1e6
8  fboost=1e6
9  kpboost=0.0049
10 kiboost=1.7956
11 kdboost=0
12 kpbuck=1
13 kibuck=100
14 kdbuck=0.0025
15
```

Figure 70: PLECS Designed WP Model Initialization Commands

The WP of the controllers chosen after the earlier parameters have been selected, would solely depend on the values given to the output voltage as reference (*V0ref*) and the *L2* current reference (*IL2ref*). It is considered important enough to recall that the value *V0ref* depends on *Vgen* (as stated in the *Design of Controllers* section). Therefore, the control values of each converter.

6. SIMULATION ANALYSIS

6.1 Software Choice

Continuing with the previous chapter's statement, PLECS has been chosen to run the simulations as well. Its way of implementing scopes and the high control of switching devices makes it a great simulation tool for Power Electronics applications, such as this case.

6.2 Simulations Nature & Objective

In these simulations a different arrange of WPs within the system parameters previously determined will be trialed.

By changing only *Vgen and IL2Ref* in the model initialization parameters, running simulations and discussing their results, an array of different batteries and currents that make the system work (forcing *v0 to always* follow $V0Ref = 24V$) will be determined.

Thus, obtaining the working conditions that grant the desired behavior and working periods for the designed controllers. Ultimately, learning how flexible this particular design really is, given all the conditions and circumstances.

Logically proceeding, by making the appropriate changes in the initialization parameters (*Figure 71*) in PLECS and running the simulation (clicking *"Start"* or combining *"Ctrl+T"* on the keyboard, like *Figure 72* pictures) the "*Scope*" block designed (*Figure 73*) will grant the results posed to discuss.

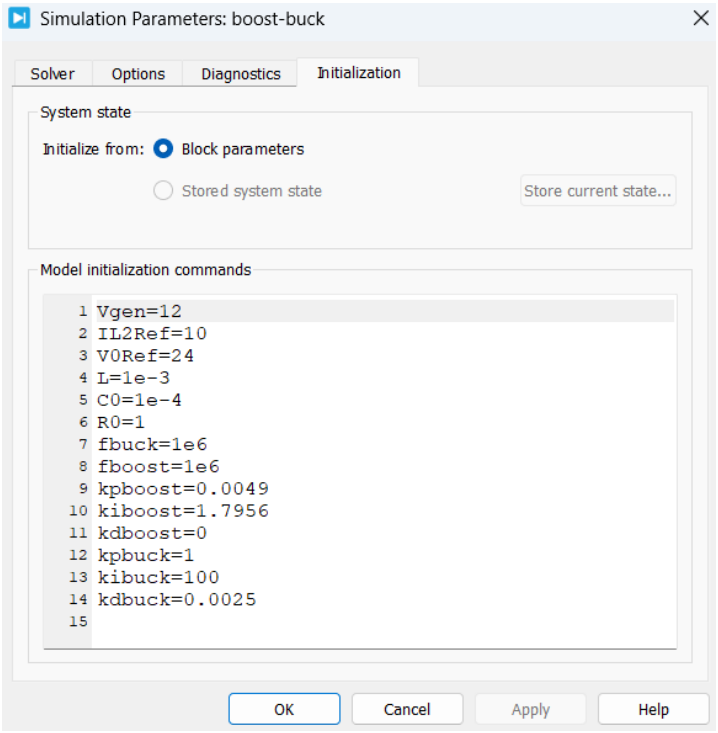


Figure 71: Model Initialization: Design's WP Example

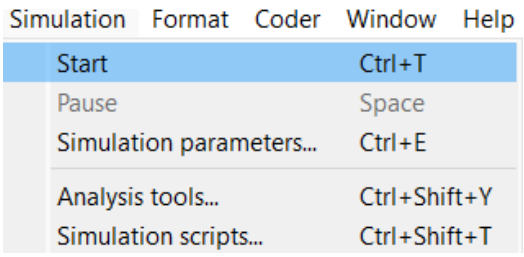


Figure 72: PLECS Simulation Display

By comparing these results, it will be possible to decide which intervals are valid for our system.

The comparison will be done by acknowledging a recognizable behavior regarding the three periods of work expected. Also, a quick and stable response, without many overshoots or way too big spikes, are some important factors to consider.

The final objective is for some intervals to be given and guarantee having acceptable control and behavior of the designed circuit through action of the previously chosen controllers. This way, a different arrange of batteries can be analyzed and guaranteed to work in the conditions researched with the designed controllers and physical parameters.

Regarding the considerations taken to determine whether adequate or not, it is understood that they all work in a reasonable, brief amount of time, stabilizing the response and turning it into what it is intended to be in each period.

6.3 Implementation and Considerations for Simulation Results Processing

The *Scope* block designed (*Figure 73*), processes and shows the results for both duty cycles, *D1* and the corrected *D2,* and the real-time control objective values: The capacitor's voltage *V0* and the inductor's current *iL2*. The graphics will show the evolution of these four variables from start to finish.

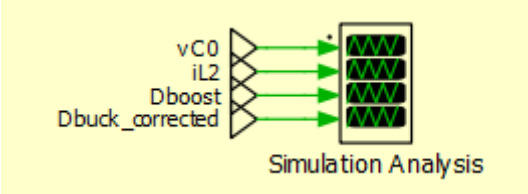


Figure 73: Simulation Analysis Scope

Back in *Figure 71*, it could be seen that the frequencies chosen for both *PWM*s are equal to $10^6\ Hz$ and this is due to various reasons: First, because it is way bigger than the Boost converter's bandwidth, which is great because the bigger the frequency the more the time switching period T_S reduces and the less it deviates from the averaging and small-signal approach. The second reason being that, as stated before in the PWMs design, it reduces the passive elements magnitudes - thus, size -, which is better for physical-layer design.

Also, even if these facts had not been clarified, experimentally it is a usual go-to value for these kinds of circuits and clearly works way better when you approach these values, as way higher frequencies do not even start the simulation (way too low T_S values) and lower present way too big ripples and are unstable.

Regarding the duty cycles shown and analyzed, the Boost converter always shows values from 0 to 1. Meanwhile, the Buck converter produces an "*offset corrected"* pre-*PWM* duty cycle, which is the one being analyzed in the next graphs).

This is due to the system's forced control nature of the Buck converter, as explained in the respective section, thus, these graphs could show duty cycle values higher than 1 and lower than 0, which is physically impossible.

However, this is not a problem with this design since the *PWM* placed after this signal's being evaluated cuts down the limits from 0 to 1 (can be rechecked in *Figure 68* and *Figure 69*), canceling these kinds of errors.

Taking this into consideration, the analysis can still be done regardless, by just analyzing the stability of the duty cycles after any disturbance and their behavioral aspects: For instance, if their signal rise the MOSFET will be 'ON' more than before, so the first period subsystem's behavior is being favored, and vice versa.

6.4 WP Simulations & Work Intervals Search: Results and Discussion

6.4.1 WP Simulation Analysis

- ***WP1 (Vgen=12 V, IL2ref=10 A)***

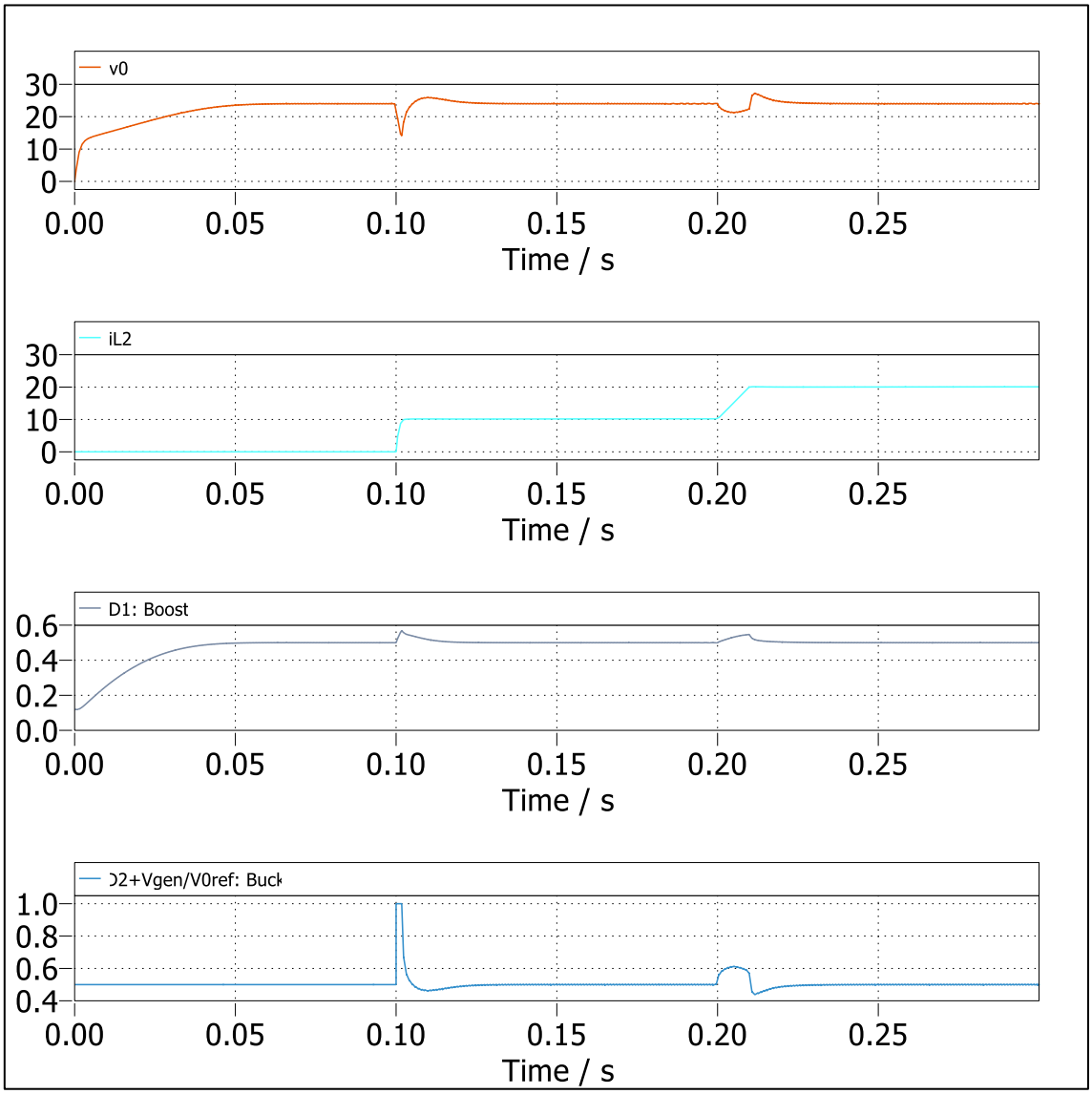


Figure 74: WP1 Control Analysis Graphs

The starting point will be this WP in which the controller was designed.

Given *Figure 74*, it works swiftly and how it was intended. It exhibits high tracking accuracy and robust disturbance rejection, resulting in a relatively fast response very close to the reference. The system demonstrates a stable and well-damped response, with minimal fluctuations due to disturbances, achieving the target behavior.

Regarding the duty cycles behavior, they both follow the boost's DC component design value $D_1 = 0.5$ (imposed in D_2 through the offset) and deviate in every period change but return quickly to the original DC value, balancing the system quite effectively.

The boost converter's duty cycle behaves very differently in each period. In the second, there is a sudden, aggressive jump to quickly overcome the buck's action, followed by a swift drop. In contrast, the third period shows a swifter start and an abrupt yet natural return (because the buck converter is already active and has more workload this time).

Translation into the physical layer varies as well, for instance, in the first transition, the boost converter clearly discharges more of the capacitor's energy into the load, and with the buck's MOSFET open into the inductor L_2. Next it rapidly reaches the desired *IL2Ref* and corrects the duty cycle to keep them both balanced.

Meanwhile, in the second one it has already settled *IL2Ref* for the first time, so now it just needs to double it. Notice how this is easier due to both converter's behaviors having already been balanced beforehand. Thus, this change in system dynamics is not so brusque.

Now, an increase in *Vgen* will be taken to see how the system's behavioral reaction develops.

- ***WP2 (Vgen=26 V, IL2ref=10 A)***

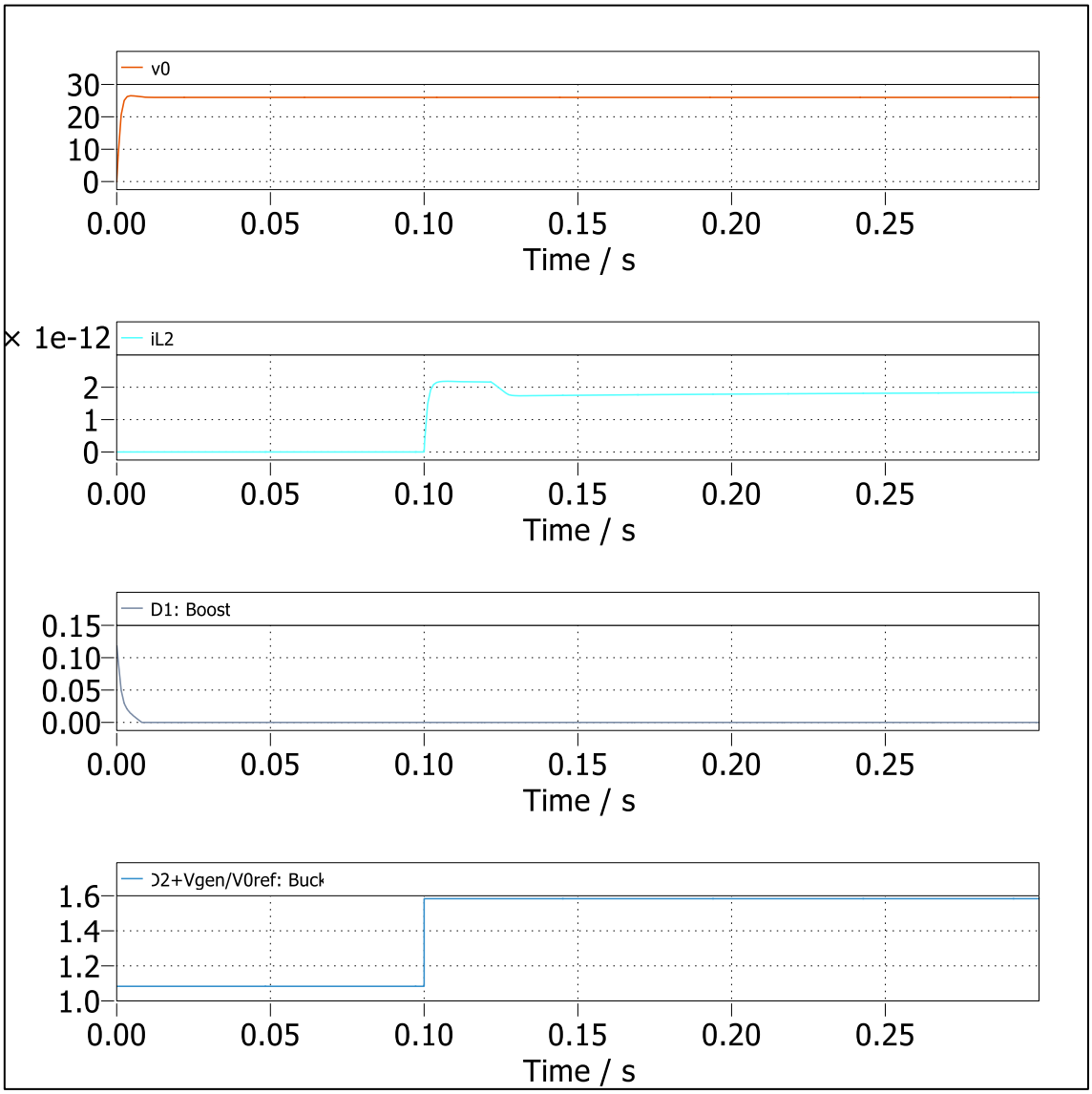


Figure 75: WP2 Control Analysis Graphs

In *Figure 75* it is easily noticeable that this does not work at all. It even makes the inductor current *IL2* drop to practically zero (amps are in the 10^{-12} range).

Furthermore, the duty cycles make no sense. The boost's D_1 is, basically all the time, null: The MOSFET's always closed, so the inductor does not get much charge and is constantly trying to supply the capacitor, to clearly almost no avail.

Theoretically speaking, a duty cycle higher than the unit would mean it is not a Boost converter anymore (as $v0 = V0Ref = 24V$ would be lower than $Vgen = 26V$).

Therefore, *Vgen*'s value will be lower than 24 and reduced unitarily in the next experiments.

- ***WP3 (Vgen=20 V, IL2ref=10 A)***

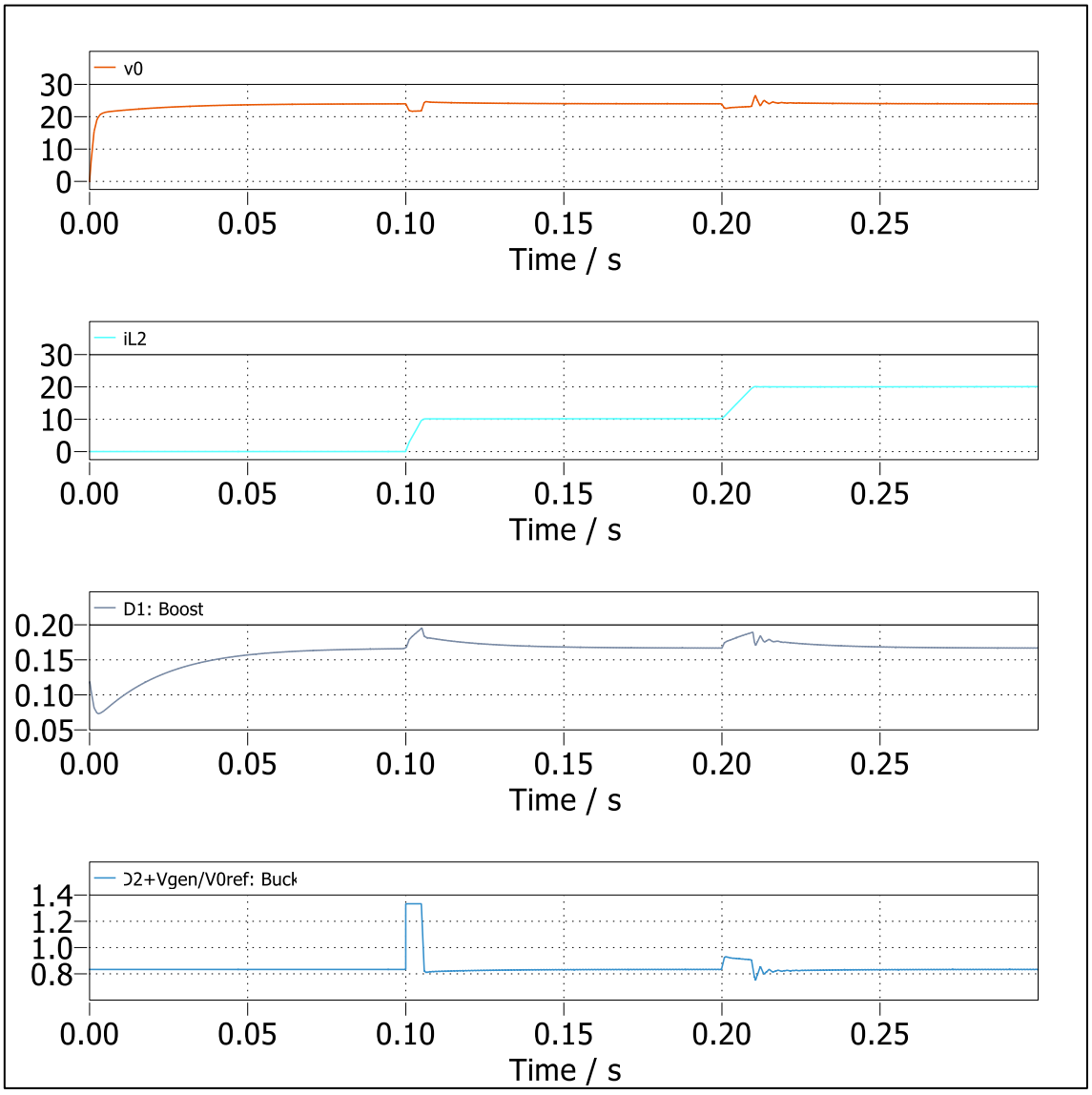


Figure 76: WP3 Control Analysis Graphs

After looking at *Figure 76*, it can be concluded that it works with a smaller difference in the capacitor's voltage but during the third period's stabilization it appears a tiny oscillation. Also, compared to the controllers' design WP (WP1), it takes a bit more time for stabilization between the first and the second periods.

It works but, given the little oscillating appearances, a more optimal result for the work interval (evading this way possible discrepancies or errors) would be preferred.

- ***WP4 (Vgen=16 V, IL2ref=10 A)***

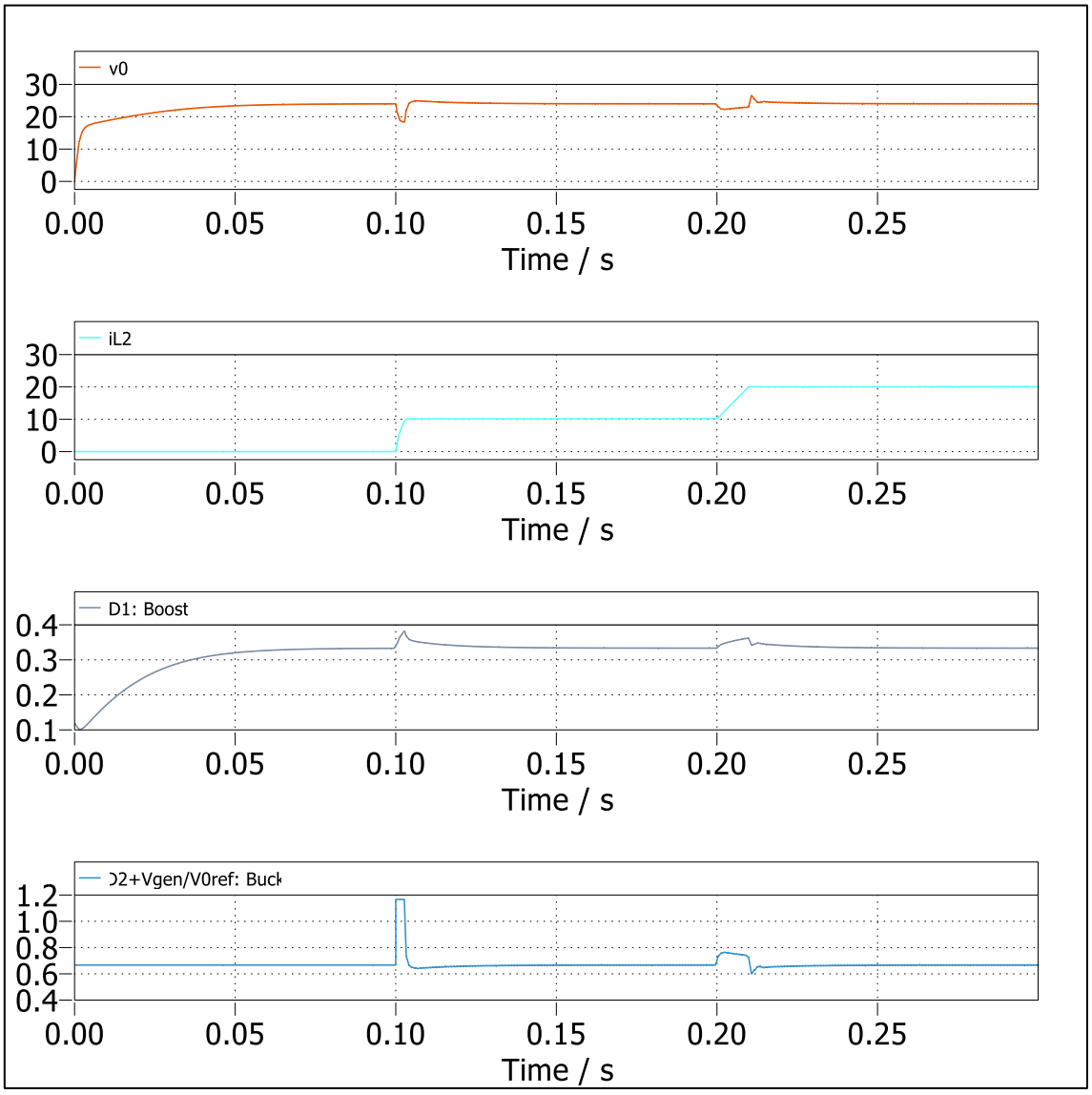


Figure 77: WP4 Control Analysis Graphs

The oscillation during the transition between the second and the third period is practically non-existent (or about to start, as seen in *Figure 77*). This WP will be set as a limit in the optimal working interval.

Following the same procedure, but instead decreasing the value of *Vgen*, the lower limit's search will take place.

- ***WP5 (Vgen=4 V, IL2ref=10 A)***

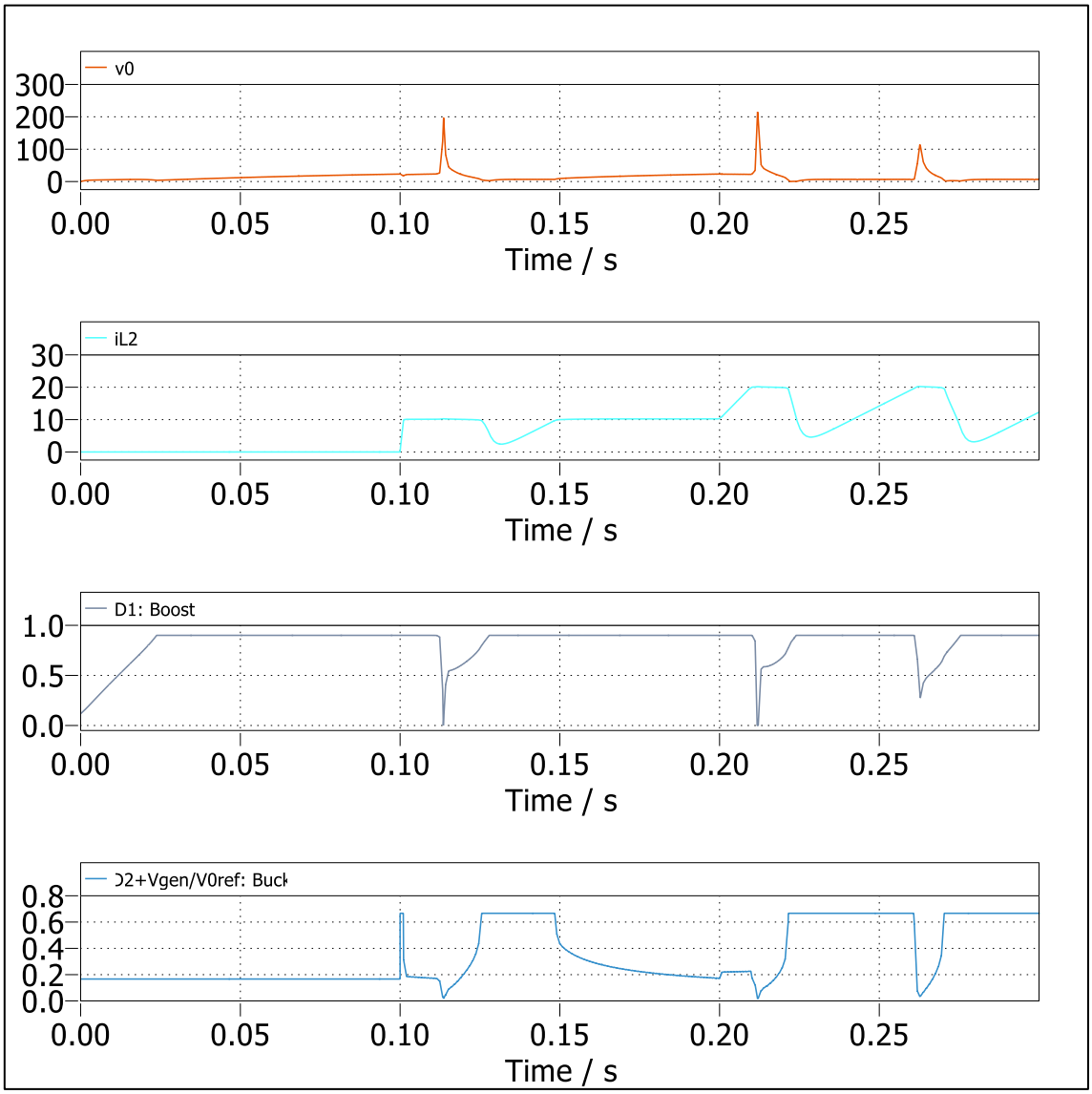


Figure 78: WP5 Control Analysis Graphs

Obviously, the WP shown in *Figure 78* is not working, since it does not follow the desired current and voltage values, nor the solicited behavior. It is not valid at all.

Next step is increasing *Vgen* unitarily until a proper and suitable response is found.

- ***WP6 (Vgen=11 V, IL2ref=10 A)***

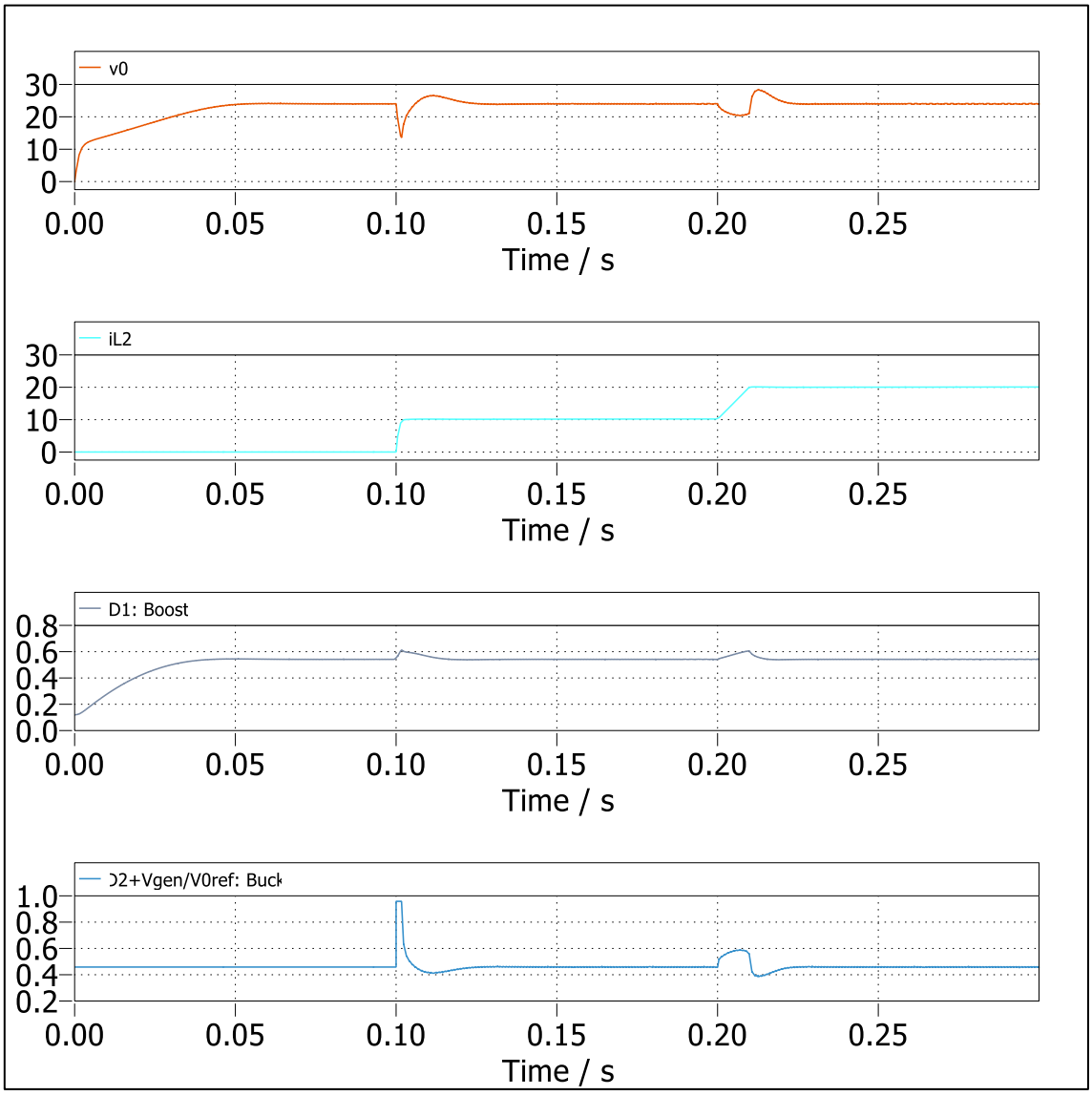


Figure 79: WP6 Control Analysis Graphs

Even with *Vgen*'s value being set at 10 V, the overshoot in the correction of *V0* seen in the beginning of the 3rd period was so big that makes the system unstable.

To take care of this, to go up closer to the starting WP was needed, obtaining WP6, depicted in *Figure 79*'s. Then again, this WP still works acceptably well, quite similar to WP1.

This makes it a system more susceptible to the decrease of *Vgen* and not as much to increasing it.

On the other hand, leaving *Vgen* still at 12 V and changing the current (following the same procedure) will be displayed in the next cases.

- ***WP7 (Vgen=12 V, IL2ref=15 A)***

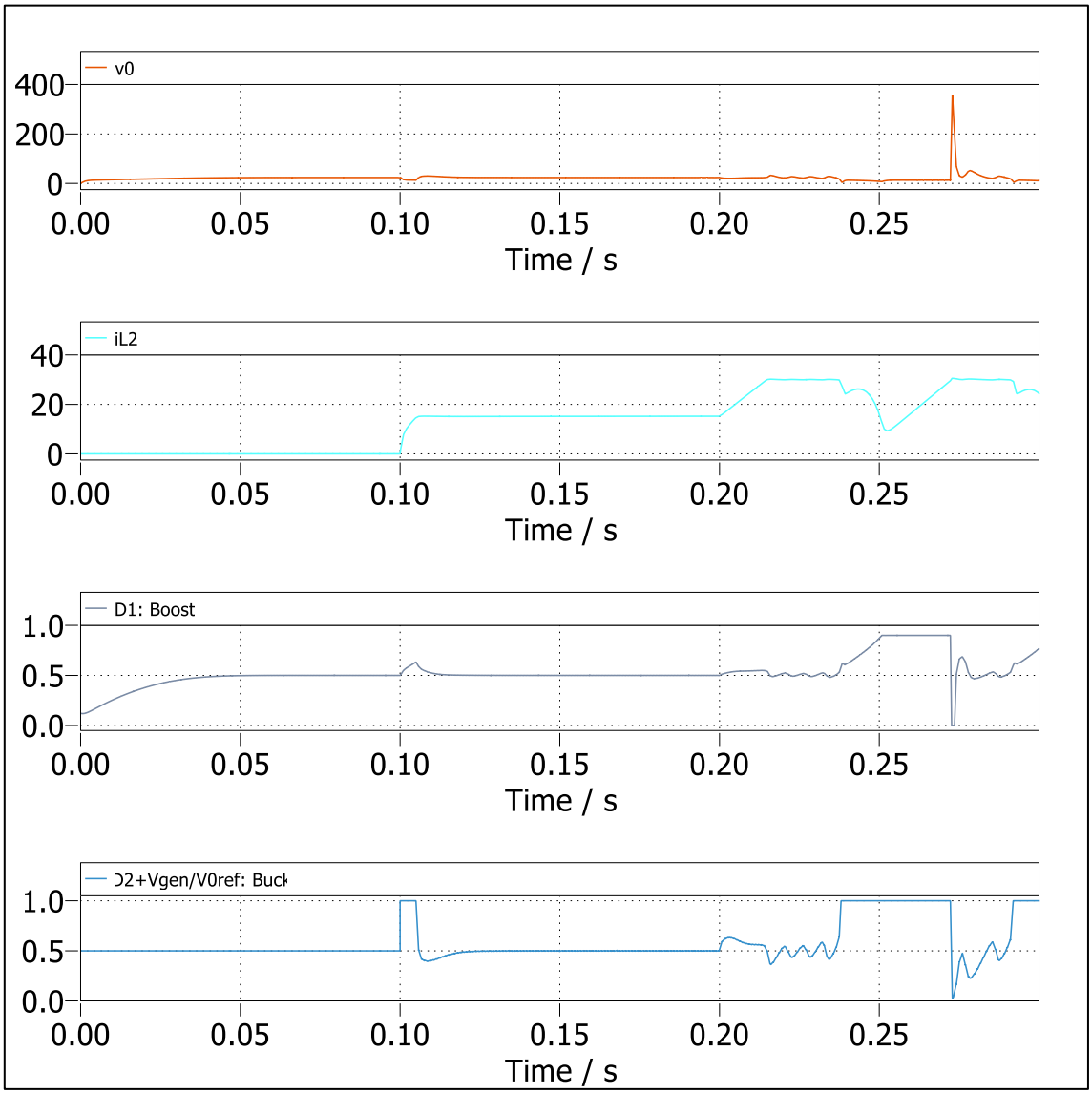


Figure 80: WP7 Control Analysis Graphs

As has happened before in the first tries, *Figure 80*'s response does not work at all, so the decreasing procedure starts again.

With 14 A the system works but has a little bit of oscillation that is just yet suboptimal. After reducing it by one more unit, the next simulation analyzed, WP 8, is reached.

- ***WP8 (Vgen=12 V, IL2ref=13 A)***

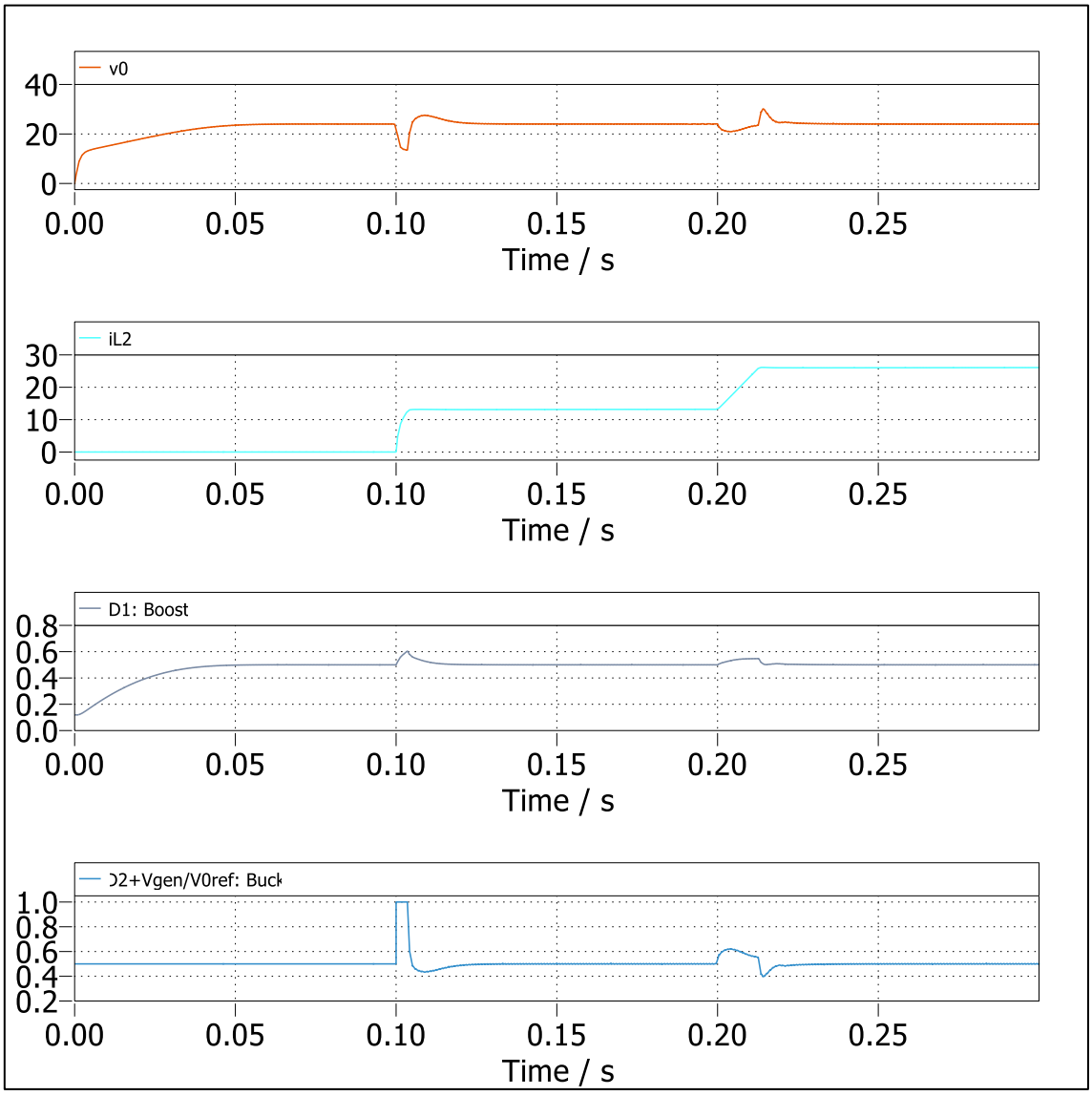


Figure 81: WP8 Control Analysis Graphs

Now, *Figure 81* exhibits what was considered before as a correct response.

Doing the same procedure for the values below the design's value, 1 A would be reached. After that the decrease changes from decremented by one to a decimal decrease until reaching 0, due to negative current not making sense, since the converters would not be the ones intended.

- ***WP9 (Vgen=12 V, IL2ref=1 A)***

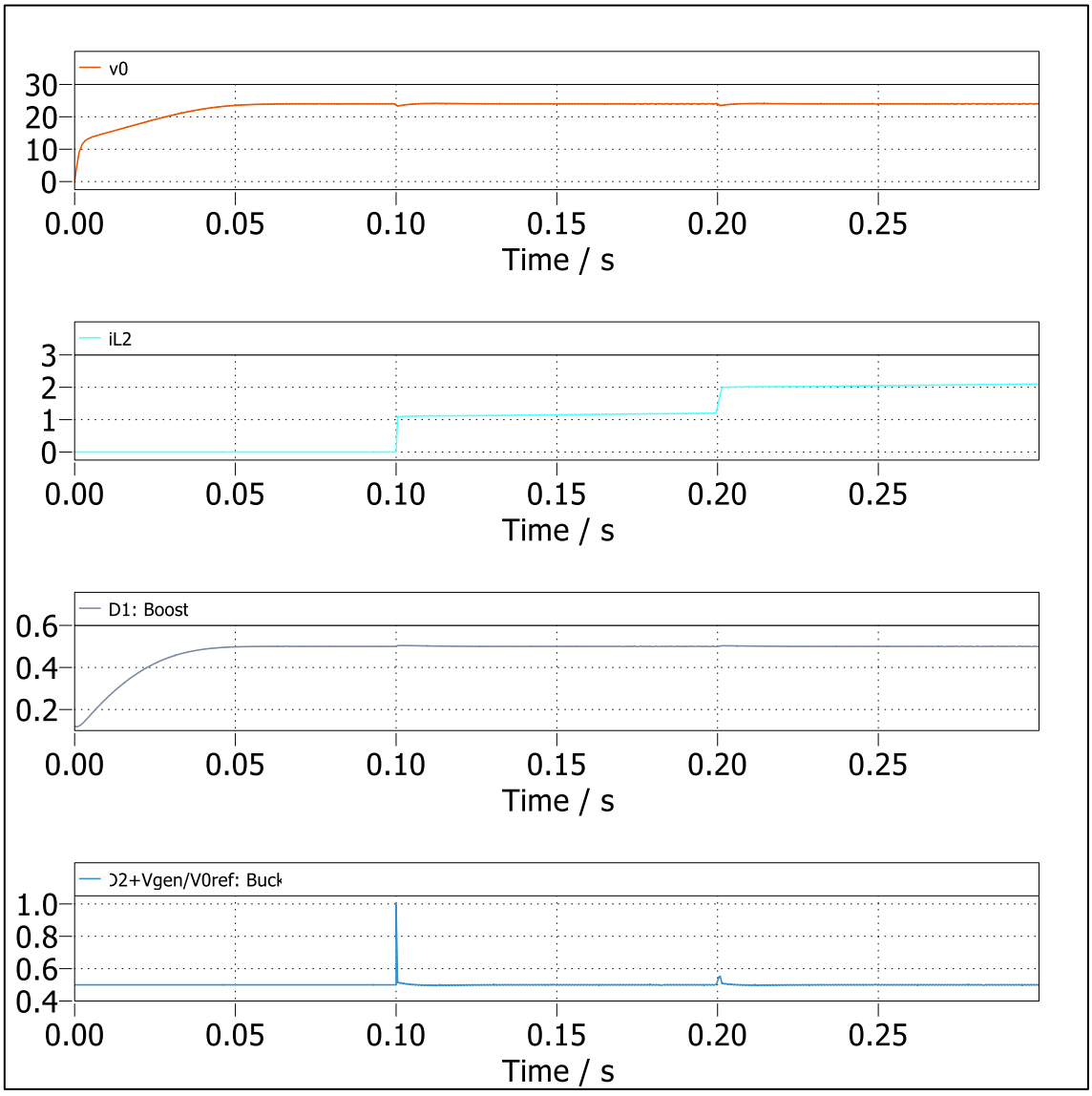


Figure 82: WP9 Control Analysis Graphs

Figure 82's response has started deviating a bit more from the desired behavior since the current does not fully stabilize (in the second period it starts and ends with a slight difference in *iL2*). The response and stabilization though are really quick and the fastest yet, probably due to needing to generate such little current.

As the decrease in the current values increases, the difference with any minimum change will be more noticeable, since the values are now smaller each time. Forced by this fact, this is accepted as the minimum optimal value for our working interval (the start of the deviation from an acceptable behavior).

For the last simulations, by using the limit examples found (WPs 4, 6, 8 and 9) and via the same observational procedure a joint working interval will be obtained. This way any combination of these values should work fine with the selected controllers.

- ***WP10 (Vgen=11 V, IL2ref=1 A)***

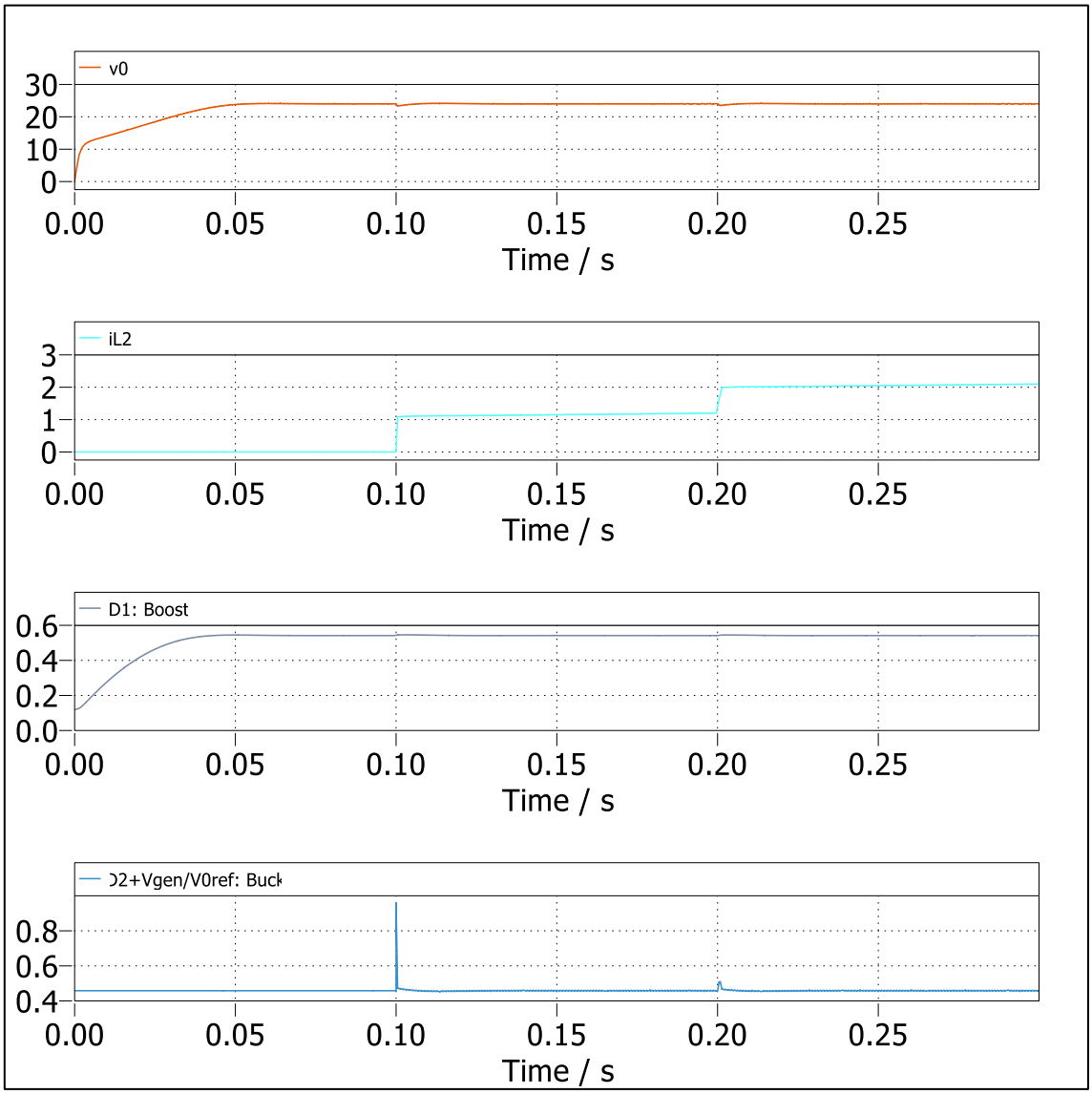


Figure 83: WP10 Control Analysis Graphs

Figure 83's response is not perfect regarding inductor's current but will be considered adequate.

- ***WP11 (Vgen=11 V, IL2ref=13 A)***

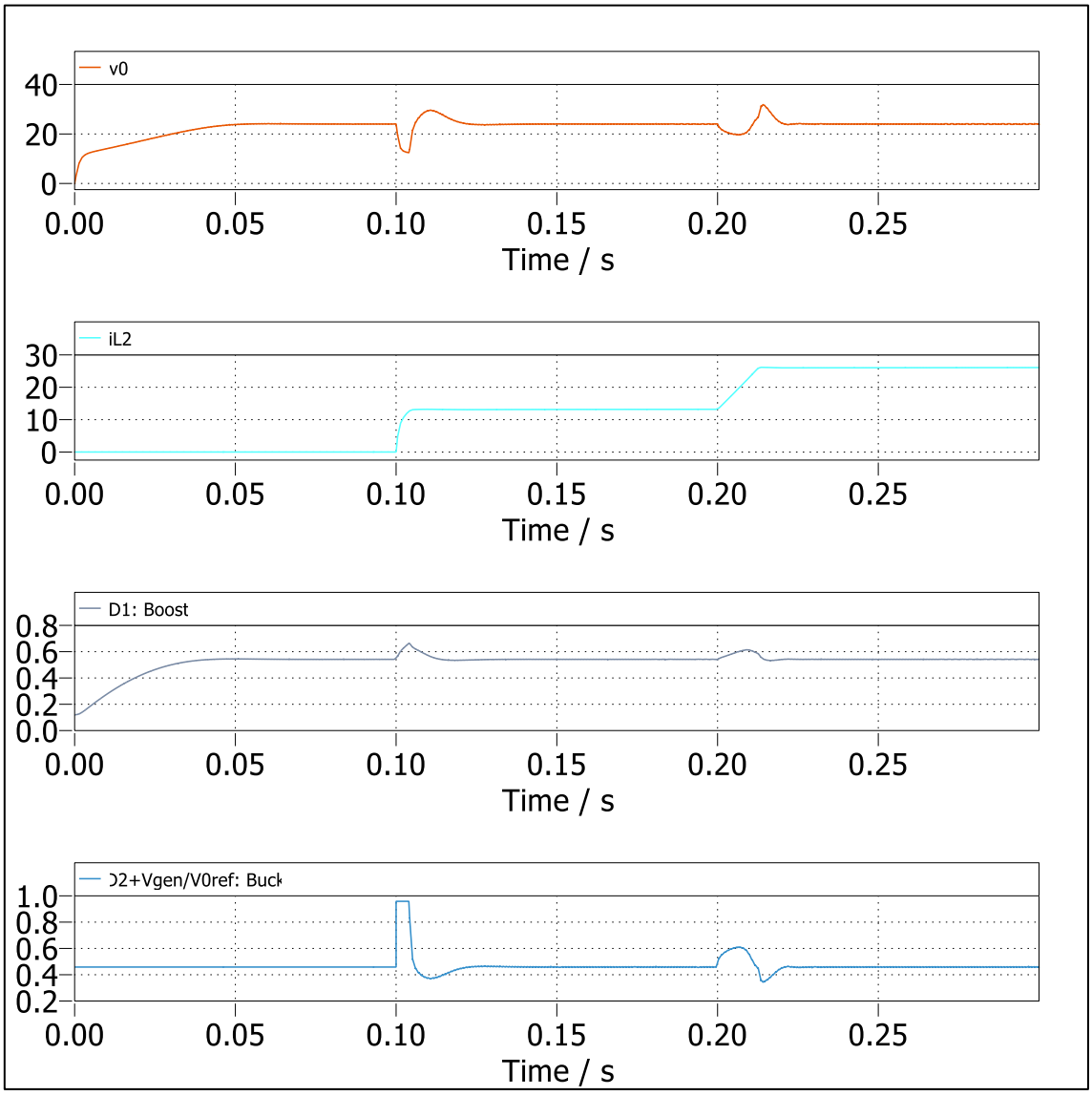


Figure 84: WP11 Control Analysis Graphs

Figure 84's simulation works as well with a steadier current but takes more time to stabilize the voltage in each period's transition to the next.

- ***WP12 (Vgen=16 V, IL2ref=13 A)***

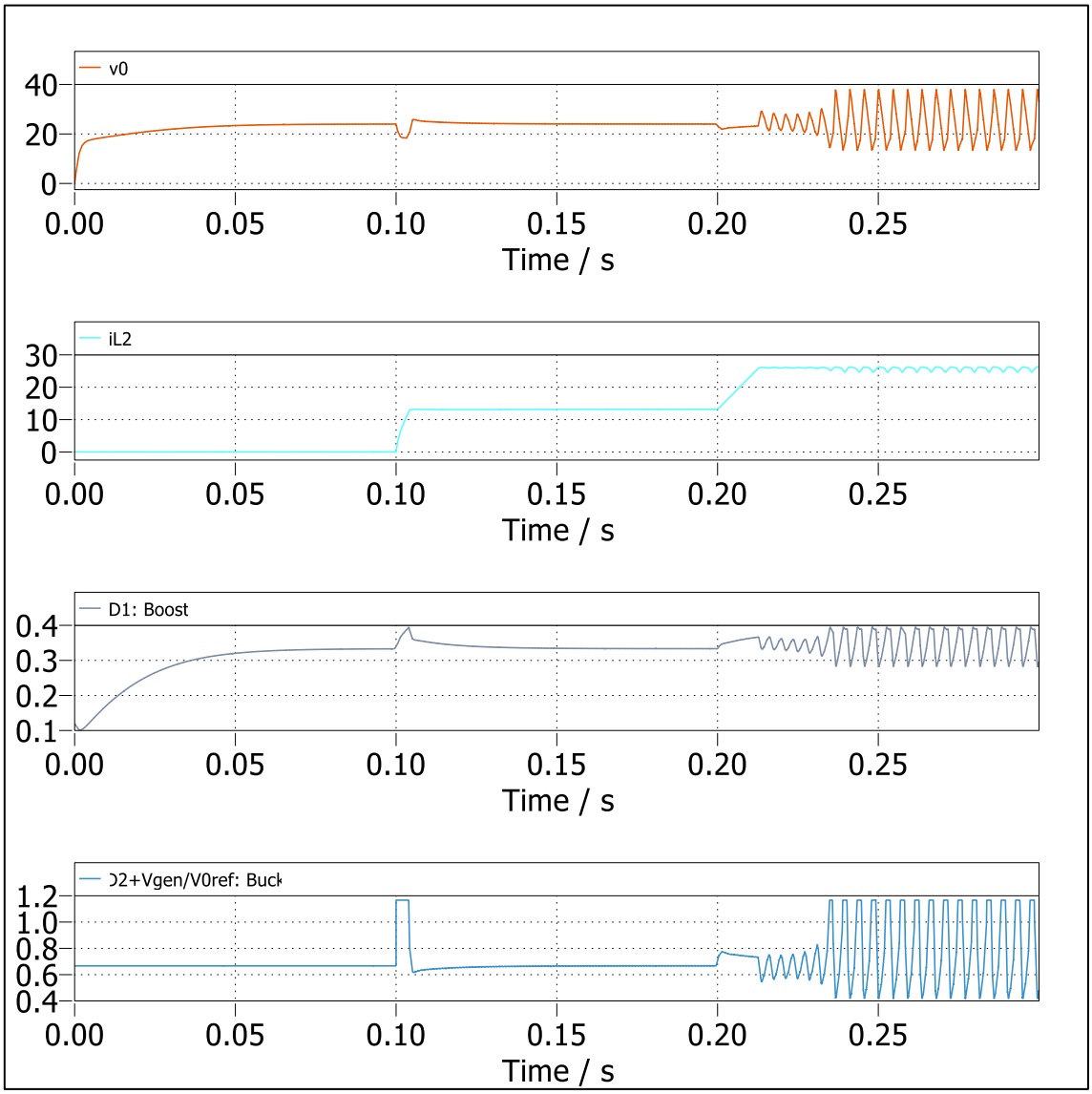


Figure 85: WP12 Control Analysis Graphs

Clearly, as *Figure 85* exhibits, in this WP a big oscillation occurred, and this behavior is not acceptable.

- ***WP13 (Vgen=13 V, IL2ref=13 A)***

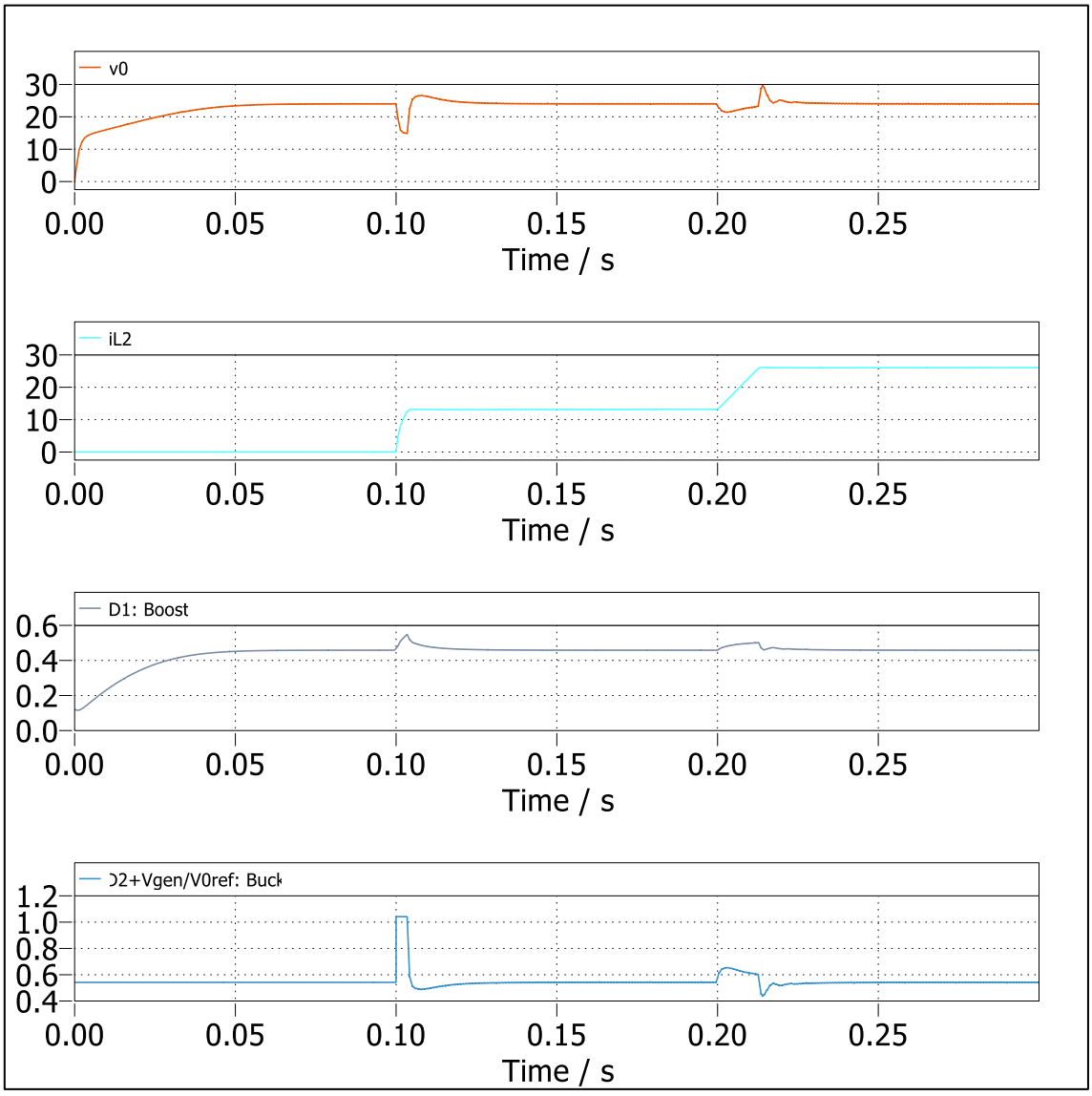


Figure 86: WP13 Control Analysis Graphs

Considering everything explained before, *Figure 86*'s response is considered adequate behavior.

- ***WP14 (Vgen=13 V, IL2ref=1 A)***

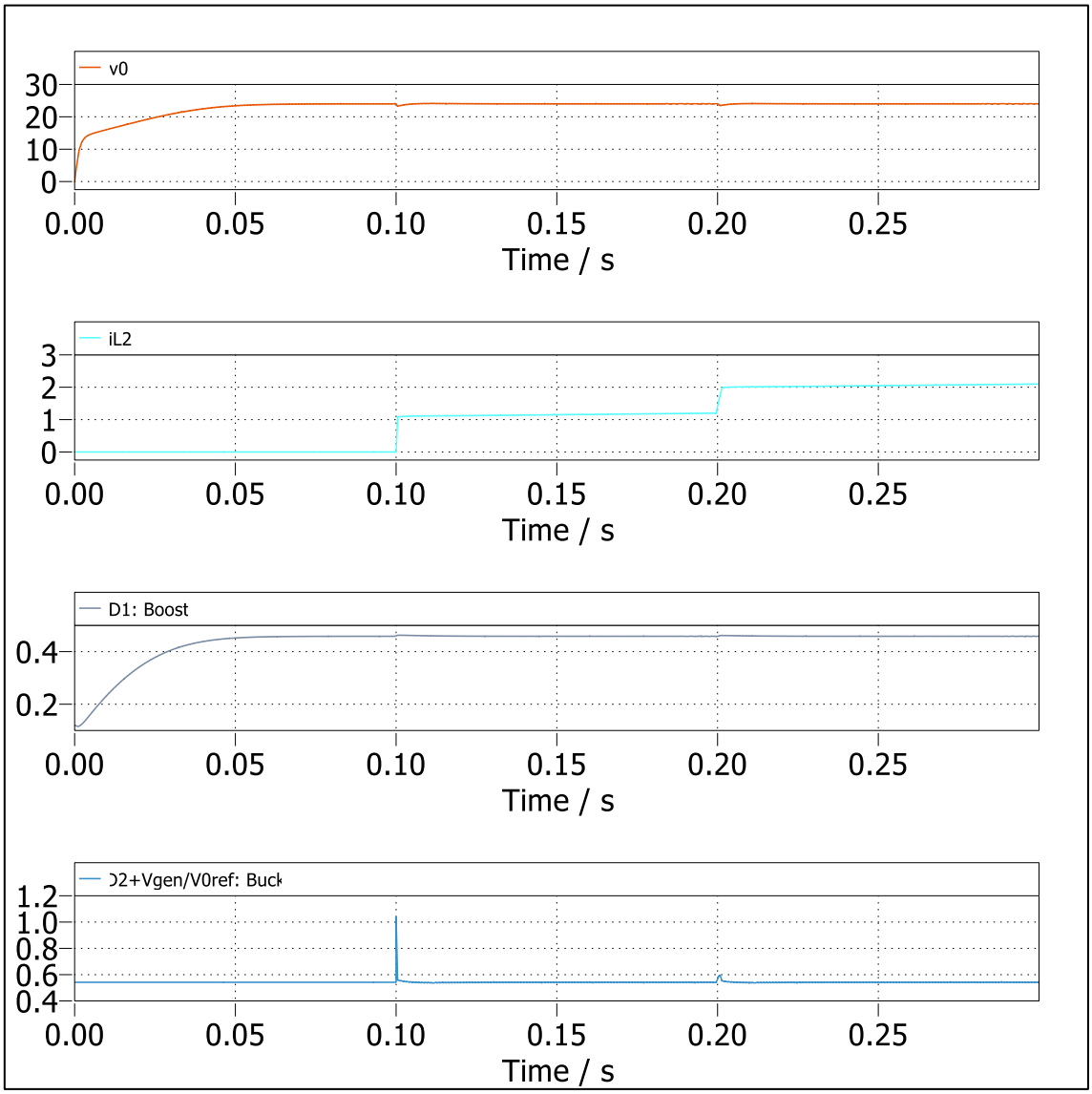


Figure 87: WP14 Control Analysis Graphs

Figure 87's WP works with the previously accepted deviation, since I*L2ref* is really small.

6.4.2 Working Intervals Definition

Considering the run of simulations finished, the acceptable work intervals for the system with the designed controllers would be:

$$\boldsymbol{If\ Vgen\ =\ 12\ V,\quad then,\quad IL2ref\ =\ [1,13]\ A}$$

$$\boldsymbol{If\ IL2ref\ =\ 10\ A,\quad then,\quad Vgen\ =\ [11,16]\ V}$$

Also, it is determined that the joint working interval found is:

$$\boldsymbol{(Vgen, IL2Ref)\ =\ ([11,13],[1,13])\ (V, A)}$$

Regarding the considerations taken to determine whether adequate or not, it was understood that they all work in a reasonable, brief amount of time, stabilizing the response turning it to what it is intended to be in each period.

6.4.3 Working Conditions Overview

To further clarify the conditions stated in *Table 18*, the joint interval means that any combination of both intervals will work properly as intended.

Working Conditions of the Designed System	
If $\boldsymbol{Vgen\ =\ 12\ V}$	$\boldsymbol{IL2ref\ =\ [1,13]\ A}$
If $\boldsymbol{IL2ref\ =\ 10\ A}$	$\boldsymbol{Vgen\ =\ [11,16]\ V}$
Joint Interval	$\boldsymbol{(Vgen, IL2Ref)\ =\ ([11,13]\ V, [1,12]\ A)}$

Table 18: Working Conditions Summary

7. CONCLUSIONS

7.1 Technical Conclusions

After the analytical discussion, the simulation experiments demonstrate that the chosen range of controllers are effective enough and let the system work in the desired way, at least with the specific physical parameters chosen.

Therefore, these intervals would be good enough for developing an arrangement of a different set of systems with the same controllers. Plus, the values found for the working Conditions and the joint interval are feasible, from a day-to-day point of view.

Nonetheless, the question that arises would be whether it is practical to do so, thus marching forward into the physical layer of development or not.

To begin with, it is worth noticing that the adjustment of the Buck controller is close to non-essential, due to the stiffness of the system being given by the Boost and the basis assumption of it controlling perfectly *V0* and keeping it constant. Because of this, any change in the Buck's controller parameters makes no change in the system's control and it can be seen in the simulations.

Also added to the last point of discernment, the fact of ignoring the capacitor's parasitic currents and other power losses of the system and our circuit elements -passive or not-, simplified things a lot.

Nonetheless, taking all this into consideration, the system works out just fine and the stabilization of systemic behavior is fast and valid, but as it was stated earlier the R1 used in this example is way too low and would end up meaning a lot of power loss, since power is understood as $P = V * I = V/(R\text{^}2)$. This is one of the most important considerations to consider, as in real-world practice, this resistance would be absurd.

Consequently, it is stated that PID control might not be enough robust for using this system in a real-life application

Nevertheless, although this step would not be recommended yet, it is, surely, a good approximation of how the system hypothetically could work in CCM and a good starting point for turning the idea into a physical reality.

7.2 Legal and Professional Responsibility

The development of a dynamic control system of this kind endorses a number of critical legal and professional responsibilities within the engineering field.

First, it needs to adapt to the existing industry standards and safety regulations, particularly in applications like BMSs for EVs. Compliance with international standards is of vital importance to ensure the final product is safe, reliable and legally marketable.

Furthermore, having everything meticulously documented not only facilitates future work and upgrades but also provides clear legal responsibility, so it has been a must and properly conducted.

Intellectual property is a key consideration. In this case, the circuit design idea is propriety of UniPr's Department of Architecture and Engineering. The rest of the project's development has

been a collaboration between the thesis author and both universities, UPM and UniPr. This must be addressed for any kind of potential patentability and must not infringe upon existing intellectual property rights.

7.3 Ethical and Social Responsibility

Given its potential application in the rapidly expanding EV and renewable energy sectors, the ethical implications of this project are significant.

The efficient and reliable power conversion that this work aims to achieve would contribute to the advancement of sustainable technologies, which would have a positive ethical impact.

On the other hand, being responsible also includes considering the potential environmental impact of the project. The engineer has an ethical duty to design systems that are not only efficient but also environmentally responsible.

While as for right now, this project's impact is little (just relying on a single computer and the software), thinking forward, the manufacturing processes and the end-of-life disposal (electronic waste and residues) would mean evaluating whether there is an appropriate positive balance or not. Also, any possible development or use of this project's future aim that can do wrong (maybe sustainable generators for weaponry) should be considered and lawfully regulated.

Nevertheless, theoretically speaking, the positive aspects would win over the negative and could pose a contribution to the United Nation's Sustainable Development Goals. It is directly involved in the SDGs 7, 9 and 13: Affordable and Clean Energy, Industry, Innovation, and Infrastructure, and Climate Action.

Figure 88: United Nation's Sustainable Development Goals

8. FUTURE RESEARCH

To further develop the project, the next step within the train of thought should be, firstly, to be able to step into physical layered development. To start with a scalable prototype and then go on to a more precise and day-to-day full-scale device.

For that purpose, the imperative need to use other types of control, more complex and proper for this situation, would dictate the next steps. Adaptive PID Tuning, combinations of PID's or other approaches destined for non-linearity could be a better solution.

This conclusion was reached due to many tries with manual adjustment of the PID and analysis of the open-loop and Bode diagrams. These ending with no success whatsoever, always enclosing values that were each time closer to the one returned by MATLAB's "PIDTuner" function.

As soon as the prototype design phase could finally be green lit, the use of this thesis background market analysis could be valuable, for instance, to choose each component's type and design. Once this was sorted out, the prototype could start the creation phase.

Apart from this, after being sorted out other controllers that granted using a more realistic value of the resistance, next step would be thinking about implementing more of these systems in parallel, meanwhile the capacitor is equally used by all of them in common… Or similar ideas, to obtain more power range.

Looking in the same direction, what could also be implemented is doing the current mode analysis of the Boost, with the respective transfer functions, to have both working modes available.

Also, doing the critical and discontinuous conduction mode analysis to have, furthermore, an even bigger view of the behavior of said system would be interesting. These modes occur when the inductor's current drops to 0 and when it turns negative, respectively, which are the cases not studied yet.

This way, it could turn real the optimal goal of having more batteries, even more power and keeping control over the power flux and, likewise, efficiency.

For more dexterity, bi-directional architecture should be implemented, since with the current design only unidirectional power flux is regarded. This could be achieved by substituting the diodes with other MOSFETs and putting diodes in parallel with them, for instance.

An example of the design can be found in *Figure* 89. The Buck and Boost converters working on both sides and changing power flux direction would turn a reality. This way, the ideal sustainable system in which one battery charges the other one when needed, thus, extending the system's lifespan (as well as working with higher resistances and having a lower power loss) would be closer.

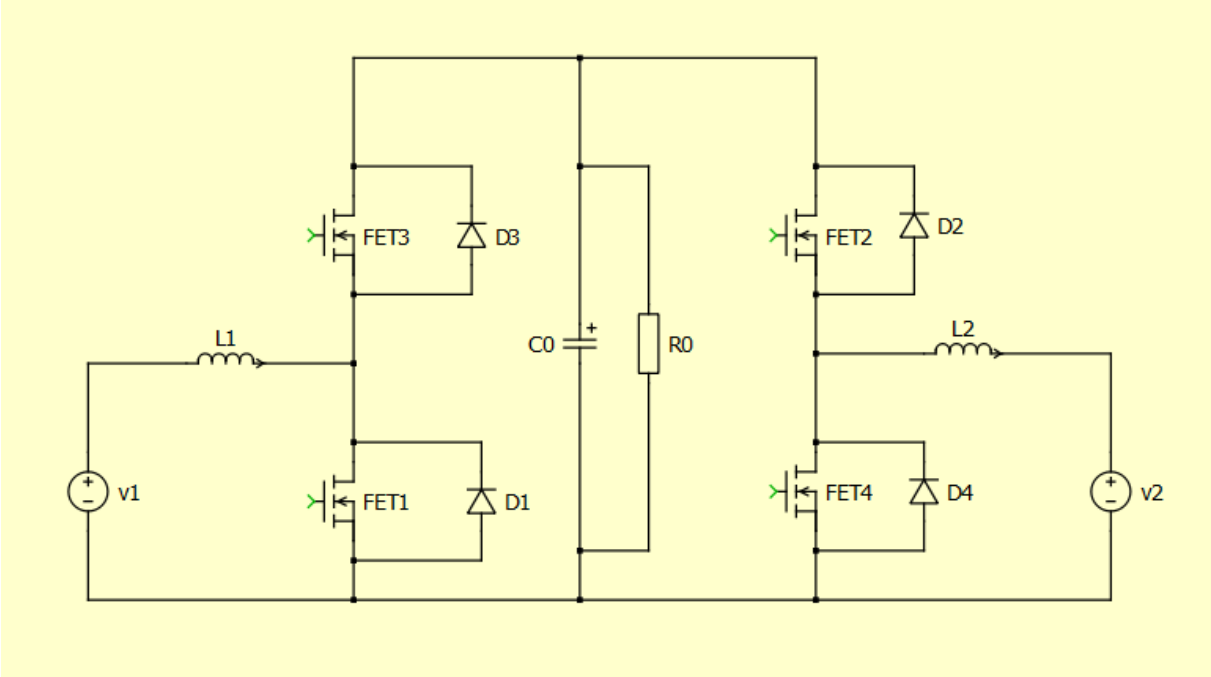


Figure 89: PLECS Dual-Bridge Bidirectional DC-DC Converter Design Example

By carrying on with all these goals, other more complex purposes, such as the cold start of an electric vehicle through control of battery temperature overshoot or the future applications regarded in the introduction chapter *1.4 Thesis Applications*, could be possible.

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TIMELINE AND BUDGET

Timeline (“Full-Time Job” Focus)

The proposed work is planned over an ideal program of approximately 18 weeks. Considering possible difficulties and obstacles, a maximum of 6 months, while fully invested in the project, is expected to start and give closure to this whole project.

It has been structured into the following phases:

1. **Literature Review and Research (3 weeks)**
   Review of relevant literature and background, analyze existing systems and define requirements and scope.
2. **Architecture and System Design (3 weeks)**
   Develop the overall system architecture, select appropriate software and design the main modules and components.
3. **Implementation and Development (4 weeks)**
   Code and integrate the system and its simulation tools, perform functional tests and debug the system according to design specifications.
4. **Testing and Evaluation (2 weeks)**
   Start objective-specific tests, identify and correct errors and summarize the results.
5. **Documentation and Writing (4 weeks)**
   Prepare the final thesis document, including figures, tables, equations and compile all project results into a full bachelor’s thesis according to UPM’s standards.

However, this plan serves as an approximation. Feedback is, as this project exhibits, really important in all levels of work, due to these all 5 phases are interconnected. They are being revised periodically whenever a new problem, idea or doubt appears.

Therefore, realistically, all the phases are interconnected and continue to develop after being “finished” in the timeline. That costs a “delay” and deviates from the ideal plan.

The approximate real-life approach to this “full-time job” thesis development timeline is offered in the Gantt Chart shown in *Figure 90.* It lasts for an approximate duration of 20 weeks.

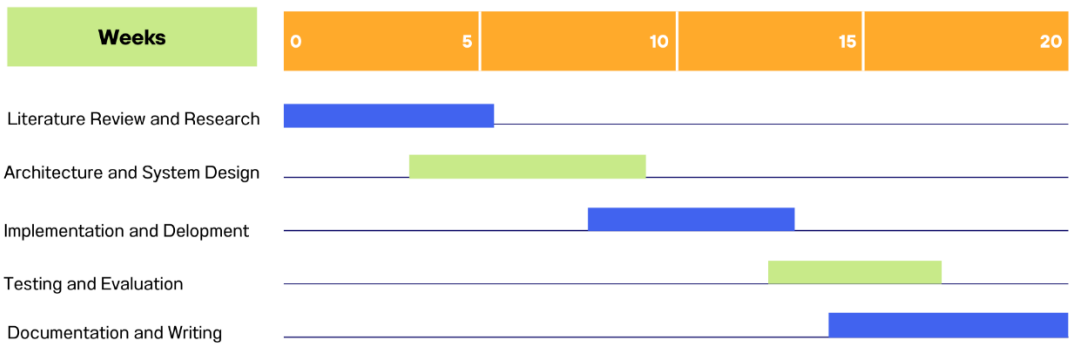

Figure 90: Gantt-Chart for the Estimated Project’s Timeline

Budget

The estimated budget has been prepared in *Table 19* to cover hardware, software and the printing and binding for the thesis, ensuring that the project can be completed effectively.

Item	Description	Estimated Cost (€)
Hardware	Modern Laptop (*Dell XPS 15 9530*)	1000
Software	Individual Licenses: MATLAB (student) and PLECS (annual)	4,000 (PLECS) 49 (MATLAB)
Printing and Binding	Production of the thesis final document	40
Total Estimated Budget: 5089€		

Table 19: Total Estimated Budget (Without Institutional Help)

This seems clearly expensive for this research's nature, however, thanks to UPM and UniPr, there has been no need to pay any license. Likewise, the laptop was already acquired for personal use before the start of the project.

Due to this the final cost will only be destined to printing and binding.

Thus, the final **real estimated budget will be 40€** for printing and binding.

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ABBREVIATIONS AND ACRONYMS

- **UPM:** Universidad Politécnica de Madrid (Politechnic University of Madrid)
- **UniPr:** Università degli Studi di Parma (University of Studies of Parma)
- **UM:** Universidad de Murcia (University of Murcia)
- **UNESCO:** United Nations Educational, Scientific and Cultural Organization
- **TFG:** Trabajo de Fin de Grado (Bachelor's Thesis)
- **US/D:** United States / Dollar
- **ETSII:** Escuela Técnica Superior de Ingenieros Industriales
- **MATLAB:** Matrix Laboratory
- **PLECS:** Piecewise Linear Electrical Circuit Simulation
- **PID:** Proportional-Integral-Derivative
- **CCM:** Continuous Conduction Mode
- **IEA:** International Energy Agency
- **REE:** Red Eléctrica Española (Spanish National Grid)
- **DC:** Direct Current
- **MOSFET:** Metal-Oxide-Semiconductor Field-Effect Transistor
- **AC:** Alternating Current
- **SiC:** Silicon Carbide
- **GaN:** Gallium Nitride
- **IC:** Integrated circuit
- **HEMTs:** High-electron-mobility transistors
- **EV:** Electric vehicle
- **BMS:** Battery Management System
- **CAGR:** Compound Annual Growth Rate
- **USD:** United States Dollar
- **SOH:** State-of-Health
- **SOP:** State-of-Power
- **PWM:** Pulse Width Modulator
- **FLC:** Fuzzy Logic Control
- **MPC:** Model Predictive Control
- **V2G:** Vehicle-to-Grid
- **RHPZ:** Right Half-Plane Zero
- **WP:** Working Point
- **SDG:** Sustainable Development Goal

UNITS

- **V:** Volts
- **A:** Amps
- **Hz:** Hertz
- **W:** Watts
- **s:** Seconds
- **rad:** Radians
- **%:** Percentage
- **€:** Euros
- **kWh:** Kilowatt-hour
- **dB:** Decibels