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Presented by: Amine BENTIFOUR and Fares TAKHERIST

Theme

Control Design of a Boost Converter

Defended publicly, on 29/06/2025, before the jury composed of:

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Dedication

I dedicate this work to my beloved parents, whose unwavering support and sacrifices since my childhood have shaped the person I am today I will never forget their efforts.

I also dedicate this work to the most wonderful woman, my dear wife Ahlem, who supported me through every stage of this period with love, patience, and encouragement.

To my brothers, my grandmother, and my entire family thank you for always being there for me.

To my friend Amine BENTIFOUR, whose commitment, insightful collaboration, and shared experiences have greatly contributed to the value of this work.

This achievement is also yours.

F. TAKHERIST

Dedication

I dedicate this work to those who hold a special place in my heart.

To my parents, for their unconditional love, silent prayers, and constant support.

To my brothers and my sister, for their presence, encouragement, and affection.

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To all those who, directly or indirectly, contributed to the completion of this project. Your trust, your words, and your kindness have fueled my determination throughout this journey.

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Abstract

This thesis focuses on the modeling and simulation of a control system for a DC-DC Boost converter using the Processor-in-the-Loop (PIL) method. A PI controller is implemented on a Raspberry Pi 4 and connected to a Simulink model of the converter. The objective is to validate the interaction between the physical controller and the simulated system, exploring the integration of hardware components in power conversion system development.

Key-words: power electronics, DC-DC converter, Boost, PI control, PIL, Raspberry Pi, modeling, simulation.

Résumé

Ce mémoire porte sur la modélisation et la simulation d’un système de commande appliqué à un convertisseur DC-DC Boost à l’aide de la méthode Processor-in-the-Loop (PIL). Un contrôleur PI est implémenté sur un Raspberry Pi 4 et connecté à un modèle Simulink du convertisseur. Cette démarche vise à valider l’interaction entre le contrôleur physique et le système simulé, en explorant les possibilités offertes par l’intégration matérielle dans le développement de systèmes de conversion d’énergie.

Mots-clés : électronique de puissance, convertisseur DC-DC, Boost, commande PI, PIL, Raspberry Pi, modélisation, simulation.

الملخص

يتناول هذا البحث تصميم ومحاكاة نظام تحكم لمحول مستمر-مستمر بواسطة تقنية المعالج في الحلقة، تم وضع المتحكم براسبيري باي 4 وربطه بنموذج المحول في سيمولينك، تهدف هذه الخطوة إلى التحقق من التفاعل بين المتحكم المادي والنظام المحاكى، من خلال استكشاف الإمكانيات التي توفرها التكاملات المادية في تطوير أنظمة تحويل الطاقة.

الكلمات المفتاحية: إلكترونيات القدرة، محول مستمر-مستمر، محول رافع للجهد، راسبيري باي، نمذجة، محاكاة PI, PIL,

Content list

List of abbreviations

DC : Direct current
PIL : Processor-in-the-Loop
PI: Proportional-Integral
MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor
IGBT: Insulated-Gate Bipolar Transistor
D: Duty cycle
T_{on}: On-Time
T: Period
BJT: Bipolar Junction Transistor
Pn layer: P-type and N-type semiconductor layers
PT / NPT: Punch-Through / Non-Punch-Through
V_{gs}: Gate-to-Source voltage
Vin: Input voltage
Vo / Vout: Output voltage
Beta (β) : fraction of the switching period during which the inductor current is zero
EMI: Electromagnetic interference
P: Proportional
I: Integral
D: Derivative
PD: Proportional-Derivative
PID: Proportional-Integral-Derivative
PWM: Pulse Width Modulation
Kp: Proportional gain
Ki: Integral gain
s: Laplace variable
SMC: Sliding Mode Control
FLC: Fuzzy Logic Control
L: Inductance
C_{out}: Output capacitor
f_s: Switching frequency
R: Resistance
D_0: Nominal duty cycle

$\Delta d(t)$: Small variation in duty cycle

IL_0: Steady-state inductor current

$\Delta iL(t)$: Small variation in inductor current

V_{out_0}: Steady-state output voltage

$\Delta V_{out}(t)$: Small variation in output voltage

V: Voltage

I, i: Current

K: DC Gain

ωz: zero.

$\omega 1$, $\omega 2$: System corner frequencies (poles)

Ku: Ultimate gain

tu: Ultimate period

t: Time

MIL: Model-in-the-Loop

MBD: Model-Based Design

SIL: Software-in-the-Loop

HIL: Hardware-in-the-Loop

I/O: Input/Output

TCP/IP: Transmission Control Protocol / Internet Protocol

RISC: Reduced Instruction Set Computer

IoT: Internet of Things

GPIO: General Purpose Input/Output

CPU: Central Processing Unit

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Chapter II

Chapter III

General introduction

General introduction

In a technological context marked by the continuous pursuit of energy efficiency, reliability, and reduced hardware footprint, power electronics plays a central role in the development of intelligent, autonomous, and high-performance systems. Static power converters particularly DC-DC converters are essential in this field, ensuring voltage conversion and regulation to meet the specific requirements of a wide variety of loads. From powering portable devices to managing energy in electric vehicles or photovoltaic systems, these converters serve as a crucial link between the energy source and the end application.

Among the various existing topologies, the Boost converter stands out due to its ability to step up a low input voltage to a higher output level without relying on bulky transformers. This characteristic makes it an ideal solution for applications that demand compactness, high efficiency, and continuous input current. However, achieving optimal performance with such converters depends on precise and stable output voltage regulation especially when operating conditions such as input voltage, load, and temperature are subject to fluctuation.

This thesis untitled "**Control Design of a boost converter**" is built upon that premise. It presents a comprehensive, structured study that begins with a fundamental understanding of how the Boost converter works and progresses through to the implementation of an embedded control system using Processor-in-the-Loop (PIL) simulation. This approach is designed not only to accurately model the dynamic behavior of the converter but also to develop an effective control strategy using a Proportional-Integral (PI) controller, and finally validate its behavior using a hardware platform such as the Raspberry Pi**.**

The main objective of this work is to demonstrate, through both analytical and experimental methods, the importance of advanced simulation techniques in the design and validation of control systems for power converters. The project illustrates how simulation and real-time implementation can work hand-in-hand to create robust, efficient, and adaptive systems ready to operate in complex and dynamic environments.

Chapter I: DC-DC converters and the boost topology

Chapter I: DC-DC Converters and the Boost Topology

I.1. Introduction

In the modern era of energy-conscious electronics, power conversion plays a crucial role in ensuring efficiency, stability, and adaptability across a wide range of applications from portable electronics and electric vehicles to renewable energy systems and telecommunication infrastructure. DC-DC converters are at the heart of this transformation, enabling the regulation and transformation of voltage levels to meet specific load requirements while maintaining optimal energy use.

Among the various topologies, the boost converter stands out as a widely used step-up regulator, capable of increasing a lower input voltage to a higher, more usable level without requiring bulky transformers. Its compact structure, high efficiency, and continuous input current make it ideal for applications requiring voltage elevation. To fully understand its operation, it is essential to first explore the primary families of DC-DC converters, then delve deeper into the boost converter's structure, components, operating modes, and performance characteristics.

This chapter introduces the foundational principles of DC-DC conversion, presents the major converter types, and focuses on the detailed analysis of the boost converter highlighting its architecture, key components (such as MOSFETs, IGBTs, inductors, capacitors, and diodes), mode of operation, and advantages and limitations. Through this comprehensive overview, we build a solid understanding of the role of the boost converter in modern power electronics systems.

I.2. Main types of DC-DC converters

DC-DC converters are essential in power electronics, with various topologies tailored to specific applications such as communication systems, electric vehicles, and renewable energies. Each type operates differently and offers unique advantages and limitations. The common converter types are:

I.2.1. Step-Down (Buck) converter

A buck converter steps down the input voltage to a lower output voltage using a high-speed switching transistor and an inductor-capacitor filter. During the ON phase, energy is stored in the inductor, during the OFF phase; this energy is transferred to the load via a diode, ensuring smooth output. It is widely used in applications requiring voltage reduction with high efficiency. [1]

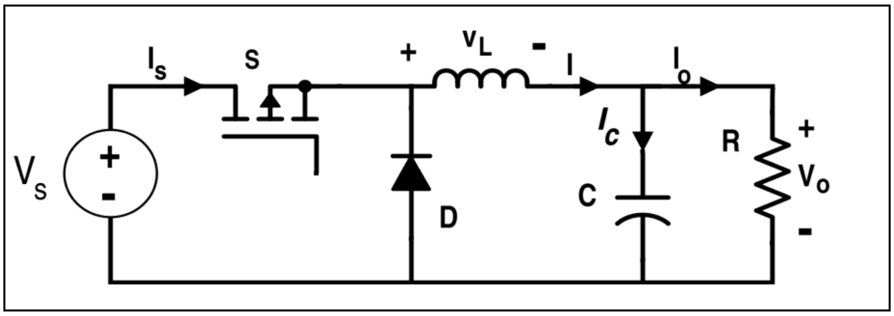


Fig I.1: Buck converter schematic [2]

I.2.2. Step-Up (Boost) converter

A boost converter increases the input voltage to a higher output voltage. When the switch is ON, energy is stored in the inductor while the diode is reverse-biased. When OFF, the inductor and input supply energy to the load. A large output capacitor helps maintain a stable voltage. This topology is common in regulated power supplies and motor braking systems. [3]

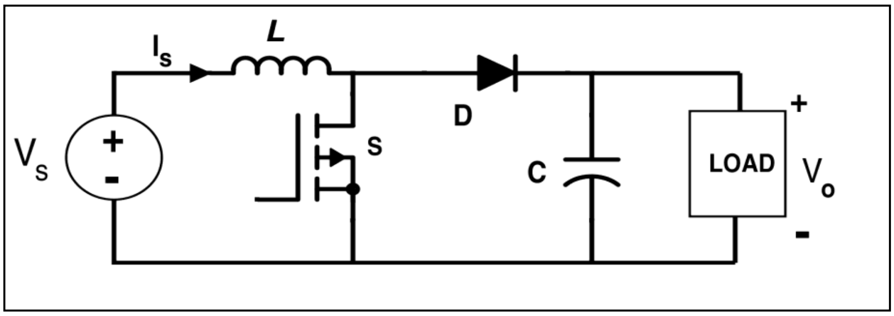


Fig I.2: Boost converter schematic [2]

I.2.3. Buck-Boost converter

The buck-boost converter can output a voltage higher or lower than the input, but with reversed polarity. It uses a controlled switch (transistor) and an uncontrolled one (diode). Energy is stored in the inductor during the ON phase and delivered to the output during the OFF phase, via the diode and capacitor. It’s efficient and adaptable to varying voltage requirements. [4]

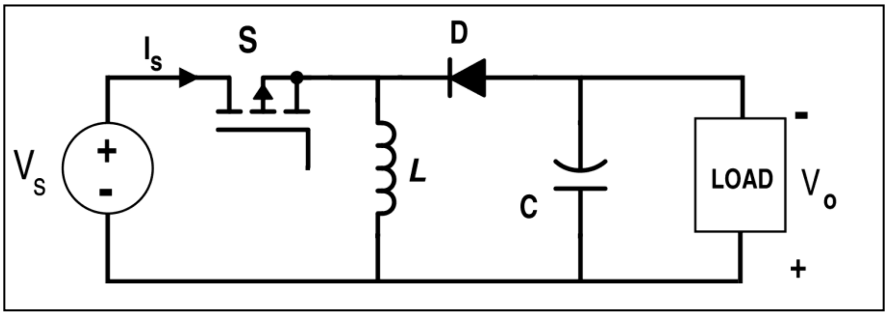


Fig I.3: Buck-Boost converter schematic [2]

I.2.4. Ćuk converter

The ćuk converter produces an inverted output voltage that can be higher or lower than the input. It features two inductors, two capacitors, a switch, and a diode. During switching, energy is transferred via the coupling capacitor. This topology provides continuous input and output currents and reduces ripple. [1]

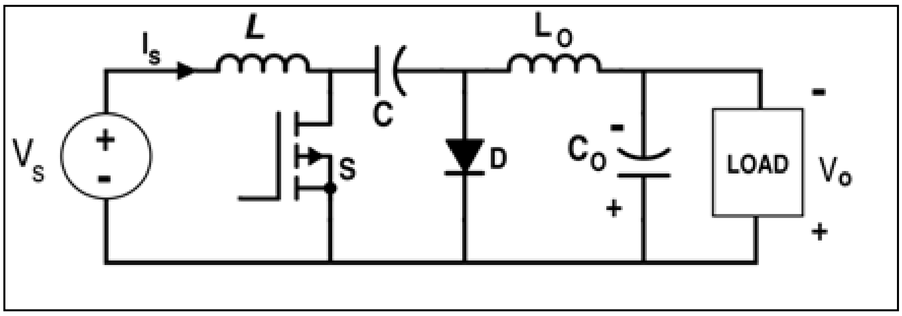


Fig I.4: Ćuk converter schematic [2]

I.2.5. Full Bridge DC-DC converter

The full-bridge converter uses a transformer and four switches to apply the full input voltage across the primary winding. Switching pairs alternate to reverse the polarity and transfer energy to the output through diodes. A capacitor (Cfw) prevents core flux imbalance. This converter reduces current stress and improves efficiency in high-power applications. [1]

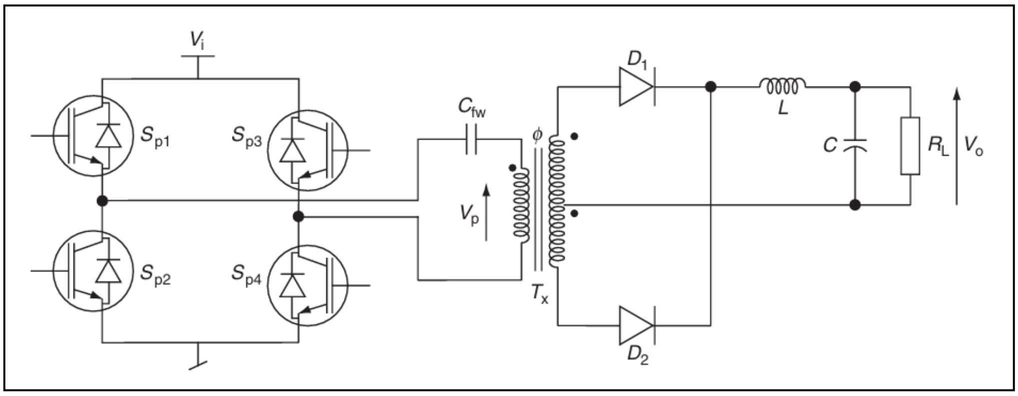


Fig I.5: Full-bridge DC-DC converter schematic [1]

I.3. Boost converter

A boost converter is a type of DC-DC converter that increases the output voltage above the input voltage, hence its name. Unlike converters that require transformers, the boost converter can step up voltage levels without one, relying solely on an inductor, a diode, a power MOSFET, a capacitor, and the load. This makes it simpler, more compact, and generally more efficient. The circuit operates in two main modes. When the MOSFET is switched on, current flows through the inductor and the transistor, causing energy to be stored in the magnetic field of the inductor. During this phase, the diode is reverse-biased and does not conduct. When the MOSFET is turned off, the inductor's polarity reverses to maintain current flow, and energy is transferred through the now-conducting diode to the output capacitor and the load. This switching cycle repeats continuously. [4]

One major advantage of the boost converter is its ability to efficiently step up voltage with only a single active switch, which contributes to high overall efficiency. Additionally, the input current is continuous, which helps reduce electromagnetic interference. However, the boost converter also has some drawbacks. The power transistor must handle high peak currents, especially at low duty cycles, which can impact reliability. Moreover, the output voltage is highly sensitive to changes in the duty cycle (D), making the system more difficult to stabilize under varying conditions. Another important consideration is that the average output current is lower than the average inductor current by a factor of approximately $1/(1-D^2)$ This implies that the RMS current through the output capacitor is significantly higher, necessitating the use of a larger capacitor and a bigger inductor than those used in a buck converter to ensure smooth operation and voltage regulation. [4]

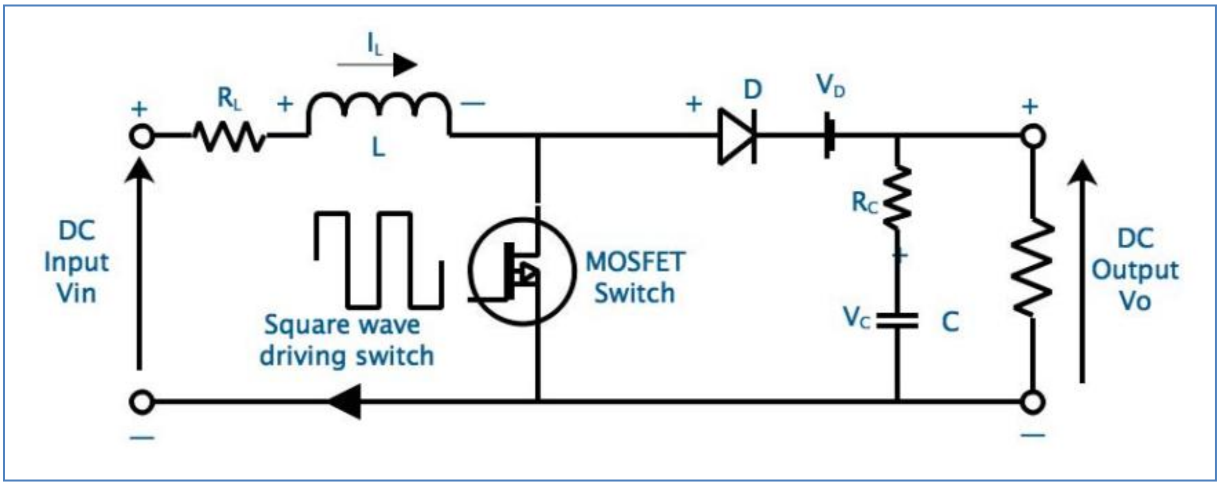


Fig I.6: Boost converter schematic [5]

The duty cycle D is the ratio between the time during which the switch S is in the conducting state (S ON) and the total period, as shown in the following relation:

$$D = \frac{\text{The time during which the switch is in the conducting state}}{\text{The total period}} = \frac{T_{on}}{T} \qquad \text{I.1}$$

With $0 < D < 1$.

I.4. Main components of a boost converter

I.4.1. Switch (S)

The switch is the fundamental component in the boost converter, responsible for regulating the flow of energy between the input source and the output load. By periodically opening and closing the circuit (typically through high-speed switching) it enables the inductor to store and release energy efficiently. This switching operation is performed using semiconductor devices such as MOSFETs or IGBTs especially, depending on the application's voltage and current requirements:

I.4.1.1. IGBT transistor

An IGBT (Insulated Gate Bipolar Transistor) merges the key advantages of BJTs and MOSFETs it features high input impedance like a MOSFET and low on-state conduction losses similar to a BJT, while avoiding the second breakdown issue typical of BJTs. Structurally, it resembles a MOSFET but includes a p^+ substrate layer that enables minority carrier injection, giving it performance characteristics closer to a BJT. The device consists of four PNPN layers, but internal design elements, such as the n$^+$ buffer and thick base region, prevent latch-up. IGBTs are voltage-controlled like MOSFETs: applying a positive gate voltage allows conduction, while removing it turns the device off. They are available in two main structures punch-through (PT) and non-punch-through (NPT) each optimized for different performance traits. IGBTs offer high current and voltage ratings and are widely used in medium-power applications like motor drives and power supplies. [4]

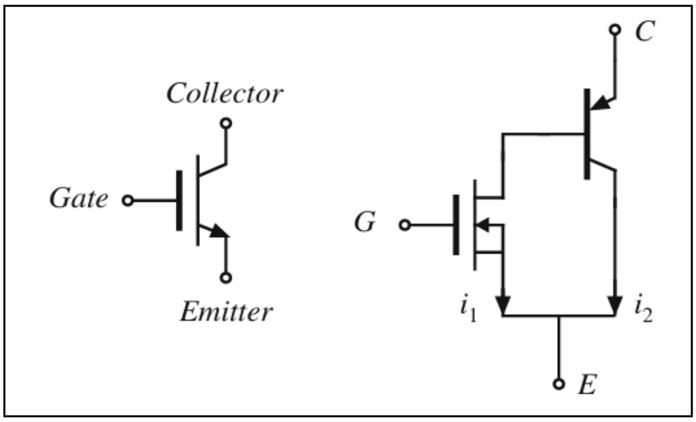


Fig I.7: Symbol of an IGBT transistor [6]

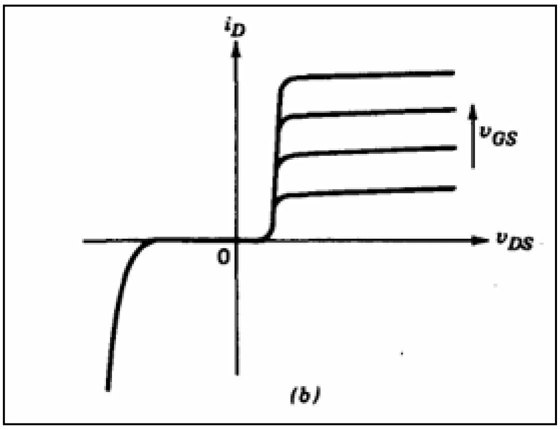


Fig I.8: Static V-I characteristic of an IGBT transistor [3]

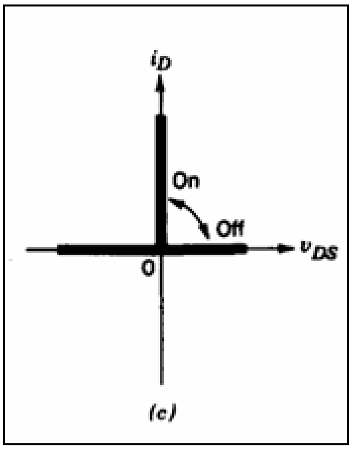


Fig I.9: Idealized V-I characteristic of an IGBT transistor [3]

I.4.1.2. MOSFET transistor

The MOSFET is a voltage-controlled semiconductor device widely used in power electronics for switching and amplification purposes. It consists of three terminals: Gate, Drain, and Source. The MOSFET operates by varying the voltage between the Gate and Source V_{gs} control the flow of current between the Drain and Source. When V_{gs} is below a certain threshold V_{th} the device remains off, acting as an open switch with no significant current flow. When V_{gs} exceeds the threshold, a conductive channel forms, allowing current to pass through from Drain to Source and the MOSFET behaves like a closed switch. Only a small current flows into the Gate during switching transitions, due to the charging and discharging of the gate capacitance, which enables high-speed operation. Because of its high switching speed, low on-resistance $R_{DS(on)}$, and minimal gate drive power, the MOSFET is especially suited for high-efficiency power conversion applications.[3]

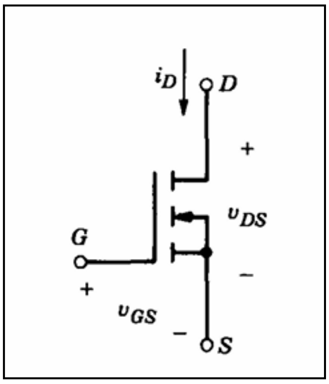


Fig I.10: Symbol of a MOSFET [3]

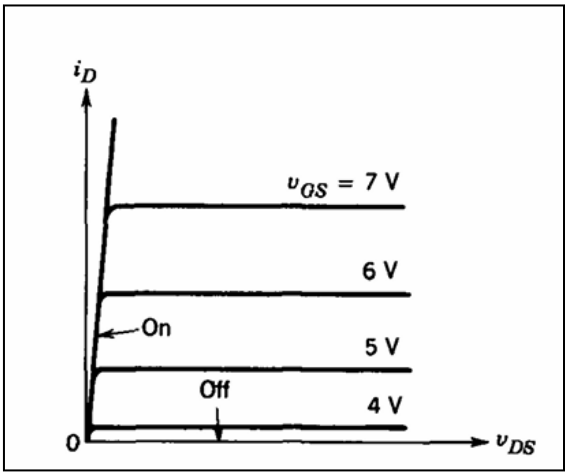


Fig I.11: Static V-I characteristic of a MOSFET [3]

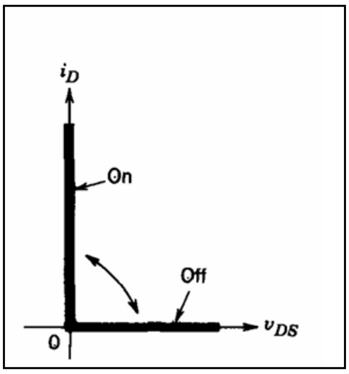


Fig I.12: Idealized V-I characteristic of a MOSFET [3]

I.4.2. Diodes

A power diode is a two-terminal semiconductor device formed using techniques like alloying, diffusion, or epitaxial growth, allowing precise control of its properties. It conducts current in forward bias (anode > cathode) with a low forward voltage drop, and blocks current in reverse bias, allowing only minimal leakage current. If the reverse voltage exceeds the breakdown voltage, avalanche conduction may occur. Power diodes are commonly modeled as ideal switches and are essential components in rectifiers, power supplies, and switching circuits. [4]

Based on their recovery characteristics and manufacturing techniques, power diodes are classified into the following three categories:

- Standard (or general-purpose) diodes

- Fast-recovery diodes
- Schottky diodes

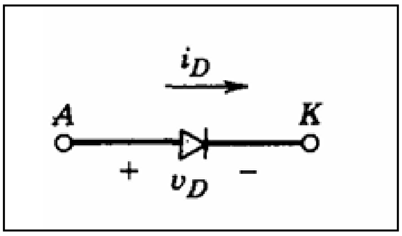


Fig I.13: Symbol of a diode [3]

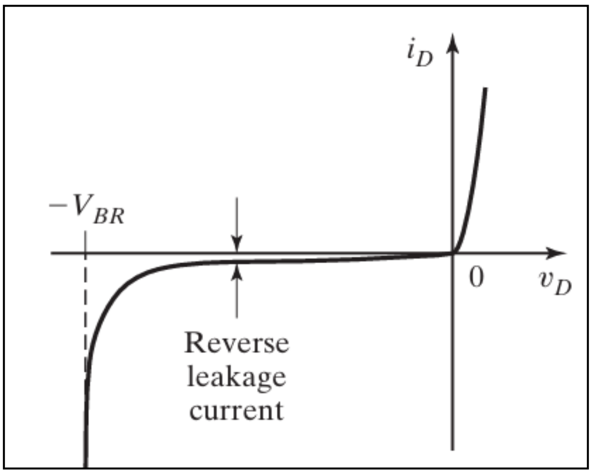


Fig I.14: Static V-I characteristic of a diode [2]

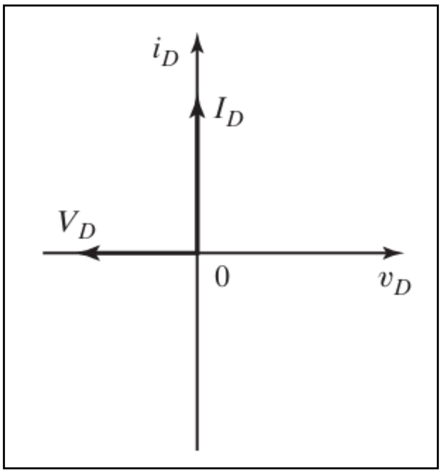


Fig I.15: Idealized V-I characteristic of a diode [2]

I.4.3. Inductor

An inductor is a passive electrical component that stores energy in a magnetic field when current flows through it. In the case of DC-DC converters, especially choppers (such as buck, boost, or buck-boost converters), the inductor plays a central role in energy transfer and voltage regulation.

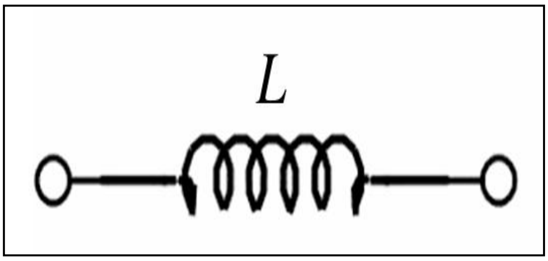


Fig I.16: Inductor symbol [7]

I.5. Operating analysis

I.5.1. Continues mode

I.5.1.1. First case

$0 < t < DT$, S is ON.

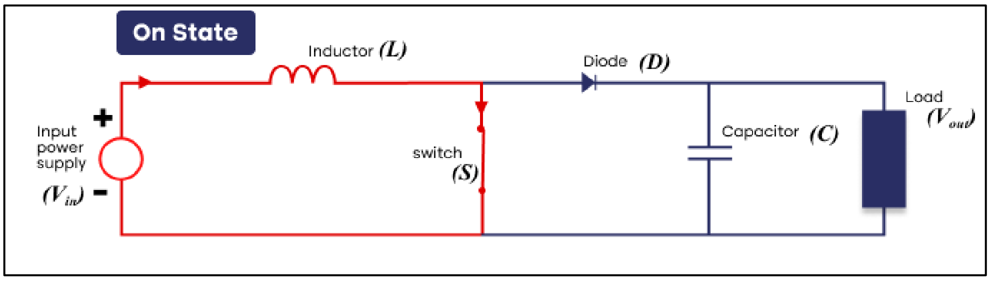


Fig I.17: The first case (S is ON) [8]

$V_D = -V_O$, the diode is OFF.

$$V_s = V_L = L\frac{di_L}{dt}(t) \Rightarrow i_L(t) = \frac{V_s}{L} \times t + A \tag{I.2}$$

$$i_L(0) = \frac{V_s}{L} \times 0 + A = i_{min} \Rightarrow A = i_{min} \quad \text{I.3}$$

$$i_L(t) = \frac{V_s}{L} \times t + i_{min} \quad \text{I.4}$$

I.5.1.2. Second case

$DT \ < t < T$, S is OFF.

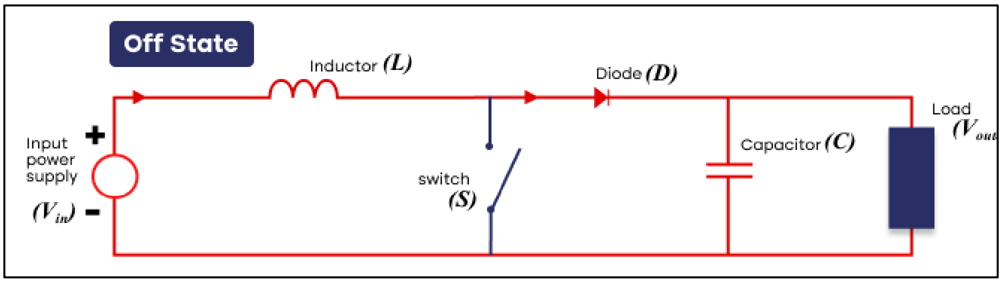


Fig I.18: The second case (S is OFF) [8]

$I_L \neq 0$, The inductor forces the diode to conduct current, so the diode is ON.

$V_{in} = V_o + L\frac{di_L}{dt}(t)$ With $i_L(T) = i_{min}$ and $i(DT) = \ i_{max}$

$$V_s = V_o + L\frac{di_L}{dt}(t) \Rightarrow V_s - V_o = \ L\frac{di_L}{dt}(t) \Rightarrow \ i_L(t) = \frac{V_{s-}V_o}{L} \times t + A \quad \text{I.5}$$

$$i_L(DT) = \frac{V_{s-}V_o}{L} \times DT + A = i_{max} \Rightarrow A = i_{max} - \frac{V_{s-}V_o}{L} \times DT \quad \text{I.6}$$

$$i_L(t) = \frac{V_{s-}V_o}{L} \times (t - DT) + i_{max} \quad \text{I.7}$$

I.5.1.3. Relationship between input and output voltages

In steady-state operation, the average voltage across the inductor is zero. Therefore:

$$\int Ldi_L = 0 \Rightarrow \frac{1}{T}\int_0^{DT} V_s dt + \frac{1}{T}\int_{DT}^{T} V_s - V_o(t)dt = 0 \Rightarrow D.V_s$$
$$+ (1 - D).\left(V_s - V_{omoy}\right) = 0 \quad \text{I.8}$$

$$\Rightarrow V_s = (1-D).V_{omoy} \tag{I.9}$$

So

$$V_{omoy} = \frac{V_s}{1-D} \tag{I.10}$$

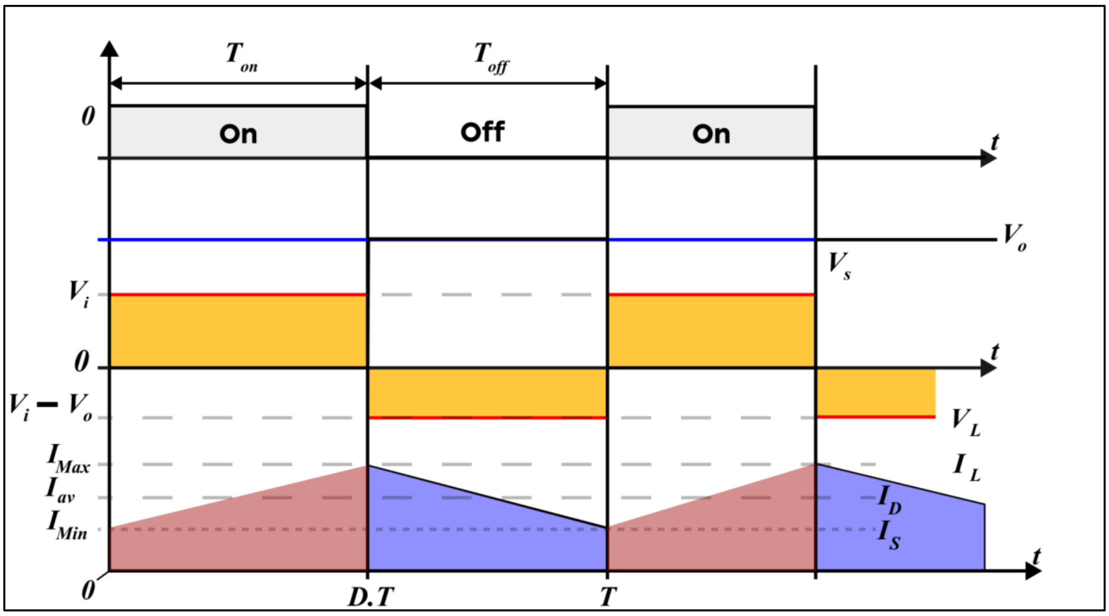


Fig I.19: Waveforms of the main quantities in boost converter in continuous mode [8]

I.5.2. Discontinues mode

Conduction is discontinuous if the minimum value IL_{MIN} of the current becomes zero in each period at t = βT, where βT ∈ [DT, T]; that is, i(βT) = 0.

I.5.2.1. First case

$0 < t < DT$, S is ON.

$$V_{in} = V_L = L\frac{di_L}{dt}(t) \Rightarrow i_L(t) = \frac{V_{in}}{L} \times t + A \tag{I.11}$$

$$i_L(0) = \frac{V_{in}}{L} \times 0 + A = 0 \Rightarrow A = 0 \qquad \text{I.12}$$

$$i_L(t) = \frac{V_{in}}{L} \times t \qquad \text{I.13}$$

I.5.2.2. Second case

$DT < t < \beta T$, S is OFF.

$V_{in} = V_o + L\frac{di_L}{dt}(t)$ with $i_L(T) = i_{min}$ and $i(DT) = i_{max}$

$$V_s = V_o + L\frac{di_L}{dt}(t) \Rightarrow V_s - V_o = L\frac{di_L}{dt}(t) \Rightarrow i_L(t) = \frac{V_{s-}V_o}{L} \times t + A \qquad \text{I.14}$$

$$i_L(DT) = \frac{V_{s-}V_o}{L} \times DT + A = i_{max} \Rightarrow A = i_{max} - \frac{V_{s-}V_o}{L} \times DT \qquad \text{I.15}$$

$$i_L(t) = \frac{V_{s-}V_o}{L} \times (t - DT) + i_{max} \qquad \text{I.16}$$

I.5.2.3. Third case

$\beta T < t < T$, S is off, the diode is OFF.

$V_{in} = U_s$; $V_D = V_{in} - V_o$; $i_s = 0$, $i_D = 0$ i_D , $i_L = 0$ and $V_L = 0$.

I.5.2.4. Relationship between input and output voltages

$$i_{max} = \frac{V_s - V_o}{L}.(\beta T - DT) = \frac{V_s}{L}.(DT) \Rightarrow \beta = D.\frac{V_s}{V_o - V_s} \qquad \text{I.17}$$

$$V_{omoy} = \frac{\beta}{\beta - D}.V_s \qquad \text{I.18}$$

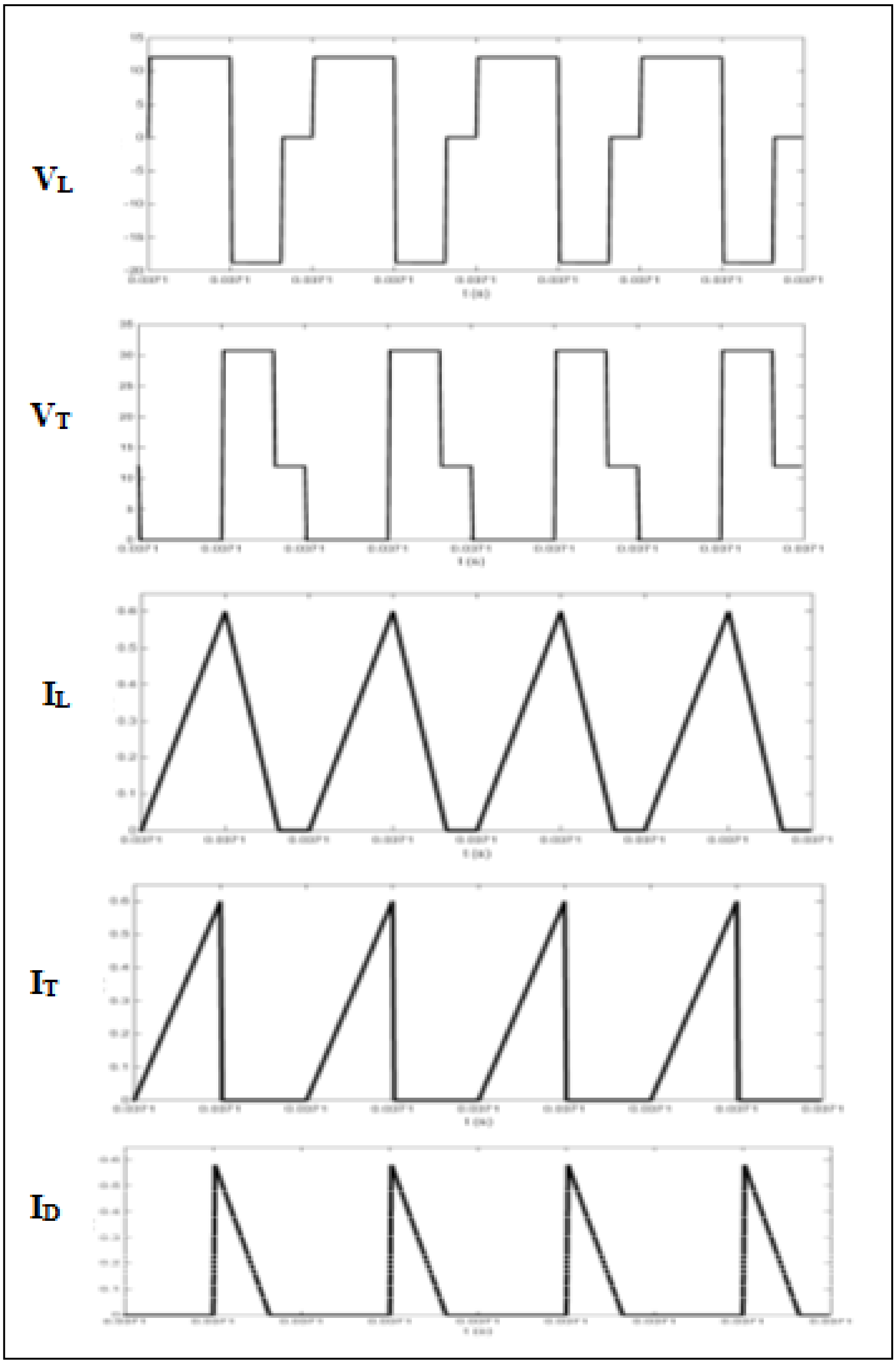


Fig I.20: Waveforms of the main quantities in boost converter in discontinuous mode [9]

I.6. Advantages and disadvantages of the Boost converter

Understanding the strengths and limitations of the boost converter is essential to evaluate its suitability for various applications. This section outlines the main advantages and disadvantages associated with this DC-DC conversion topology.

I.6.1. Advantages of the boost converter

The boost converter offers several key benefits, which contribute to its widespread use in power electronics: [10]

- High Efficiency in Voltage Step-Up: Boost converters are highly efficient when it comes to increasing the input voltage to a higher output level. When operating within their optimal conditions, they can achieve impressive efficiency rates, minimizing power losses.
- Compact and Lightweight Design: Due to their relatively simple structure, boost converters can be designed to occupy minimal space. This makes them particularly suitable for compact systems such as portable electronics, embedded devices, and wearable technologies.
- Low Output Voltage Ripple: Compared to some other converter topologies, boost converters typically generate output voltages with lower ripple. This characteristic is beneficial in applications where a stable and clean supply voltage is critical for proper operation.
- Capability for Moderate to High Output Power: Boost converters are well-suited for applications requiring moderate to high power delivery. Their design supports relatively high output power levels without significant performance degradation.
- Wide Input Voltage Tolerance: One of the notable features of boost converters is their ability to operate effectively across a broad range of input voltages. This makes them adaptable in systems where input conditions may fluctuate significantly.
- Ideal for Battery-Powered Systems: In battery-operated devices, boost converters play a crucial role in stepping up the battery voltage to meet the load requirements. This not only extends battery life but also ensures consistent performance as the battery discharges.

I.6.2. Disadvantages of the boost converter

Despite its advantages, the boost converter also presents certain drawbacks that must be considered during the design and implementation phases: [10]

- Electromagnetic Interference (EMI): Due to high-frequency switching, boost converters can generate significant EMI, which may interfere with nearby sensitive electronic equipment. Proper filtering and shielding techniques are often required to mitigate these effects.

- Increased Voltage Stress on Components: Components such as inductors, diodes, and capacitors experience higher voltage stress in boost converter circuits. This necessitates the use of components with higher voltage ratings, potentially increasing the cost and size of the overall system.
- Design and Control Complexity: Boost converters often require sophisticated control strategies to ensure stability and performance. This involves detailed analysis, including frequency-domain techniques like Bode plots, making their design more involved than simpler regulators.
- Lack of Electrical Isolation: Standard boost converters are non-isolated, meaning there is a direct electrical connection between the input and output. While this may be acceptable in many applications, systems requiring galvanic isolation for safety or EMI immunity will need additional isolation circuitry.
- Limited Output Current Capacity: Although capable of delivering high output power, boost converters may be constrained in terms of output current. This can be a limiting factor in high-current applications such as motor drives or high-power LED systems.

I.7. Applications and examples

Boost converters are commonly used in many applications thanks to their ability to increase input voltage. Below are some typical uses across various domains: [11]

- Power Supplies: They provide a stable, higher output voltage from a lower input, making them ideal for battery-powered and portable devices where voltage may drop over time. Examples include laptop adapters, USB chargers, and power banks.
- LED Lighting: In LED systems, especially in automotive lighting, boost converters maintain a constant current to ensure uniform brightness despite input voltage fluctuations.
- Solar Power Systems: Boost converters are key in solar energy systems, particularly in MPPT controllers, where they adjust the output voltage to maximize power extraction from solar panels and deliver it efficiently to batteries or the grid.

- Electric Vehicles: These converters step up battery voltage to levels required by high-power components like traction motors, or power steering, enabling efficient energy use.
- Telecommunications: Used to generate stable high voltages from low sources, boost converters ensure the consistent performance of RF transmitters, base stations, and related equipment.
- Sensor Systems: They supply stable voltage to sensitive electronics especially in systems powered by unstable sources like batteries or energy harvesting devices in remote monitoring applications.

I.8. Conclusion

The boost converter is a fundamental component in power electronics, offering an efficient and compact solution for stepping up voltage in a variety of applications. By utilizing basic yet powerful components such as an inductor, switch, diode, and capacitor, it achieves voltage regulation with high efficiency and continuous current flow, which is essential in battery-powered and renewable energy systems.

This chapter outlined the key types of DC-DC converters before focusing on the boost converter’s topology, operational principles in both continuous and discontinuous conduction modes, and detailed analysis of each component’s function. Furthermore, the advantages and disadvantages of the boost converter were discussed, emphasizing its suitability for applications requiring moderate to high power with a compact footprint and stable output.

As power demands continue to grow in both complexity and scale, understanding and optimizing converter technologies like the boost converter will remain a cornerstone in the design of advanced energy systems. In the following chapters (Chapter 2 and Chapter 3), the focus will be on improving the performance and efficiency of the boost converter by implementing regulation and control loops. These enhancements aim to address dynamic response, output stability, and adaptability under varying conditions, ensuring the converter operates reliably in real-world applications.

Chapter II: Design and Simulation of a PI Controller for Boost Converter

Chapter II: Design and Simulation of a PI Controller for Boost Converter

I. Introduction

Power electronic converters are fundamental components in a wide range of modern applications, including renewable energy systems, electric vehicles, and embedded power management. Their primary role is to convert electrical energy efficiently while adapting voltage and current levels to suit specific needs. Among the different types of DC-DC converters, the Boost converter is particularly valued for its ability to step up low input voltages to higher levels using a straightforward and compact topology. This makes it ideal for systems like solar panels or battery-powered devices where input voltages often fluctuate below the required output level.

However, the Boost converter's performance can be highly sensitive to changes in operating conditions such as input voltage, load demand, and switching frequency. These variations can lead to instability in the output voltage if not properly controlled. To ensure consistent and reliable operation, a robust control system is essential.

This chapter explores the design and simulation of a Proportional-Integral (PI) controller intended to regulate the output voltage of the Boost converter. Unlike open-loop configurations, which do not compensate for disturbances or system changes, the closed-loop PI controller dynamically adjusts the duty cycle of the converter to maintain voltage regulation.

We begin by presenting the main control strategies commonly used in DC-DC converters, followed by the mathematical modeling of the Boost converter to understand its dynamic behavior. The Ziegler–Nichols tuning method is then applied to optimize the PI controller parameters. Finally, simulation results using MATLAB/Simulink are provided to evaluate the performance of the controller and validate its effectiveness.

II.2. Overview of control techniques

II.2.1. Comparison between open and closed-loop control

In an open-loop control system, the control action is defined exclusively by the input signal, with no feedback from the output. These systems assume a fixed relationship between input and output, which simplifies their design and operation. However, they cannot detect or correct deviations caused by disturbances or changes in system parameters. Any variation in the process or external conditions will directly affect the output, since the system has no mechanism to measure performance or adjust its behavior accordingly. As a result, open-loop systems lack adaptability and are generally unsuitable for applications requiring high accuracy, robustness, or dynamic response to external changes. [12]

For example, in a Boost converter operating in open loop, a sudden drop in the input voltage or a change in the load resistance can cause the output voltage to drift significantly from its desired value, since the system is unable to compensate for such variations.

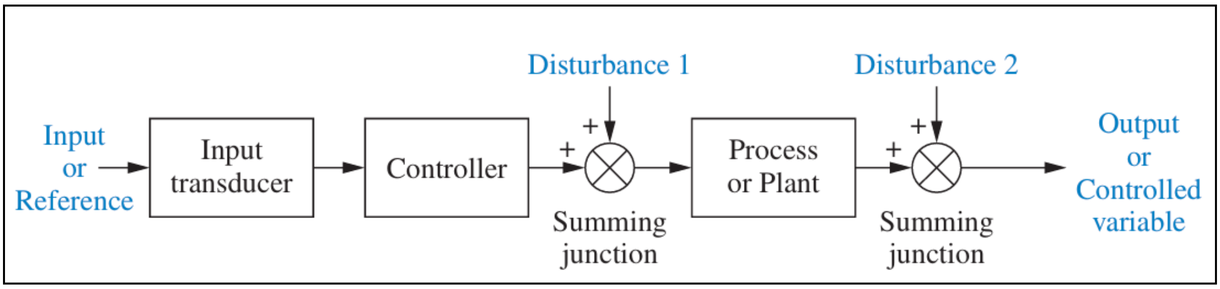


Fig II.1: Schematic of an open loop system [12]

In closed-loop control systems, the output is continuously compared to a reference input through a feedback loop. This comparison generates an error signal, which is used by the controller to adjust the system's behavior. By reacting to disturbances and environmental changes, closed-loop systems provide significantly improved accuracy and robustness compared to open-loop systems. The feedback mechanism allows the system to maintain the desired output even in the presence of noise or parameter variations. Additionally, the transient and steady-state performance can be fine-tuned by adjusting the controller gain or redesigning the controller itself, a process known as system compensation. [12]

For exemple, in a Boost converter operating in closed loop, the output voltage is constantly measured and compared to a set reference. If a disturbance such as a drop in input voltage or a variation in load occurs, the controller modifies the duty cycle of the PWM signal to correct the output. This ensures that the output voltage remains stable and close to the desired value, making the system suitable for applications requiring precise voltage regulation.

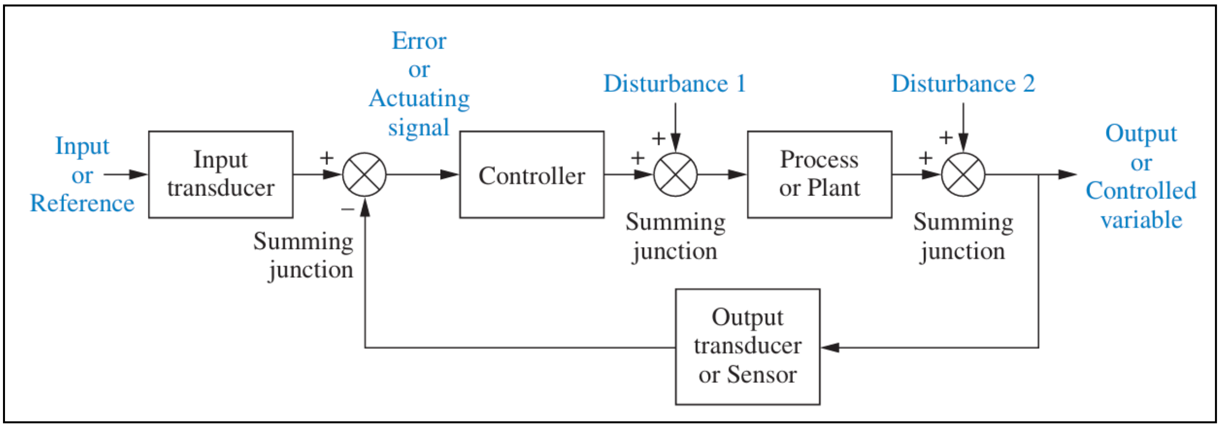


Fig II.2: Schematic of a closed loop system [12]

II.2.2. P, I, D, PI, PD, PID controllers

In power electronics, several classical controllers are commonly used to regulate system behavior and improve dynamic performance: [13]

The proportional (P) controller reacts instantly to the current error between the reference and the measured value. It ensures a fast system response, but it cannot eliminate steady-state error, often resulting in a residual offset.

The integral (I) controller accumulates the error over time and adjusts the output accordingly. This allows the system to eliminate the steady-state error and reach the exact desired value. However, this action is slower and may introduce overshoot or instability if not properly tuned.

The derivative (D) controller anticipates future behavior by reacting to the rate of change of the error. Its main role is to dampen oscillations and enhance system stability, especially in rapidly changing processes.

To combine the strengths of these individual actions, more advanced structures are used: [13]

The proportional integral (PI) controller links the output to both the current error and its integral. The proportional term provides fast response, while the integral term ensures elimination of steady-state error. This combination offers a good balance between speed and accuracy and is widely used in power electronics.

The proportional derivative (PD) controller combines proportional and derivative actions, allowing the system to respond quickly to changes while anticipating future trends. The proportional part handles immediate deviations, while the derivative term predicts and dampens potential oscillations. However, without the integral component, steady-state error cannot be fully corrected.

The proportional integral derivative (PID) controller integrates all three terms proportional, integral, and derivative into one control strategy. It offers fast response (P), zero steady-state error (I), and improved damping and stability (D).

II.2.3. Control challenges in boost converters

The control of a Boost converter presents some challenges because the system is nonlinear due to its switching nature. The duty cycle affects both the inductor current and the output voltage at the same time, and the output can also change with variations in the input source or the load. In addition, working in Continuous or Discontinuous Conduction Mode adds more complexity. For this reason, using an averaged linear model and a feedback controller is a common and practical solution.

II.3. Controller Selection

II.3.1. Justification of choosing PI over other controllers

The selection of a suitable controller is critical in ensuring stable and robust regulation of the Boost converter output. In power electronics, where systems are highly nonlinear and time-varying, various control strategies have been investigated.

However, the PI controller is commonly used in engineering applications where maintaining a stable output and eliminating steady-state error are essential. By combining the immediate responsiveness of proportional action with the long-term correction of integral action, they offer effective control while remaining relatively simple to implement. [14]

Additionally, in the case of Boost converters operating under pulse width modulation (PWM), PI controllers are generally preferred over PID controllers, as the combination of high-frequency current ripple and derivative action can increase variability and degrade system performance. [15]

In this project, where the control will later be implemented using a Raspberry Pi in a real-time simulation environment, the simplicity and efficiency of the PI controller are particularly advantageous.

The general transfer function of a PI controller is:

$$C(s) = K_p \times \frac{K_i}{s} \tag{II.1}$$

Where:

- Kp is the proportional gain
- Ki is the integral gain
- s is the laplace variable

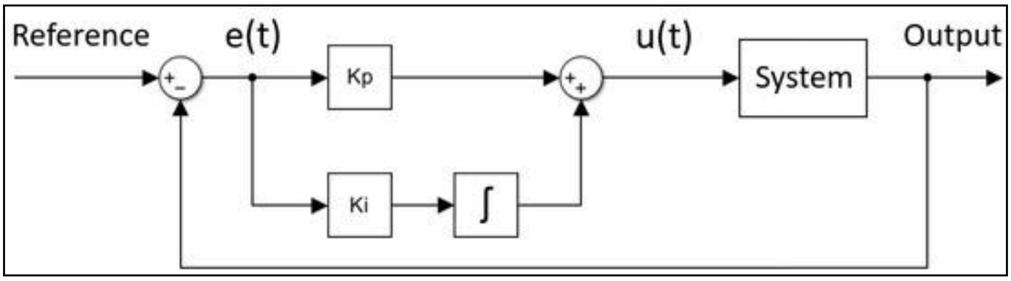


Fig II.3: Block diagram of a PI control schematic [14]

II.3.2. Comparison with advanced control methods

Several advanced control methods have been developed to improve the performance and robustness of power converters. Such as:

- Sliding mode control (SMC) is a nonlinear control strategy valued for its high resilience to system uncertainties and disturbances. It operates by creating a specific surface in the state space called the sliding surface and adjusting the control input to push the system states toward and along this surface. Once reached, the system’s dynamics become less sensitive to parameter variations and external disruptions. [16]

  This level of robustness makes SMC especially appropriate for power electronic systems, which often face fluctuations due to changing load conditions or aging components. However, a known drawback of SMC is the chattering effect, a rapid oscillation in the control signal caused by its switching nature. To address this, techniques such as boundary layer smoothing **or** higher-order sliding modes are frequently used. [16]

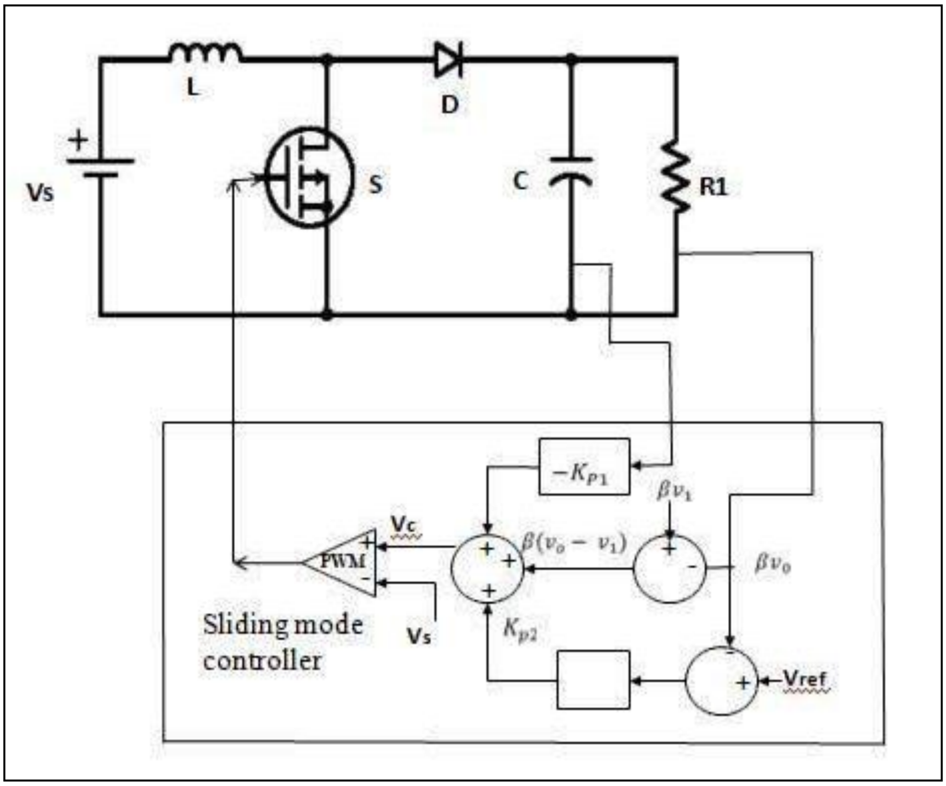


Fig II.4: Block diagram of sliding mode control [17]

- Fuzzy Logic Control (FLC) is a nonlinear control strategy introduced to manage systems with uncertainty and imprecision. Unlike traditional control methods that depend on exact mathematical models, FLC uses approximate reasoning through fuzzy sets, linguistic variables, and rule-based logic. This allows it to mimic human decision-making, making it especially useful for systems with vague or poorly defined dynamics, such as those commonly found in power electronics. [18]

  FLC offers strong advantages, including robustness to nonlinearities and disturbances, adaptability to varying conditions, smooth control output, and the ability to integrate expert knowledge through linguistic rules. These features make it highly effective for applications like DC-DC converters and motor drives. However, FLC also comes with drawbacks such as high computational demands, lack of formal design methods, and the need for time-consuming tuning and optimization. Additionally, its heuristic nature can limit analytical understanding and complicate performance validation. [18]

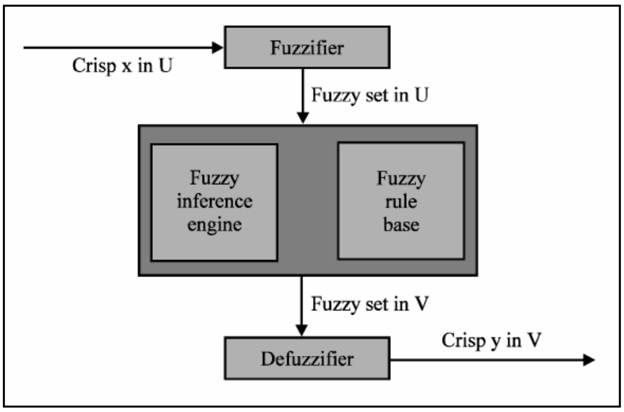


Fig II.5: fuzzy logic control process [19]

- Neural network control is an intelligent control strategy inspired by the structure and function of the human brain. It has emerged as a promising solution for managing the complex and nonlinear behavior often found in power electronic systems, where traditional linear methods may fall short. By learning from data rather than relying on explicit models, neural networks are capable of approximating system behavior and optimizing control responses accordingly. [20]

Neural network controllers offer several strengths, including adaptability through learning, robustness against nonlinearity and uncertainty, and the ability to perform fast parallel computations crucial for real-time control. However, they also present challenges. Designing and tuning an effective neural network requires substantial expertise, and models may overfit training data, reducing their generalization ability. Additionally, neural networks operate as "black boxes," offering little insight into their internal decision-making processes. Their training and implementation can also demand significant computational power. Despite these limitations, neural networks remain a powerful tool in advanced control, with ongoing research aiming to address current drawbacks. [20]

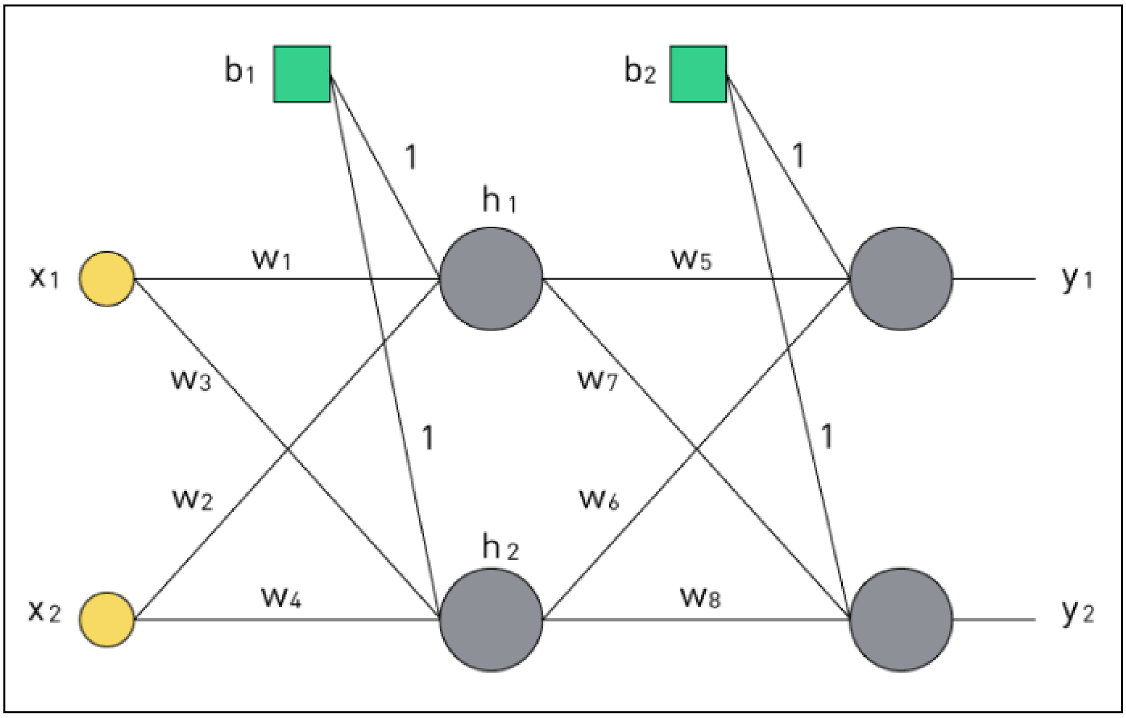


Fig II.6: Structure of a simple neutral network [20]

In academic contexts where implementation constraints exist, PI control remains a practical and effective solution.

II.4. Mathematical modeling of the boost converter

II.4.1 Operating principle

A Boost converter increases the input DC voltage by alternating between two modes:

- Mode 1 (Switch ON): The inductor stores energy from the input source.
- Mode 2 (Switch OFF): The inductor releases energy to the output capacitor and load.

II.4.2. System parameters

Before selecting the Boost converter parameters, it is essential to understand the mathematical expressions that govern its behavior. The key equations used in the design process are:

- The duty cycle:

$$D = 1 - \frac{V_{in}}{V_{out}} \qquad \text{II.2}$$

- The Inductor selection:

$$L = \frac{V_{in} \times D}{\Delta \mathrm{I_L} \times \mathrm{f_s}} \qquad \text{II.3}$$

- The output capacitor selection:

$$C_{out} = \frac{I_{out} \times D}{\Delta \mathrm{V_{out}} \times \mathrm{f_s}} \qquad \text{II.4}$$

Parameter	**Symbol**	**Value**
Input Voltage	V_{in}	5 V
Switching Frequency	f_s	25 kHz
Inductance	L	1.5 mH
Output Capacitor	C	250 µF
Resistor	R	200Ω

Table II.1: Boost converter parameters

II.4.3. State-Space averaged model

The state-space averaging method allows expressing the converter’s dynamics during both ON and OFF switching states. By weighting each state by the duty cycle D, an averaged model is obtained.

Let :

$$\begin{cases} x_1 = i_L \\ x_2 = V_{out} \end{cases} \qquad \text{II.5}$$

The averaged state-space become:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L} \times (V_{in} - (1 - D) \times V_{out}) \\ \dfrac{dV_{out}}{dt} = \dfrac{1}{C} \times \left((1 - D) \times i_L - \dfrac{V_{out}}{R} \right) \end{cases} \qquad \text{II.6}$$

These equations are nonlinear due to the multiplication involving the duty cycle.

II.4.4. Small-Signal transfer function

Small perturbations around the steady-state duty cycle D_0 are introduced:

$$\begin{cases} d(t) = D_0 + \Delta d(t) \\ i_L(t) = i_{L_0} + \Delta i_L(t) \\ V_{out}(t) = V_{out_0} + \Delta V_{out}(t) \end{cases} \qquad \text{II.7}$$

Where:

- D_0 is the nominal (steady-state) duty cycle,
- Δd(t) is a small variation in the duty cycle,
- IL_0 is the steady-state inductor current,
- ΔiL(t) is a small variation in the inductor current,
- $Vout_0$ is the steady-state output voltage,
- ΔVout(t) is a small variation in output voltage.

After linearization and Laplace transformation, the small-signal transfer function from Δd(s) to ΔVout(s) is given by:

$$G(s) = \frac{\Delta V_{out}(s)}{\Delta d(s)} = \frac{G_0\left(1 - \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{\omega_1}\right)\left(1 + \frac{s}{\omega_2}\right)} \qquad \text{II.8}$$

$$G(s) = \frac{\Delta V_{out}(s)}{\Delta d(s)} = \frac{1 - \frac{s}{RC(1 - D_0)^2}}{LCs^2 + \frac{L}{R}s + \frac{(1 - D_0)^2}{RC}} \qquad \text{II.9}$$

Where:

- G_0 is the gain,
- ω_z is a zero,
- ω_1 and $\boldsymbol{\omega_2}$ are the system's corner frequencies (poles).

These parameters depend on the values of L, C, R, and the steady-state duty cycle D_0**.** The transfer function enables frequency-domain analysis and facilitates controller design.

II.5. Ziegler–Nichols method for PI tuning

II.5.1. Methodology and empirical basis

The Ziegler–Nichols tuning method is an approach used for tuning PID and PI controllers. It is based on experimentally determining the ultimate gain Ku and the oscillation period Tu of the system by placing the system in closed-loop with only a proportional controller and increasing the gain until the system starts oscillating. [21]

Once Ku and Tu are determined, the controller parameters are calculated using standard formulas.

For PI control:

$$K_p = 0.45K_u \tag{II.10}$$

$$T_i = \frac{T_u}{1.2} \tag{II.11}$$

$$K_i = \frac{K_p}{T_i} \tag{II.12}$$

II.5.2. Simulation-Based tuning procedure

To apply Ziegler–Nichols tuning, the following steps were followed in Simulink:

1. Implemented a Boost converter model with no feedback (open-loop).
2. Added a P-controller only in a unity feedback configuration.
3. Gradually increased the gain Kp until the oscillations were observed.
4. Measured the amplitude and period of the resulting output oscillation.
5. Applied Ziegler–Nichols formulas to compute Kp and Ki for the PI controller.

II.5.3. Determination of Kp and Ki

Based on the closed-loop simulation and following the Ziegler–Nichols tuning method, the ultimate gain and oscillation period were determined and with applying the Ziegler–Nichols formulas, the final PI controller used in simulation has:

$$Kp = 0.029 \tag{II.13}$$

$$Ki = 5 \qquad \text{II.14}$$

These values provide a fast response with limited overshoot and satisfying steady-state performance. [13]

II.6. MATLAB/Simulink modeling and simulation

II.6.1. Simulation environment

Simulink is a visual programming tool used for modeling, analyzing, and simulating systems that involve multiple domains. It allows engineers to create system models using a block-based interface, supporting tasks such as control design, embedded system development, and automatic code production. Simulink includes a rich collection of functional blocks, a user-friendly editor for building models, and numerical solvers for simulating system dynamics over time. Seamlessly connected to MATLAB, it enables integration of MATLAB code into simulation workflows and facilitates post-processing and analysis of results. [22]

Ii.6.2. Block diagram of the system

The full simulation model consists of:

- Boost converter power stage
- Feedback loop with measured output voltage
- Error computation block
- PI controller
- PWM generator

Below is a block diagram of the boost converter in both open loop and closed loop:

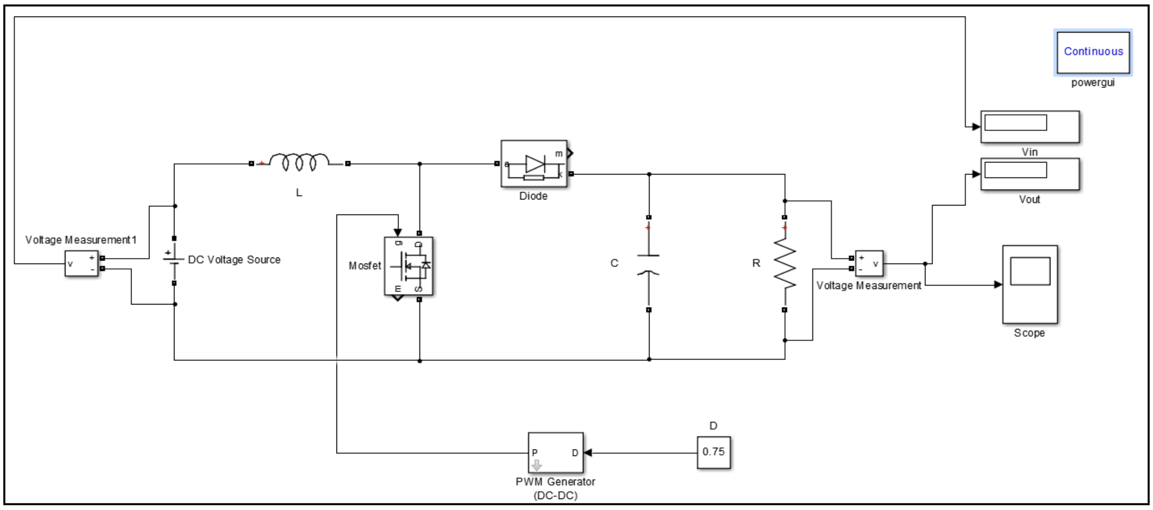


Fig II.7: Block diagram of the boost converter in open loop

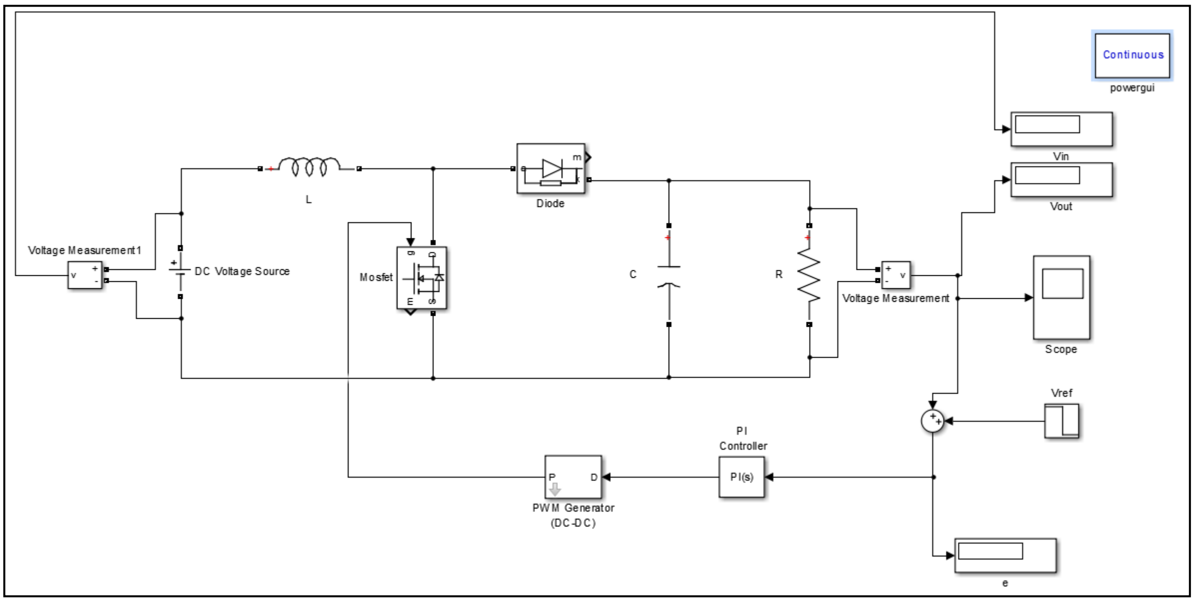


Fig II.8: Block diagram of the boost converter in closed loop with PI controler

II.6.3. PWM Generation and Modulation

The output signal from the PI controller is directed to the PWM generator, which is responsible for producing the gate pulses. This is achieved by comparing the PI signal with a triangular waveform. Based on this comparison, the PWM generator creates a series of pulses whose width varies according to the PI output. These pulses define the duty cycle applied to the MOSFET, which allows control over the converter's switching behavior and helps maintain a stable output voltage. [23]

Key parameters:

Parameter	Value
Switching Frequency	25 kHz
Period	40µs
PI output range	Between 0 and 1

Table II.2: The key parameters of the PWM

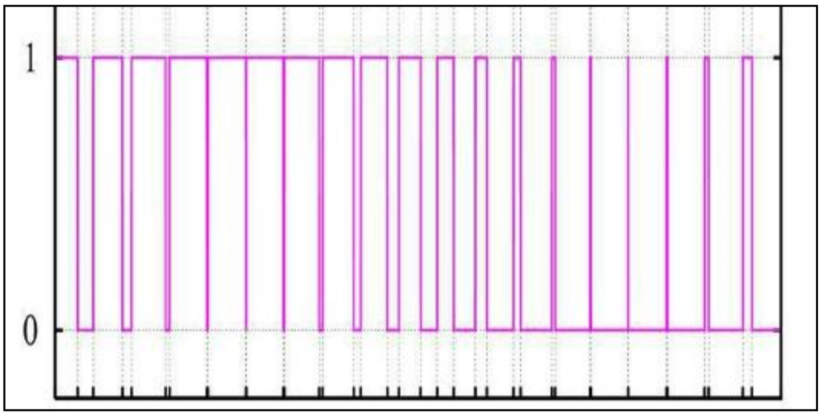


Fig II.9: Control and PWM signals [23]

II.7. Simulation results and performance evaluation

This section presents the simulation results for the Boost converter under both open-loop and closed-loop conditions. The goal is to demonstrate how the PI controller regulates the output voltage to 30 and switched to 20 V at t = 2.5s, regardless of input voltage variations.

II.7.1. Open-loop simulation

The open-loop behavior of the Boost converter is evaluated to illustrate its uncontrolled response to different input voltages. In this configuration, the duty cycle is 0.75 and no feedback regulation is applied.

Case 1: nominal input voltage (Vin = 5 v)

- Output voltage ≈ 19.07 v

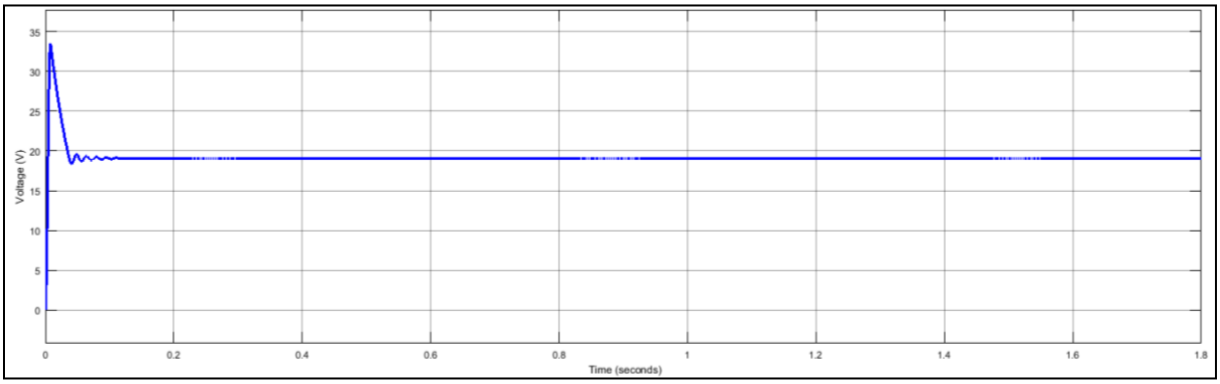


Figure II.10: Output voltage under nominal input 5V

- Observation: The Boost converter exhibits a fast startup with an initial voltage overshoot reaching around 35 V, followed by a damped oscillatory response that stabilizes near 19.07 V. This behavior is typical of an open-loop system with low damping, where the absence of active regulation leads to transient overshoots. Although the output voltage is close to the desired 20 V, a slight undervoltage is observed, likely due to intrinsic losses in the components, such as the inductor's series resistance, the diode's forward voltage drop, and switching losses in the power transistor.

Case 2: Input voltage drop (Vin = 3 V)

- Output voltage ≈ 11.12 v

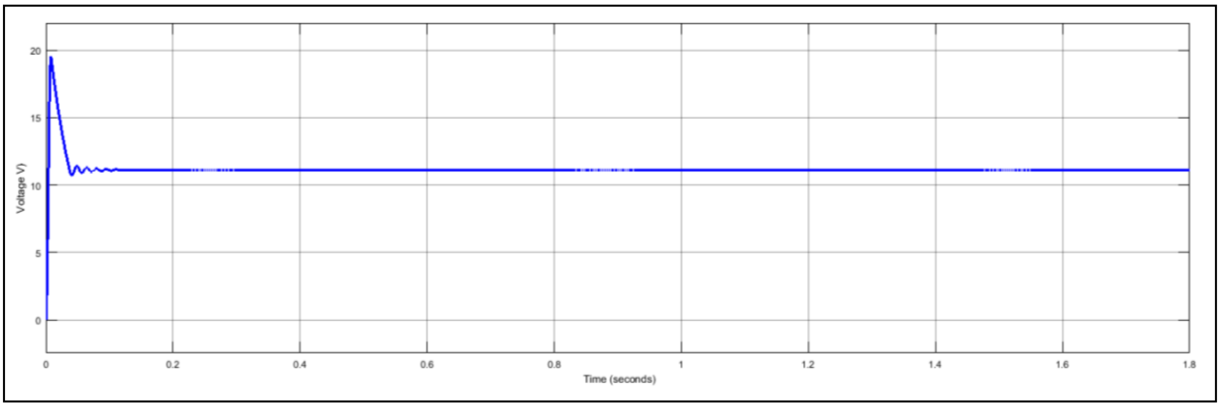


Figure II.11: Output voltage under input voltage drop Vin = 3V

- Observation: When the input voltage is reduced to 3 V, the output voltage significantly drops to about 11.12 V. The dynamic response remains similar to the nominal case, with a small overshoot followed by stabilization. However, the efficiency of the converter decreases in this condition, and the fixed duty cycle applied is no longer sufficient to maintain the target output voltage. This highlights the limitations of open-loop operation, where the output voltage is directly affected by input variations without any corrective feedback.

Case 3: Input voltage increase (Vin = 10 V)

- Output voltage ≈ 38.95 v

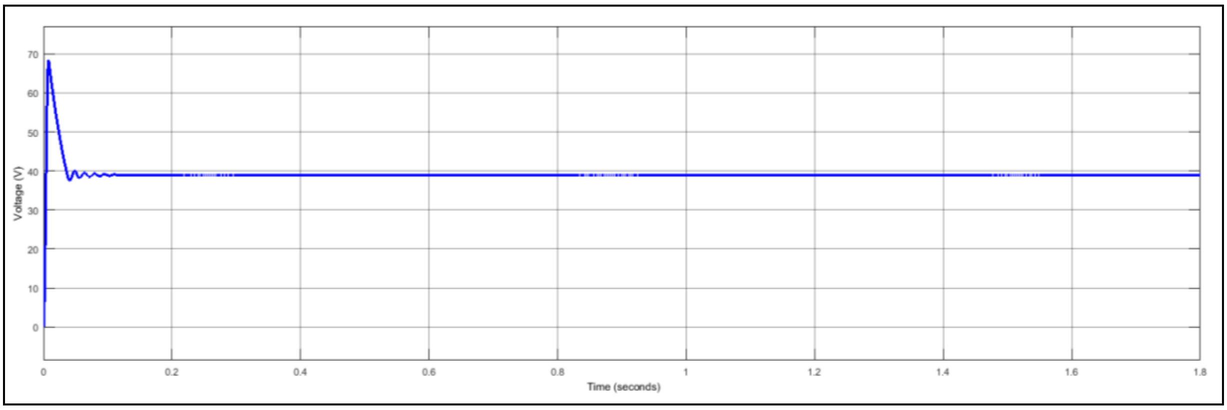


Figure II.12: Output voltage under higher input voltage Vin = 10V

- Observation: With an increased input voltage of 10 V, the converter produces an output of 38.95 V, nearly double the target value. A much larger initial overshoot is observed, peaking around 70 V before settling at a final steady-state voltage. This behavior demonstrates the risks of operating in open-loop mode, a higher input voltage results in a dangerously high output voltage, potentially exceeding the safe limits of the components or the load. This underscores the need for closed-loop regulation to maintain the output voltage within specified bounds, regardless of input fluctuations.

These results clearly show that open-loop control cannot guarantee voltage regulation, especially under varying input conditions.

II.7.2. Closed-loop simulation with PI controller

In this section, the Boost converter is simulated with a PI controller tuned previously using the Ziegler–Nichols method. The controller dynamically adjusts the duty cycle to maintain the output at 30 V and then switched to 20 V at t = 2.5s, regardless of input voltage.

Case 1: Nominal operation (Vin = 5 V)

- Output voltage (t < 2.5) ≈ 30V.
- Output voltage (2.5 < t) ≈ 20V.

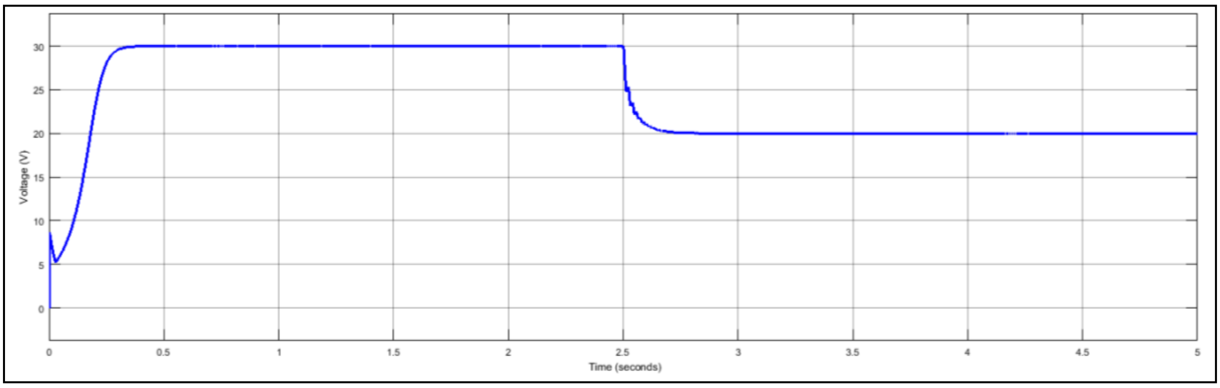


Figure II.13: Regulated output voltage under nominal input 5V

Case 2: Low input voltage (Vin = 3 V)

- Output voltage (t < 2.5) ≈ 30V.
- Output voltage (2.5 < t) ≈ 20V.

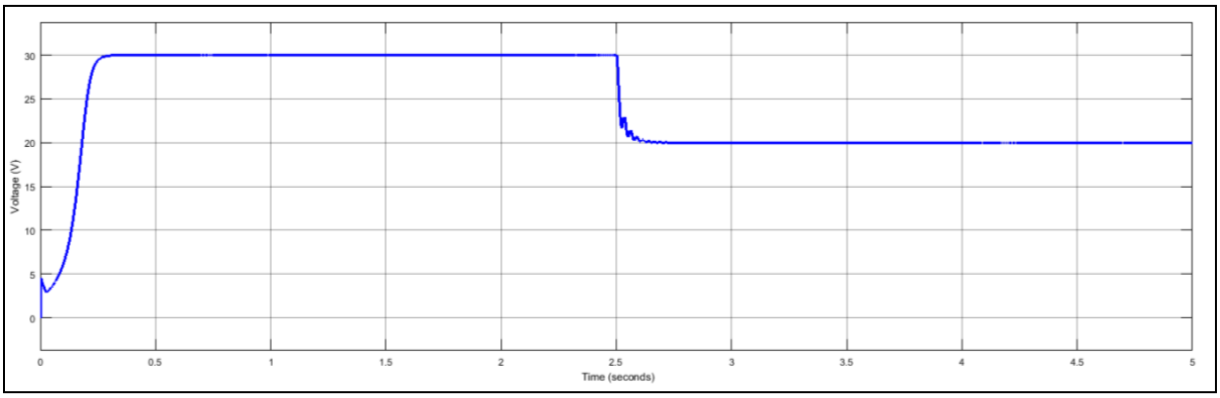


Figure II.14: Regulated output voltage under low input voltage 3V

Case 3: High input voltage (Vin = 10 V)

- Output voltage (t < 2.5) ≈ 30V.
- Output voltage (2.5 < t) ≈ 20V.

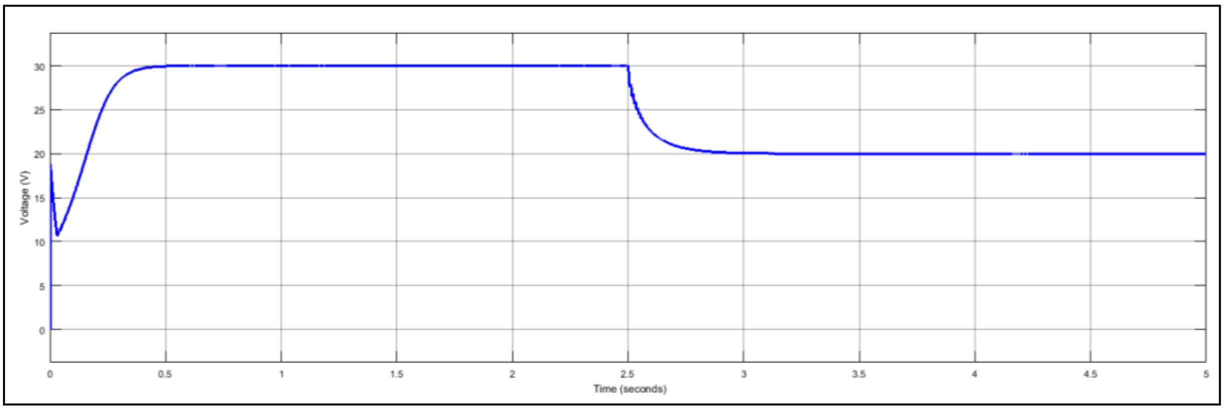


Figure II.15: Regulated output voltage at high input voltage 10V

- Observation: The closed-loop response of the boost converter, tested with input voltages of 3 V, 5 V, and 10 V, demonstrates stable and accurate regulation in all cases. The output voltage rises smoothly to the initial target of 30 V, with only a slight undershoot and no significant overshoot, indicating proper controller tuning. At t = 2.5 seconds, the reference voltage is lowered to 20 V. The system quickly adapts, transitioning smoothly and maintaining the new voltage level with precision.

Compared to the open-loop configuration, the PI controller greatly improves performance by correcting deviations caused by input voltage variations and ensuring consistent output regulation. Although the closed-loop response is slightly slower, this delay improves system stability and accuracy. Overall, the controller is capable of adapting effectively to reference changes and input variations, ensuring reliable operation of the boost converter.

II.8. Conclusion

In this chapter, various control strategies commonly used in power electronics were first introduced, highlighting their respective strengths, and limitations. Among these methods, the Proportional-Integral (PI) controller was selected due to its simplicity, ease of implementation, and proven effectiveness in voltage regulation tasks. After justifying this choice, the mathematical model of the Boost converter was derived and the Ziegler–Nichols method was applied to determine appropriate PI parameters, offering a practical balance between responsiveness and system stability.

To evaluate performance, both open-loop and closed-loop simulations were conducted using MATLAB/Simulink, under three different input voltage conditions: 3 V, 5 V, and 10 V. The open-loop tests revealed critical limitations, such as sensitivity to input variations, significant output deviation, and in extreme cases, dangerous overshoots. In contrast, the PI-based closed-loop configuration provided accurate output regulation of 30 V initially, the successfully switched to 20 V at 2.5s in all scenarios, with smooth transient behavior, and improved robustness. While the response time in closed-loop mode was slightly longer, it contributed to enhanced system stability and control precision.

Overall, this study demonstrated the limitations of open-loop operation and confirmed the relevance of PI control for Boost converters, particularly under varying input and output conditions. The successful simulation results lay a strong foundation for real-time implementation in the next chapter, which will involve deploying the controller on a Raspberry Pi platform and validating it through Processor-in-the-Loop (PIL) testing.

Chapter III: Processor-in-the-Loop for Boost Converter Control Using Raspberry Pi

III.1. Introduction

The increasing complexity of embedded control systems, particularly in power electronics, demands robust and reliable methods for design validation and performance testing. As systems become more software-driven, traditional hardware-only testing approaches are often insufficient, costly, or risky in early development phases. To address these challenges, simulation techniques have become an essential part of the engineering workflow, enabling developers to model, test, and refine control algorithms in a safe and flexible environment.

Among these techniques, Processor-in-the-Loop (PIL) simulation offers a practical solution by combining the realism of executing code on actual hardware with the flexibility of a simulated system model. This hybrid method allows developers to observe how embedded software performs under real-world processor constraints, such as computation limits, and memory usage, without the need for the complete physical system. By enabling early detection of implementation issues and offering a realistic testing environment, PIL contributes significantly to improving the reliability, efficiency, and safety of embedded control applications.

In this chapter, various validation techniques used in control system design are introduced, followed by an overview of suitable hardware platforms. The focus is then placed on the detailed implementation and application of the PIL method.

III.2. validation techniques in control system design

Control system design involves various techniques, each tailored to a particular phase of the system development lifecycle and aimed at ensuring accurate verification and validation of embedded systems:

III.2.1. Model-in-the-Loop (MIL)

Model-in-the-Loop (MIL) is a simulation-based verification method used in the early stages of Model-Based Design (MBD). It involves testing system models within a fully virtual environment to ensure that they perform according to design specifications. Using tools such as MATLAB/Simulink, engineers can simulate the behavior of control algorithms or system logic without involving any physical hardware or generated code. MIL helps validate the functional correctness of the model by applying test inputs and observing the output responses. This process enables the early detection of design errors, logic flaws, or integration issues before moving on to more complex stages like code generation or hardware implementation. Because testing in MIL is entirely software-based, it offers a flexible and cost-effective way to run extensive scenarios including edge cases and fault conditions that may be difficult to replicate physically. The ability to iteratively refine and simulate models in this environment accelerates development while reducing risk and rework in later phases. [24]

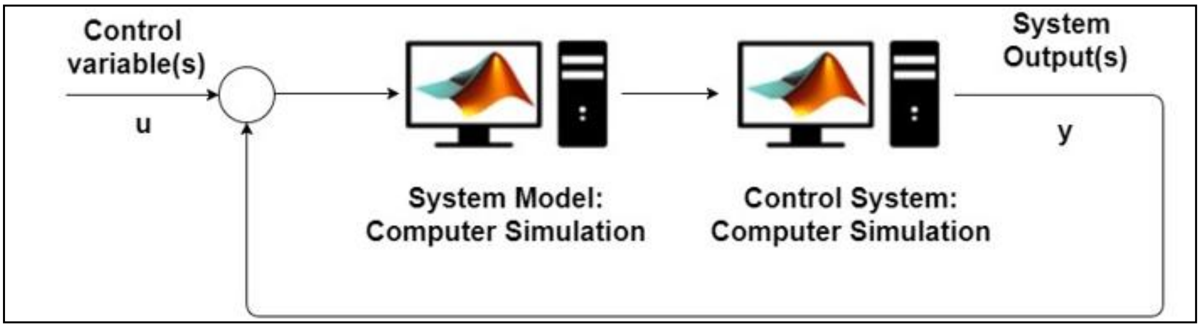


Fig III.1: Schematic view of Model-in-the-loop [25]

III.2.2. Software-in-the-loop (SIL)

Software-in-the-Loop (SIL) is a simulation-based testing method used to validate and debug embedded software early in the development cycle. It involves executing comPILed code within a virtual environment to evaluate functionality, stability, and performance without the need for physical hardware. SIL helps developers identify issues quickly and cost-effectively by running automated test scenarios on a standard computer, enabling rapid feedback and continuous refinement of the code. This approach supports iterative development, where individual modules or components can be tested independently, even before the full system is complete. Because tests are performed entirely in software, they can often run faster than in real time and be repeated consistently, improving debugging efficiency. The quality and effectiveness of SIL depend on the accuracy of the simulation models and the design of the test cases, which aim to replicate real-world conditions and edge cases as closely as possible. [26]

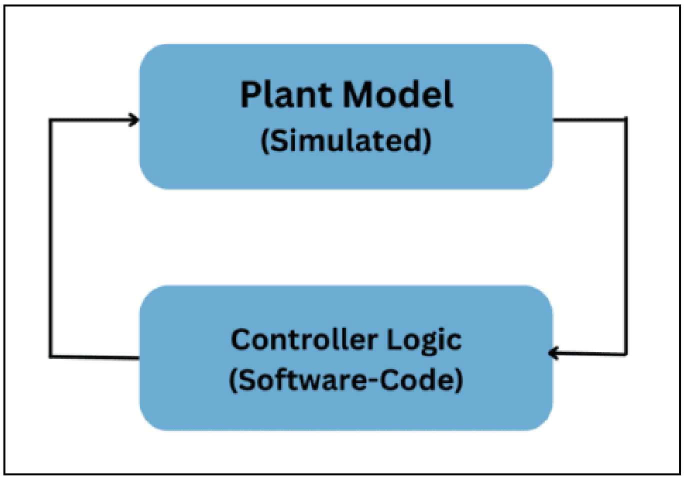


Fig III.2: Schematic of Software-in-the-loop [27]

III.2.3. Processor-in-the-Loop (PIL)

Processor-in-the-Loop (PIL) is a simulation technique where the code generated from a control model is comPILed and executed on a specific target processor**.** This method involves both the simulation model and the actual onboard processor intended for deployment. PIL is typically used after the development of validated and stable models and just before the final integration phase. It is supported by various modeling environments such as MATLAB/Simulink**,** enabling developers to test and verify the behavior of the embedded code directly. [28]

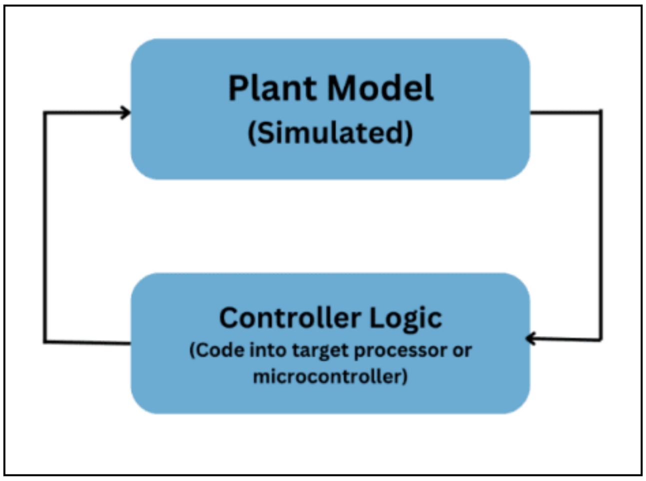


Fig III.3: Schematic of Processor-in-the-loop [27]

III.2.4. Hardware-in-the-Loop (HIL)

Hardware-in-the-Loop (HIL) simulation is a development and testing method used in embedded systems engineering. It connects the actual controller hardware to a simulated model of the physical system, enabling real-time interaction through input/output (I/O) channels. This setup is widely applied in fields like aerospace and automotive to verify the integration between hardware and software components. HIL allows engineers to evaluate control strategies and I/O behavior early in the development process before the complete physical system is built thereby reducing risk, speeding up design iterations, and ensuring system reliability without exposing real hardware to potential damage. [29]

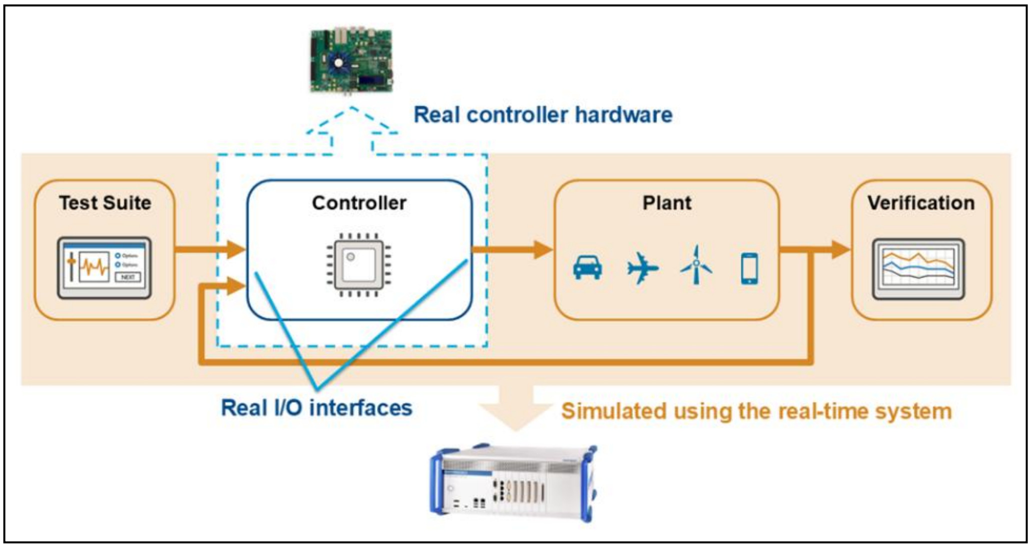


Fig III.4: Schematic of Hardware-in-the-loop [29]

III.2.5. Comparison between simulation techniques

Technique	Controller	Connections	Plant	Related Products
MIL	Simulated (model)	Virtual	Simulated	Simulink
SIL	ComPILed code (software)	Virtual	Simulated	Simulink, Simulink Coder™, Embedded Coder®

PIL	Real processor	TCP/IP or serial	Simulated	Simulink, Simulink Coder, Embedded Coder
HIL	Real controller hardware	Analog and digital signals	Simulated in real time	Simulink, Simulink Coder, Embedded Coder, Simulink Real-Time™

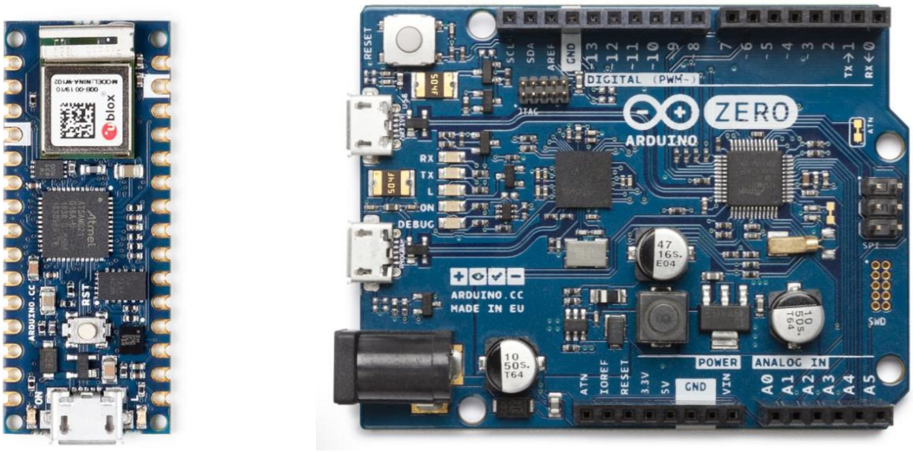
Table III.1: Comparison between simulation techniques in control system design [29]

III.3. Overview of target hardware platforms

Embedded controllers play a crucial role in controlling systems by executing control algorithms. These microcontrollers or single-board computers are used to mimic the behavior of actual control units in embedded systems, making them ideal platforms for prototyping, testing, and validation during the development process. The most commonly used controllers include:

III.3.1. Arduino

Arduino is a programmable platform designed to interact with external electronic components through software. It supports a wide range of hardware, including lights, sensors, actuators, displays, and speakers, which can be connected via cables or wireless interfaces. Due to its low cost and user-friendly design, Arduino is widely used for building prototypes in applications such as monitoring, manufacturing, and security systems. It is particularly accessible to beginners, requiring no prior knowledge of electronics or programming. [30]



FigIII.5: Arduino boards [31]

III.3.2. STM32

STM32 is a family of 32-bit microcontrollers developed by STMicroelectronics, built on the Arm Cortex-M architecture. Designed for high efficiency, these microcontrollers use a Reduced Instruction Set Computer (RISC) core, which enables fast and power-efficient processing by simplifying complex instructions into smaller, optimized tasks. STM32 devices offer a broad range of features including real-time performance, digital signal processing, low power consumption, and advanced connectivity options. Their flexibility and rich development ecosystem make them ideal for a wide variety of embedded applications, from industrial automation and smart metering to consumer electronics and Internet of Things (IoT) solutions. [32]

Fig III.6: STM 32 board [33]

III.3.3. Raspberry Pi

Raspberry Pi is a compact and affordable single-board computer developed by the Raspberry Pi Foundation to promote accessible computing and programming education. It runs mainly on Linux and is equipped with GPIO (General Purpose Input/Output) pins, allowing it to interface with electronic components for physical computing tasks. Despite its small size and low cost, it supports a wide range of applications such as programming**,** home automation**,** IoT projects**,** robotics**,** and even industrial control systems**.** Its flexibility and ease of use make it a valuable tool for both educational and professional purposes. [34]

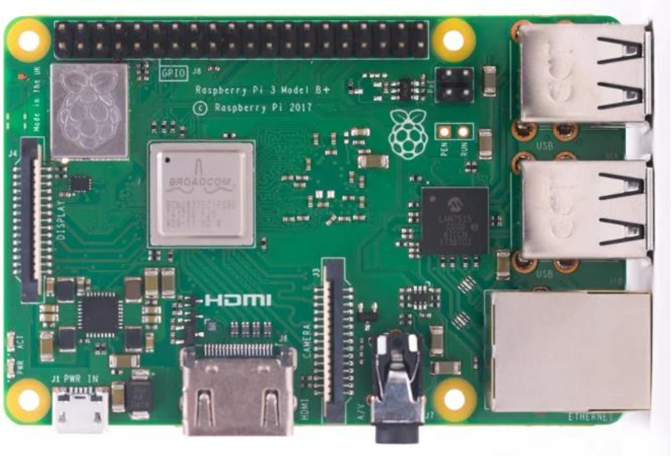


Fig III.7: Raspberry Pi board [34]

Each of these platforms provides unique advantages in terms of cost, complexity, and computational capability. The choice of controller depends on the specific requirements of the control technique, including real-time constraints, interfacing needs, and development tools.

III.4. Processor-in-the-loop

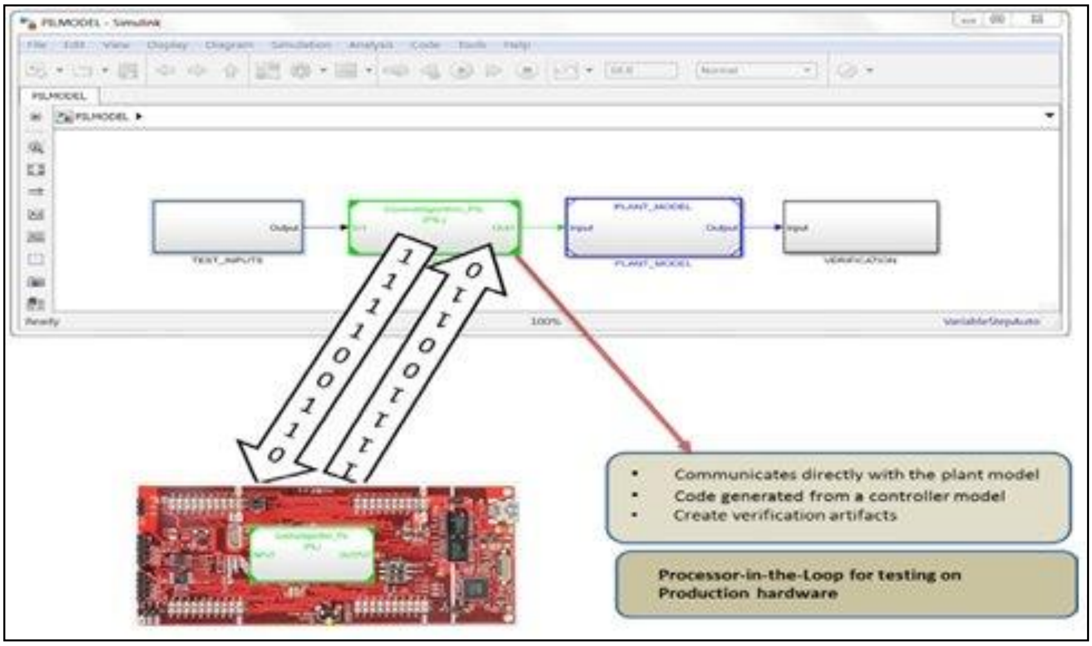
III.4.1 Definition of Processor-in-the-Loop (PIL)

Processor-in-the-Loop (PIL) is a testing method where the control algorithm is deployed onto an embedded processor and executed in a closed-loop simulation with a simulated plant. In this setup, the original controller model is replaced by a PIL block that runs the comPILed control code directly on the hardware. This process helps determine whether the target processor can reliably execute the developed control logic, and it allows early detection of performance issues or implementation errors before full system integration. [35]

III.4.2: Key component of the Processor-in-the-Loop (PIL) method

The PIL approach involves two key components:

- A Simulink model.
- A target board equipped with a processor, such as Arduino, Raspberry Pi, or similar.



- Communicates directly with the plant model
- Code generated from a controller model
- Create verification artifacts

Processor-in-the-Loop for testing on Production hardware

Figure III.8: Schematic describing the principle of PIL [36]

III.4.3. Difference between PIL and traditional simulation

The main distinction between PIL and traditional simulation is that the PIL testing enhances the validation process by reflecting the real constraints of the target microcontroller, such as limited processing capabilities and memory usage factors often overlooked in software-only simulations. It also facilitates early-stage testing of hardware interaction, helping to detect compatibility issues before full system integration. Moreover, PIL enables the software to operate alongside simulated hardware features, ensuring the control logic behave as intended within the embedded environment. [37]

III.4.4. Benefits of Processor-in-the-Loop (HIL) Testing

Processor-in-the-Loop (PIL) enables early validation of comPILed code on the target processor, allowing developers to assess performance under real hardware constraints. It also present other advantages such as: [38]

- Minimized Hardware Dependence: Testing can begin without requiring a complete physical prototype.
- Accelerated Debugging**:** Hardware-specific issues in the generated code are quickly detected and resolved.
- Optimized Resource Usage**:** Developers gain clearer insights into memory consumption and CPU load.
- Scalable Testing: Numerous test cases can be executed on a single processor with minimal setup changes.
- Reduced Development Risk**:** Early-stage validation of control code helps avoid costly design revisions later.

III.4.5. Best practices for implementing Processor-in-the-Loop (PIL)

Achieving successful results in PIL testing relies on defining the system architecture, and structuring data acquisition processes are essential to ensure reliable and repeatable outcomes. Ensure Model and Code Accuracy: High-fidelity simulation models should reflect the actual functional behavior of the target system. It’s important to verify that parameters are accurate. Validated model components previously helps reduce errors and accelerates development. Performance: When testing on real processors, developers must carefully consider factors such as the processor speed. [38]

Automate Monitoring and Result Analysis: Automated data logging enhances traceability and simplifies the detection of issues. Monitoring tools that capture processor performance, sensor feedback, and system status flags allow to quickly identify anomalies. A robust data analysis workflow not only reduces debugging time but also builds trust in the final system performance. [38]

III.5. Practical implementation of PIL simulation for a boost converter

This section outlines the practical implementation of a Processor-in-the-Loop (PIL) simulation setup specifically designed to validate the control of a Boost converter. The objective of this implementation is to evaluate the performance of a control algorithm executed on a physical controller (Raspberry Pi 4) while interacting with a simulated power electronics system modeled in MATLAB/Simulink.

III.5.1. Project-Specific implementation

In this project, a Processor-in-the-Loop (PIL) simulation environment was developed to test and validate the performance of a PI controlled boost converter. The control algorithm, written in Python, was deployed on a Raspberry Pi 4, acting as the physical controller. The boost converter model was implemented in Simulink, running on a host computer and representing the power stage. Communication between the Raspberry Pi and the simulation environment was achieved via GPIO, enabling data exchange. This configuration allowed closed-loop testing and performance evaluation of the controller under different output and input conditions without requiring a physical power circuit.

III.5.2. System overview

The implemented system is composed of the following main components:

- Plant model (Boost converter): Developed in Simulink. The model simulates a DC-DC step-up converter with defined input voltage, output load, and component parameters that we already discuss in chapter II.
- Controller (PI control): Implemented in Python and executed on a Raspberry Pi 4. The controller receives the difference between the output voltage and the reference output voltage from the Simulink model and adjusts the PWM duty cycle accordingly.
- Communication: A serial data exchange mechanism connects the Raspberry Pi with the host computer running the Simulink model.

III.5.3. The control workflow

- Initialization:
  - The user launches the Simulink model and starts the simulation.
  - Simulink establishes communication with the Raspberry Pi, sending the error signal calculated as the difference between the measured output voltage and the reference value
- Control Execution:
  - The Raspberry Pi receives the voltage feedback.
  - A Python-based PI controller computes the necessary PWM duty cycle to regulate the output voltage.
- Signal Exchange:

  - The Raspberry Pi sends the updated duty cycle value back to the Simulink model.
  - Simulink applies the duty cycle to the boost converter model and updates the response.
- Iteration Loop:
  - This cycle continues iteratively, forming a closed-loop PIL simulation.

The control algorithm is represented in the following diagram:

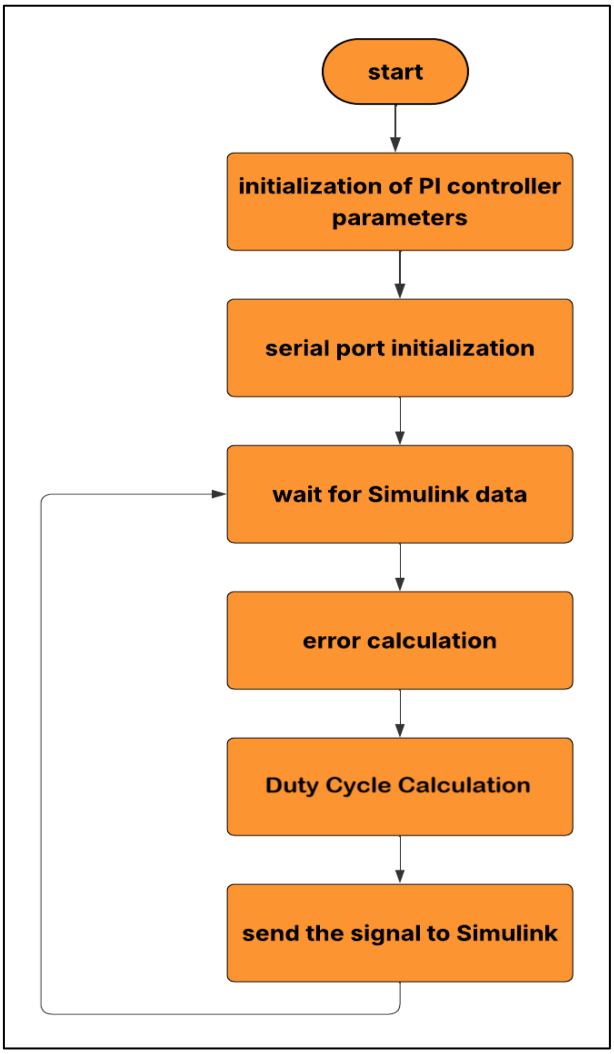


Figure III.9: Control algorithm of the PIL control technique for boost converter model

III.6. Simulation results

To analyze the dynamic behavior of the converter under varying output voltage conditions, a step change in the output voltage reference was introduced. Initially, the reference voltage was set to 30 V and then switched to 20 V at t = 1 s. This modification allows the observation of the controller's response. The results of this simulation are presented in the following figure:

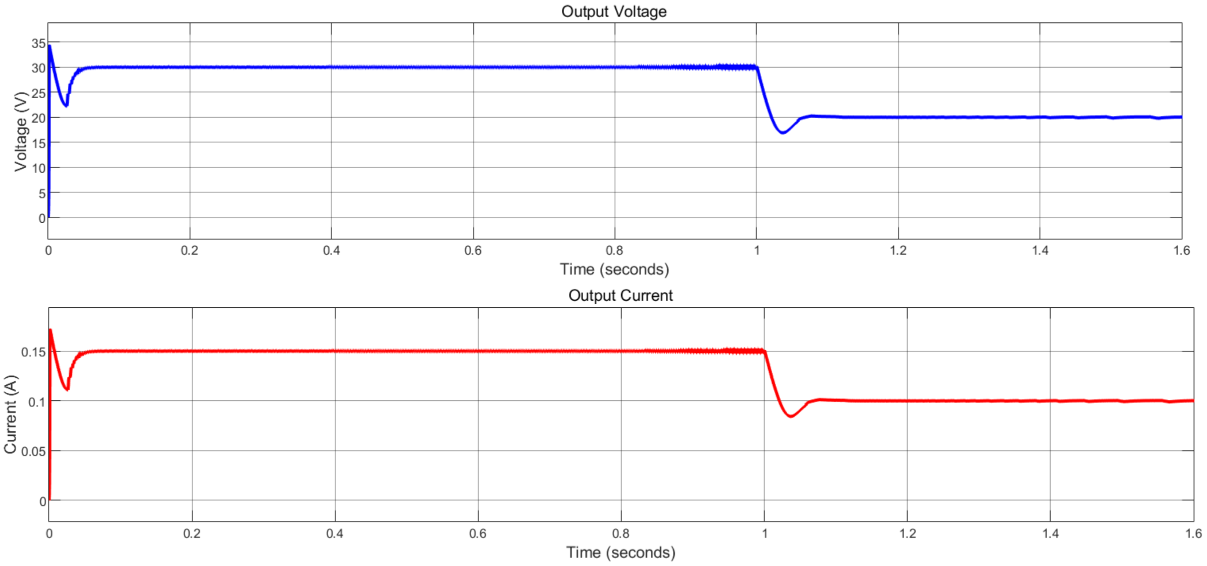


Figure III.10: Regulated output voltage of the boost converter

III.6.1. Discussion of simulation results

Observation – Reference Voltage at 30V (0 to 1s): In the initial stage of the simulation, the reference voltage is set to 30V. When the system starts, the output voltage rises quickly and overshoots the target, reaching above 35V. This is followed by a clear voltage undershoot**,** where the voltage drops below the setpoint, before gradually settling around 30V. The output current shows a similar dynamic**,** it increases rapidly, overshoots, then drops, and finally stabilizes at approximately 0.15A. These transients are typical during system startup, where the controller initially overreacts before correcting itself. So, The PI controller running on the Raspberry Pi, implemented through the Processor-in-the-Loop (PIL) approach, is able to bring both voltage and current to their expected steady-state values within a short time.

Observation – Reference Voltage Change to 20V (after 1s): At t = 1 second, the reference voltage steps down from 30V to 20V. The output voltage reacts immediately with a noticeable drop, falling slightly below the new reference. After this dip, it steadily returns and stabilizes around 20V without exhibiting significant oscillations. The output current follows a similar pattern; it decreases quickly, undershoot slightly above its steady-state value, and then stabilized at approximately 0.1s. These responses are common in systems subjected to sudden reference changes, where the controller must quickly adapt to new conditions. The PI controller running on the Raspberry Pi, using the Processor-in-the-Loop (PIL) technique, manages to restore both voltage and current to their expected levels in a relatively short time. This confirms that the control system remains stable and effective under varying operating points.

III.6.2. Performance evaluation

The converter exhibits strong dynamic and steady-state performance, demonstrating good transient behavior characterized by limited overshoot and undershoot, along with fast settling times that ensure minimal deviation from the desired output voltage. The system remains stable during both the initial start-up and the step change in reference voltage, indicating that the controller is properly tuned and effectively regulates the output under varying output conditions. The observed performance metrics confirm the controller’s ability to maintain stability, suppress transient disturbances, and rapidly converge to new set points. These characteristics highlight the converter’s suitability for applications requiring fast voltage regulation, high reliability, and robustness to load variations.

III.7. Conclusion

This chapter explored the practical implementation of Processor-in-the-Loop (PIL) simulation in a closed-loop control framework for a boost converter. The setup combined a physical controller (Raspberry Pi 4) with a simulated boost converter model developed in Simulink, enabling a realistic testing environment for embedded control software. The objective was to evaluate the system’s dynamic behavior under different operating conditions, specifically by applying step changes to the output voltage reference.

Through the conducted tests, the system’s response was analyzed during both startup and reference transition phases. The PI controller successfully managed output voltage regulation, demonstrating fast response times and acceptable transient performance. When the reference changed from 30V to 20V, the controller was able to re-establish stability in a short time, with both voltage and current returning to their new steady-state values. Although overshoots and dips were observed during transitions, these behaviors remained within expected bounds for such control systems and did not compromise overall system stability.

The results validate the effectiveness of using PIL simulation for early-stage control testing. By running the controller code on actual hardware, PIL allows designers to observe real execution behavior including computation limits, and hardware-specific constraints while still operating within a safe, simulated plant environment. This hybrid approach provides valuable insights into the interaction between software and hardware components before engaging in full hardware deployment.

In summary, PIL simulation offers a reliable and cost-efficient method for validating embedded control algorithms in power electronics. It enables early debugging, fine-tuning, and performance analysis without the risks associated with testing on physical systems. This chapter has highlighted how PIL can play a critical role in the development workflow, bridging the gap between simulation and real-world implementation.

General conclusion

General conclusion

Throughout this thesis, a methodical approach has been undertaken to address the challenges of designing, simulating, and validating a power conversion system based on the Boost converter topology. Starting from the fundamental principles of power electronics, the study has helped clarify the technical and operational challenges associated with output voltage regulation under varying operating conditions. The choice of the Boost converter proved to be well-suited for embedded and renewable energy applications due to its performance and structural simplicity.

The implementation of a PI controller in a closed-loop configuration significantly improved system stability and regulation accuracy. Compared to open-loop systems, the controlled setup showed a better ability to follow voltage references and mitigate external disturbances. This stage was validated through numerical simulations in MATLAB/Simulink**,** highlighting the effectiveness of classic control strategies within a well-modeled framework.

However, validation cannot rely on simulation alone. To address this, a Processor-in-the-Loop (PIL) approach was integrated as a final verification step. By linking a real controller (Raspberry Pi 4) with a simulated Boost converter model, this method allowed for the evaluation of the system's performance under real execution constraints such as computational delays and hardware limitations. The results confirmed the value of this hybrid technique, which combines the safety of simulation with the realism of hardware testing.

In summary, this work emphasizes the importance of combining theory, simulation, and practical implementation in the field of power electronics. It highlights how advanced validation methods like PIL play a key role in the development lifecycle of embedded systems. The outcomes of this study provide a strong foundation for future advancements whether through the optimization of control strategies (such as adaptive or intelligent control) or the exploration of other hardware architectures for more demanding applications. This thesis, therefore, reflects a rigorous and forward-looking approach to the development of modern, reliable, and intelligent energy systems.

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