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Dual Active Bridge for Electric Vehicle's Battery Charging

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Abstract

This project explores the design and operation of the Dual Active Bridge (DAB) converter, a highly efficient bidirectional DC-DC converter, with a focus on its application in electric vehicle (EV) battery charging systems. The study begins with a comprehensive review of various DC-DC converter topologies, highlighting the advantages of the DAB, such as galvanic isolation, bidirectional power flow, and high efficiency achieved through Zero Voltage Switching (ZVS). The converter's ability to operate at high switching frequencies enables the use of smaller and lighter components, making it ideal for modern energy systems.

The project delves into the operational principles of the DAB, including phase-shift modulation (PSM) and soft-switching techniques, which minimize power losses and enhance performance. A detailed analysis of the converter's steady-state and linear models is provided, along with practical considerations for leakage inductance, switching frequency, and capacitor selection. The study also examines the DAB's role in EV applications, such as onboard charging, DC fast charging, and powertrain efficiency enhancement.

Key findings demonstrate the DAB's capability to efficiently manage power transfer between the grid and EV batteries, adapting to different charging modes like Constant Current (CC) and Constant Voltage (CV). The project concludes by emphasizing the DAB's potential as a cornerstone technology for future energy systems, offering a balance of efficiency, flexibility, and compact design. This work contributes to the ongoing development of smarter and more sustainable energy solutions for electric vehicles and beyond.

Résumé

Ce projet explore la conception et le fonctionnement du convertisseur Dual Active Bridge (DAB), un convertisseur DC-DC bidirectionnel à haut rendement, particulièrement adapté à la charge des batteries des véhicules électriques (VE). L'étude compare d'abord les topologies de convertisseurs DC-DC, soulignant les atouts du DAB : isolation galvanique, transfert bidirectionnel de puissance et efficacité accrue grâce à la commutation à tension nulle (ZVS). Sa capacité à opérer à haute fréquence permet d'utiliser des composants compacts, idéaux pour les systèmes énergétiques modernes.

Le travail analyse les principes de fonctionnement du DAB, notamment la modulation par déphasage (PSM) et les techniques de commutation douce, réduisant les pertes et optimisant les performances. Une modélisation détaillée (régimes statique et dynamique) est réalisée, accompagnée d'une étude des paramètres clés (inductance de fuite, fréquence de commutation, choix des condensateurs). Le rôle du DAB dans les applications VE (charge embarquée, recharge rapide DC, optimisation de la chaîne de traction) est également examiné.

Les résultats montrent l'efficacité du DAB pour gérer le transfert d'énergie entre le réseau et les batteries, s'adaptant aux modes courants constant (CC) et tension constante (CV). En conclusion, le DAB se positionne comme une technologie prometteuse pour les futurs systèmes d'alimentation, alliant performance, flexibilité et compacité. Cette étude contribue au développement de solutions durables pour l'électromobilité et au-delà.

Acknowledgment

I am so privileged to express my deepest appreciation to Mr. GHEDAMSI Kaci for his invaluable guidance, unwavering support, and constant availability during this project. His expertise and encouragement were instrumental in its success. My sincere thanks also go to my dedicated partner, Boulkaria Faycel, for his kindness, motivation, and collaborative spirit, which made every challenge easier to overcome. To my beloved mother, Ait Moukran Lkayssa, and my beloved, TIGRINE Ldjida for her support, this achievement is as much your as mine. Your emotional support and sacrifices have been my greatest strength. This achievement would not have been possible without each of you, and I am forever grateful for your presence in my life.

TIGRINE Syphax.

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I would like to express my deepest gratitude to Mr. GHEDAMSI Kaci for his invaluable guidance, unwavering support, and constant availability during this project. My sincere thanks also go to my dedicated partner, TIGRINE Syphax, for his kindness, motivation, and collaborative spirit. To my parents who was always by my sides, thank you for your endless encouragement, patience, and love your belief in me has been my greatest strength. This achievement wouldn't have been possible without you all.

BOULKARIA Faycel.

Contents

Abbreviations:

CC : Constant Current

CV : Constant Voltage

DAB: Dual Active Bridge

DC/DC: Direct Current to Direct Current.

EVs: Electric Vehicles.

GaN: Gallium Nitride

HF: High Frequency

HFT: High Frequency Transformer.

IGBT: Insulated Gate Bipolar Transistor

MOSFET: (Metal-Oxide-Semiconductor Field Effect Transistor)

MPC: Model Predictive Control.

OBC: Onboard Charging systems

PSM: Phase-Shift Modulation

PWM: Pulse Width Modulation

SHE: Selective Harmonic Elimination

SiC: Silicon Carbide

SOC: State of Charge

SPS: Single Phase Shift

SPWM: Sinusoidal Pulse Width Modulation

SVM: Space Vector Modulation

ZCS: Zero Current Switching

ZVS: Zero Voltage Switching.

Technical nomenclatures (abbreviated Terms)

C_S(F): Energy stored in the IGBT's output capacitance

f_{sw} (Hz): Switching frequency

i_2(A): Current out of the converter

I_{ac2}(A): Secondary AC current

I_{c2}(A): Capacitor current

I_L(A): Instantaneous inductance current

I_{LK} (A): Leakage inductance current

L_K(H): Leakage inductance

L_m (H): Magnetizing inductance

n: Primary to the secondary ratio

P_{max}(w): Maximum power

P_{out}(w): Output power

T_{on}(s): is the time the signal is active or ON

T_S(s): Cycle period

T_{tot}(s): is the total period of one complete ON/OFF cycle

V_{DS}(V): voltage across the switch (drain-to-source of an IGBT)

V_{pri}(V): Primary voltage

V_{sec}(V): secondary voltage

ϕ (rad): Phase Shift

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GENERAL INTRODUCTION

The Dual Active Bridge (DAB) converter is a highly efficient, compact, and bidirectional power electronic topology, making it ideal for modern energy applications such as renewable integration, electric vehicle (EV) charging, and grid-scale storage. Unlike conventional unidirectional converters, the DAB enables bidirectional power flow, supporting advanced functions like vehicle-to-grid (V2G) systems, where EVs can supply energy back to the grid, improving stability and energy management as described by Florian Krismer and Johann W. Kolar in their work on efficiency-optimized high-current DAB converters for automotive applications [3].

The DAB's core structure, as also highlighted by Biao Zhao et al. [4], employs two H-bridge circuits tied together through a high-frequency transformer, providing galvanic isolation and voltage adaptation. By operating at kilohertz-to-megahertz frequencies, the DAB reduces magnetic component sizes compared to traditional line-frequency transformers, enhancing power density.

A key advantage of the DAB is its phase-shift modulation control, which adjusts the timing between bridges to regulate power flow while maintaining high efficiency across varying loads. Additionally, Martin Thormodsæter Ramsdal [5] emphasizes that zero-voltage switching (ZVS) minimizes switching losses, further boosting efficiency and reliability. The converter's flexibility allows it to handle dynamic power conditions, making it suitable for renewable energy systems with fluctuating generation (e.g., solar or wind) and for managing battery charge-discharge cycles in storage applications. Its scalability ensures applicability across low- to high-power systems.

As energy systems transition toward decentralized and renewable-heavy grids, the DAB's combination of high efficiency, compact design, and bidirectional capability positions it as a critical enabling technology. Its ability to meet modern power conversion demands ensures its relevance in current and future energy infrastructure developments.

CHAPTER I:

literature overview

I.1. Introduction

In this chapter, we will explore the fundamental aspects of DC-DC converters, beginning with an overview of their key characteristics and operational principles. We will then trace their historical development, highlighting major advancements that have shaped modern power electronics. A special focus will be placed on bidirectional topologies, particularly the Dual Active Bridge (DAB), due to its growing importance in applications like renewable energy systems and electric vehicle charging. In addition, we will analyze various switching strategies, control techniques, and practical applications of DAB converters, emphasizing their efficiency, flexibility, and role in enabling smart grid and energy storage solutions.

I.2. DC/DC Converter

DC-DC converters are electronic circuits designed to convert one direct current (DC) voltage level to another. They are widely used in power electronics, electric vehicles and renewable energy systems to efficiently step up/, step down, or invert voltage levels. These converters ensure a stable and regulated output voltage, enhancing energy efficiency and enabling compatibility between different components in electronic systems. Common types include buck, boost, buck-boost, and flyback converters.

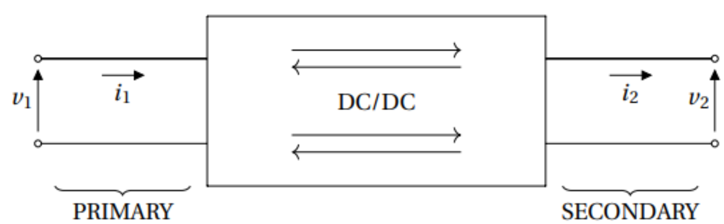

Figure I. 1: Simplified concept model of a bi-directional dc-dc converter

I.3. Utility of the DC/DC Converter

DC/DC converters are used to manage and adapt voltage levels between different components, such as the high-voltage battery and low-voltage systems (e.g., lights, infotainment) in EVs. They ensure efficient power distribution, enable battery charging, and support stable operation of auxiliary systems, thereby enhancing overall vehicle performance and energy efficiency.

I.4. DC/DC converters topologies

DC-DC converters can be classified according to various factors. One common classification is by their voltage gain, such as buck or boost mode operation. Another classification factor is their operating range on the 1 to 4 plots, where these converters can operate in one, two or four quadrants. A bi-directional converter, which operates in two quadrants, is particularly useful in many applications where it's essential to maintain constant voltage polarities, such as in the case of batteries. Alternatively, a two-quadrant converter allows voltage polarity to change while maintaining power transfer from input to output, suitable for use with DC motors. The following figure illustrates a classification of DC-DC converters according to their isolation.

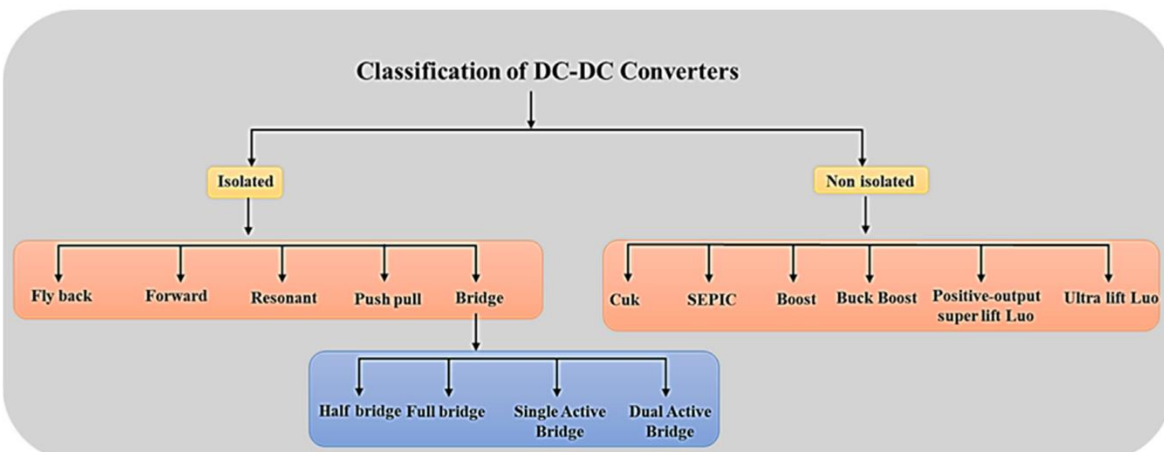

Figure I. 2: Classification of DC Converter

I.4.1. non-isolated topologies

Converters without galvanic protection are referred to as non-isolated converters. Without the need for galvanic isolation, they have a simple topology and small physical size. They are also less affected by electromagnetic interference (EMI) [6]. Non-isolated converters transfer power without any electrical separation between input and load sides. This topology reduces the overall dimensions of the converter compared to its isolated counterpart, making it more suitable for applications where size and weight are a major concern [7].

I.4.2. Isolated converter

In isolated converters, the input and output are separated using a high-frequency transformer. This separation ensures that each side has its ground, without affecting the input or output. Moreover, they support bidirectional power transfer and offer significant high voltage conversion ratios. separation is known as galvanic isolation, which plays a crucial role in our safety in some application, it prevents the current's leakage flow to our body when we're in contact with this power supply.

Isolated topologies offer significant advantages over non-isolated counterparts, including reduced switching losses, lower switch ratings, and reduced inductor size requirements. This results in enhanced overall efficiency, power density, and compactness. Additionally, decreased losses and improved efficiency lead to reductions in filter inductors and heat sinks, further enhancing the converter's performance [1].

I.5. DC/DC isolated converter types

DC-DC converters are critical components in modern electronics, providing the means for efficient voltage regulation and power management. They adjust voltage levels to guarantee optimal performance across various applications. The main types include buck, boost, and buck-boost converters [1].

I.5.1. Flyback Converter

Suitable for power levels under 100W, the Flyback converter relies heavily on the magnetizing inductance L_m of the high-frequency transformer to facilitate energy transfer [7].

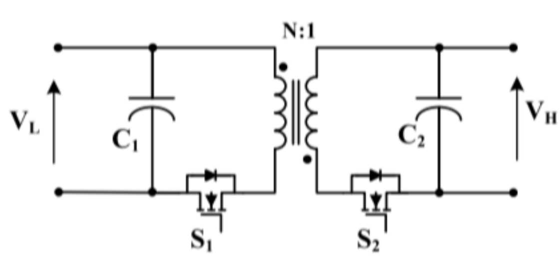

Figure I. 3: Flyback Converter

I.5.2. Forward Converter

Similar to the flyback converter but with modifications, the forward converter is favored for low and medium power levels, typically up to 500W. It features a smaller transformer core compared to the flyback [7].

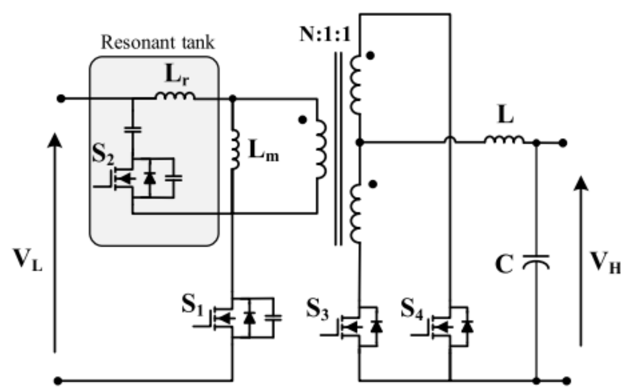

Figure I. 4: Forward Converter

I.5.3. Push-Pull Converter

Employing a transformer with a central tap, the Push-Pull converter is employed for medium to high power requirements, typically up to 1000W. Its advantages include common point transistor drive circuits and a relatively compact transformer core [7].

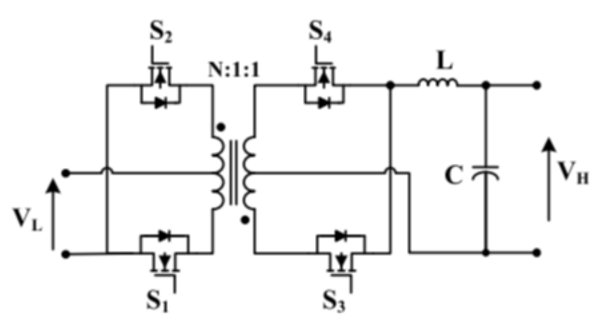

Figure I. 5: Push-Pull Converter

I.5.4. Half-Bridge Converter

Comprising a DC to AC conversion stage followed by high-frequency transformer coupling and rectification, the half-bridge converter is suitable for small ratings, supporting power ranges up to 500W. However, its limitation lies in the output voltage being half of the input voltage for a specific input voltage, leading to increased switch stress [7].

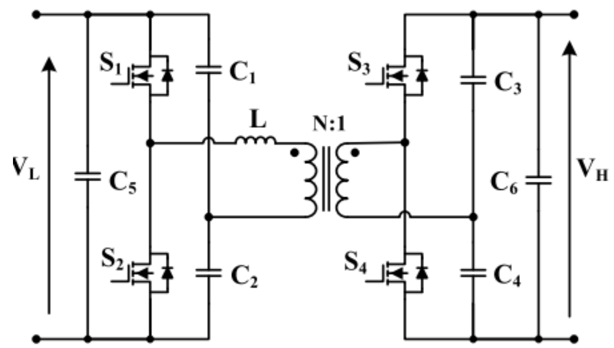

Figure I. 6: Half-Bridge Converter

I.5.5. Full-Bridge Converter

An extension of the Half-Bridge converter, the Full-Bridge converter is often preferred for high-power applications, up to approximately 2000W. However, it introduces higher voltage stress on the transistors, necessitating additional transistors and floating drive circuits as disadvantages [7]

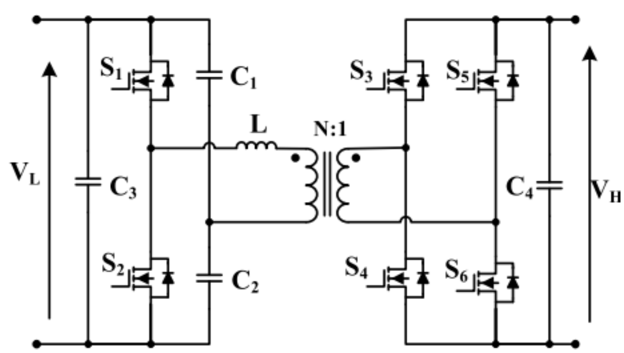

Figure I. 7: Full-Bridge Converter

I.5.6. Dual Active Bridge Converter (DAB)

Featuring two full bridges on each side of the isolation transformer, the DAB converter enables bidirectional power flow by controlling the phase shift angle between the primary and secondary. Zero voltage switching is a notable advantage of the DAB converter [7].

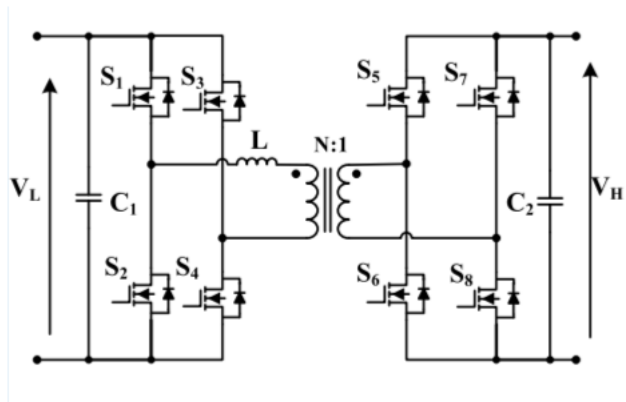

Figure I. 8: Dual Active Bridge Converter

I.5.7. Resonant LLC converters

Use LC resonant tanks (inductors and capacitors) to shape voltage or current waveforms sinusoidally, enabling soft switching (ZVS, ZCS). This reduces switching losses and EMI. By operating at the tank's resonant frequency, energy transfers efficiently between input and output through resonance. Topologies like LLC or SRM adjust frequency/pulse width to regulate power flow. Benefits include high efficiency, low noise, and adaptability to variable loads.

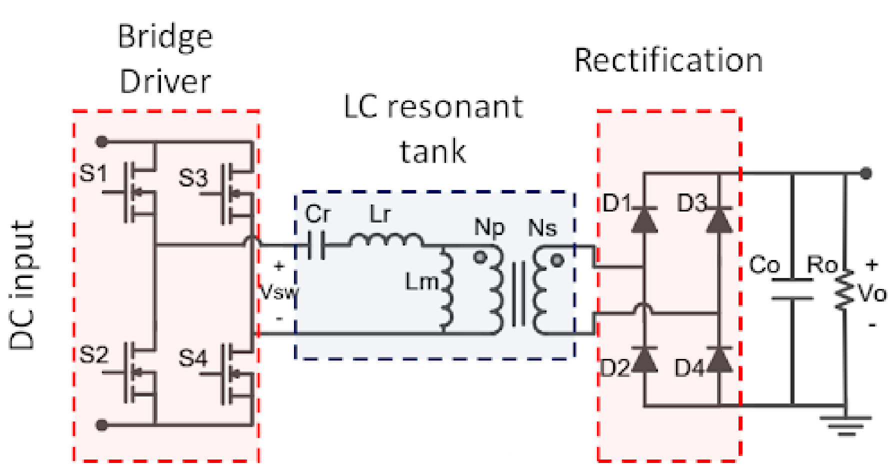

Figure I. 9: Resonant LLC converter

I.6. Dual Active Bridge (DAB)

We use it in huge amounts in EV battery DC chargers because of its high efficiency, bidirectional power flow, and the galvanic isolation. It guarantees fast charging and the ability to regulate the voltage and power transfer between the grid, batteries, or renewable sources, what make it ideal for modern EV charging systems.

The Dual Active Bridge Isolated Bidirectional DC/DC Converter topology is popular among the researchers because its essential characteristics such as bidirectional power flow between the grid and the loads, high conversion efficiency, galvanic isolation, high power density, and inherent soft switching property. These features enable the DAB an important circuit for standalone hybrid system application. The two full bridges are isolated by using the high-frequency power transformer which leakage inductance that work as an energy storage element. The primary bridge is attached to high voltage DC source and the secondary bridge is connected to low voltage energy storage device or load.

The square wave between both bridges can be conveniently phase shifted with respect to each other to enable the bidirectional power flow. The power conversion took place because of controlling the voltage difference across the energy storage element.

I.7. Historical background of the Dual Active Bridge

The Dual Active Bridge (DAB) converter has become an important solution for efficiently transferring power in both directions, especially in electric vehicles and renewable energy systems. Since its introduction in the 1990s, it has stood out for offering electrical isolation and high-power performance, along with smart features like soft-switching to reduce energy loss. Over the years, engineers and researchers have worked to make it even better more efficient, smarter, and more adaptable. Thanks to its flexible design, the DAB is now widely used in modern power grids and energy storage systems [8].

I.7.1. Early Concepts (1980s–1990s)

The Dual Active Bridge (DAB) converter emerged in the late 1980s as a solution for efficient, bidirectional DC-DC power conversion with galvanic isolation. Its architecture, featuring active full bridges on both primary and secondary sides linked by a high-frequency transformer, was designed to facilitate seamless power flow control. This innovation addressed the growing need for versatile power converters in applications such as renewable energy systems and electric vehicles [8].

I.7.2. Phase-Shift Control Strategy (1990s)

A significant advancement in DAB technology was the development of the phase-shift control strategy, which allows precise regulation of power transfer by adjusting the phase difference between the primary and secondary bridge voltages. This method enhances the converter's efficiency and performance, making it suitable for high-power applications requiring bidirectional energy transfer [8].

I.7.3. Integration of Wide Bandgap Semiconductors (2010s)

The 2010s saw the integration of wide bandgap semiconductors, such as Gallium Nitride (GaN) and Silicon Carbide (SiC), into DAB converters. These materials enabled higher switching frequencies and improved thermal performance, leading to more compact and efficient designs. This evolution was particularly beneficial for applications demanding high power density and efficiency [9].

I.7.4. Advanced Control Techniques and Applications (2020s)

Recent work has focused on smarter control methods, like model predictive control and adaptive modulation, to improve how DAB converters perform. Thanks to these upgrades, DAB converters are now used more often in areas like electric vehicle charging and renewable energy systems, where efficient and reliable power conversion is very important [9].

I.8. Modulating the DAB Converter

I.8.1. The structure

The DAB converter consists of two complete bridges (or H-bridges) connected in series. Each bridge consists of four power switches, generally semiconductor transistors such as IGBTs or MOSFETs, free-wheeling diodes, an inductor, a high-frequency (HF) transformer and a capacitor filter.

I.8.2. Power transistors (IGBTs)

The Dual Active Bridge Converter uses controllable power transistors such as IGBTs (Insulated Gate Bipolar Transistor) or MOSFETs (Metal-Oxide-Semiconductor Field Effect Transistor) equipped with fins in order to cool it and avoid high heating. These transistors enable high-frequency switching, currents and control of the output voltage.

I.8.3. Freewheeling diodes

As in other switched converters, freewheeling diodes are needed to provide a conduction path for the currents induced in the inductors when the transistors are switched off. This ensures bi-directional current flow.

I.8.4. Leakage inductance

Leakage inductance occurs when energy doesn’t fully transfer from the primary to the secondary side of a transformer, getting trapped inside. This leads to inefficiencies but can help control circuit behavior in certain cases, for example the storage magnetic energy and smooth currents

I.8.5. Capacitors

Capacitors are used to store electrical energy and smooth voltages. They are generally present in the DAB configuration to provide a stable DC output voltage.

I.8.6. High-frequency transformer

The high-frequency transformer plays a crucial role in galvanic isolation, matching voltage levels and transmitting energy between different parts of the system.

The H-bridge plays a key role in Dual Active Bridge (DAB) converters. It enables precise control of voltage and current through phase-shifted signals. This mechanism optimizes energy transfer between two DC sources while ensuring galvanic isolation, making it ideal for efficient and flexible power conversion systems.

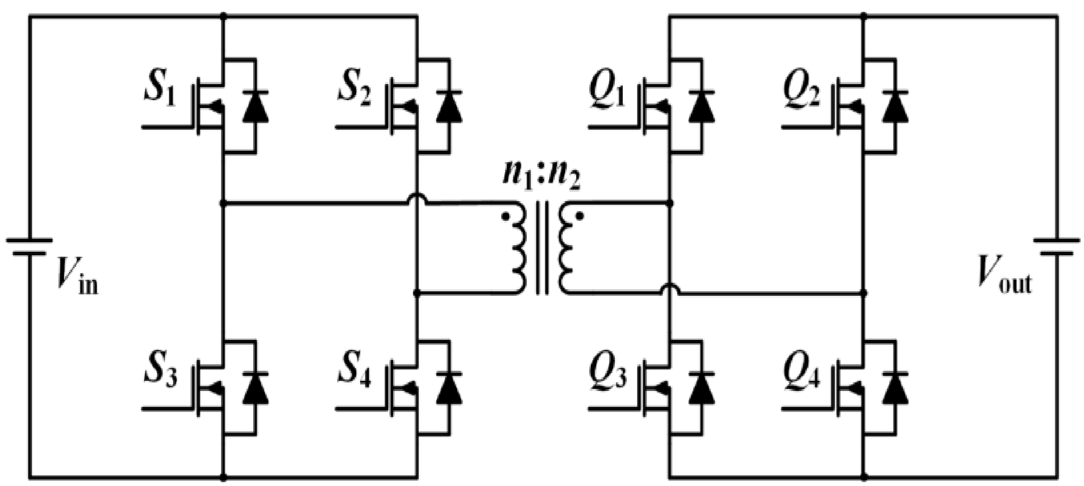

Figure I. 10: The DAB's basic structure

I.9. Principle of Operation and Power Transfer Mechanism

The Dual Active Bridge (DAB) DC-DC converter works on high-frequency bidirectional power transfer employing two H-bridges and a high-frequency transformer. It uses phase-shift modulation to control power flow by adjusting the phase difference between primary and secondary voltages, allowing efficient energy transfer, soft switching, and minimal losses.

I.10. Switching strategies

In order to control Dual Active Bridge (DAB) DC-DC converter, a lot of strategies are available that enhance system performance by limiting unnecessary currents flow which can respond and adjust different load changes, while maintaining high efficiency across different operating conditions. In this section, we'll going to examine these strategies [7]:

I.10.1. Pulse Width Modulation (PWM) technique

This is the most widely used method for DAB converters, it regulates the power flow by adjusting the phase shift between the primary and secondary waveforms, where a higher phase shift increases the power transfer and a lower phase shift reduces it, these techniques include the following [7]:

I.10.1.1. Single-Pulse Width Modulation

This simple technique uses one pulse per half cycle, adjusting its width and position to control output voltage. However, it creates more harmonic distortion, reducing overall efficiency and signal quality.

I.10.1.2. Multiple-Pulse Width Modulation

It uses several pulses in each half-cycle to lower harmonic distortion more effectively than single-pulse modulation, but this improvement leads to higher switching losses. [7].

I.10.1.3. Sinusoidal PWM (SPWM)

It compares a sine wave signal with a triangular wave to generate control pulses. This method improves harmonic rejection and is commonly used in grid-tied inverters for efficient power conversion [7].

I.10.1.4. Selective Harmonic Elimination (SHE)

The system directly calculates switching angles to cancel low-order harmonics like the 3rd and 5th. It solves nonlinear equations to produce a smoother output with fewer unwanted frequencies [7].

I.10.2. Space Vector Modulation (SVM)

This PWM method for three-phase inverters uses voltage vectors in the α-β plane. It boosts DC bus use, cuts harmonics, raises efficiency, and powers motors and renewable energy systems [7].

I.10.3. Phase-Shift Modulation (PSM)

Phase-Shift Modulation helps high-frequency inverters switch efficiently. BPSM recycles leakage energy to achieve soft switching without extra parts. UPWM creates a three-level output but can distort signals when they cross zero [7].

I.11. Soft-Switching

I.11.1. Zero Voltage Switching (ZVS)

Zero Voltage Switching ensures semiconductors (IGBTs) turn on only when voltage across them near to zero, slashing losses and EMI problems. In a Dual Active Bridge with two H-bridges and a high-frequency transformer ZVS occurs when switches activate after their voltage drops to zero via precise timing. This eliminates switching losses, enabling efficient, cool operation by avoiding overlapping voltage-current stress.

I.11.2. Zero Current Switching (ZCS)

Zero Current Switching is also a soft-switching technique where a semiconductor (IGBTs) turns on/off only when its current is near zero, minimizing switching losses. In a Dual Active Bridge ZCS complements ZVS (Zero Voltage Switching) by ensuring the switch interrupts current at zero-crossing, reducing stress and EMI. This is achieved via precise timing, resonant tank elements for instance leakage inductance, and phase-shift control, enhancing efficiency in high-frequency DC/DC conversion.

I.12. Applications of DAB converters in electric vehicles

I.12.1. Onboard Charging systems (OBC)

Is a power electronics device in electric vehicles, that convert AC power from external source, such as residential outlets, to DC power to charge the vehicle's battery pack. The DAB converters enable in this case efficient bidirectional power transfer between the grid and the EV battery, allowing for both charging and discharging.

I.12.2. DC fast charging systems

DAB play a crucial role in high-power DC fast chargers by providing galvanic isolation and efficient power conversion, reducing charging time.

I.12.3. Motor Drive Systems

The principal role of DAB in this case is to regulate and convert voltage from the battery to the required levels for different motor drive components, optimizing power distribution.

I.12.4. Powertrain Efficiency Enhancement

By dynamically controlling voltage and power flow, DAB converters improve the efficiency of EV powertrain components, reducing energy losses.

I.13. Advantages of the DAB

DAB converters bring important features to power systems, for example:

- It achieves high efficiencies between 95% and 98%.
- It provides galvanic isolation and easily adapts to different battery voltages.
- It can transfer energy in both directions, making it suitable for systems that send power back to the grid or to a home.

I.14. EV Charging Levels

Electric vehicle (EV) charging is categorized into three main levels based on power output and charging speed.

✓ **Level 1 Charging.**
uses a standard 120V household outlet, delivering 1.4 to 2.4 kW. It's the slowest method, adding 3–5 miles of range per hour, ideal for overnight charging or low daily mileage.

- ✓ **Level 2 Charging**
  operates at 240V and provides 3.7 to 19.2 kW, offering 12 to 80 miles of range per hour. This is the most common choice for home and public charging due to its balance of speed and accessibility.
- ✓ **DC Fast Charging (Level 3)**
  uses 480V or higher for rapid energy transfer from 50 to 350 kW, replenishing 60 to 200 miles in 20 to 30 minutes. It's primarily found at public stations, suited for long trips or quick top-ups.

We can notice that each level serves different needs, from daily commuting to long-distance travel, ensuring EVs remain practical and efficient. Continuous advancements aim to improve speed, affordability, and grid integration for wider adoption [9], [14].

I.15. Conclusion

DC-DC converters are essential for efficient power transfer and voltage regulation in many systems. The Dual Active Bridge (DAB) offers high efficiency, bi-directional power flow, and galvanic isolation. Its design makes it ideal for applications such as electric vehicle charging and renewable energy systems, where improving overall system performance and minimizing losses are crucial.

CHAPTER II: Dual Active Bridge and its operating modes

II.1. Introduction

In this chapter, we will be going to focus on the operational principles of the Dual Active Bridge. After previously we already explored its historical background, topologies, and bidirectional power flow. Now we'll take a closer look to the DAB practical working. We will examine its different operation's mode that determined by a variety of factors such as the power flow's direction, phase shift control. In addition, we'll explain the role of switching strategies in shaping these modes. This chapter will help us to understand the dynamic behavior of the DAB under real-world operating conditions.

II.2. Dual Active Bridge

The Dual Active Bridge is the most popular IBDC topologies now days, due to its bidirectionality power flow. In addition, its ability of zero voltage switching, this converter reduces the switching losses, what make it ideal choice for charging and discharging of the EVs' battery.

The symmetrical scheme of this converter helps us to achieve this power flow's bidirectionality. The DAB, as the name suggest constitute of two active bridges, the high and the low voltage bridge, each one contain four controllable IGBTs, separating with a high frequency transformer that ensure galvanic isolation, then an energy transfer inductor placed on the HV side due to the lower current value. Capacitors are placed on both sides in/output to decrease the current and voltage ripples.

II.3. Operating mode

The DAB uses semiconductors (IGBT): that switches in each bridge to generate a specific wave voltage. The system modulates these waves to control the power flow between bridges. The DAB operates in two modes, boost and buck. In boost mode, power flows from the low-voltage side to the high-voltage side. In buck mode, power flows in the opposite direction, from the high-voltage side to the low-voltage side.

II.4. Phase shift modulation

We use both Pulse Width Modulation (PWM) and Single-Phase Shift (SPS) in Dual Active Bridge as switching strategies. However, the Single-Phase Shift modulation is the simplest and the most used phase shift strategy.

The DAB controls power flow by phase-shifting square wave voltages between bridges. SPS modulation delays gate signals for the target bridge's switches, adjusting pulse timing. Power flows from the lagging to the leading bridge, with phase shift (ϕ) as the unique control variable, expressed in radians (or seconds/percent), ϕ ranges between -π and π. Maximum power transfer occurs at ϕ = π/2 50% of range. Soft switching suffers from limited adjustability.

II.5. Gate signals

We've eight switching signals control transistors in two bridges. The primary bridge pairs S1to S4 and the secondary pairs from S5 to S8. Each pair shares identical switching cycles but operates complementarily. All transistors (IGBTs) run at a 50% duty cycle, with cycle period T_S defined by the switching frequency. The following figure illustrates the four gate signals and phase shift ϕ between bridges, and the cycle period relation [5]:

$$T_s = \frac{1}{f_{sw}} \qquad \text{(Eq II. 1)}$$

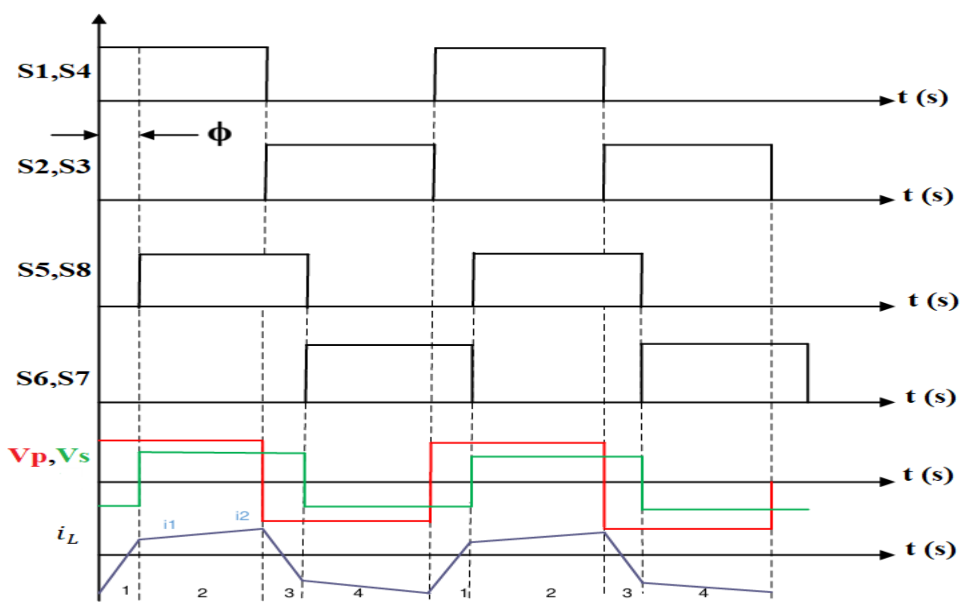

Figure II. 1: Gate signals and phase shift

II.6. Power flow

The DAB converter transfers power bidirectionally, operating in buck or boost mode. In buck mode, power flows from the primary (high voltage) to the secondary (low voltage), with the primary wave leading. Boost mode reverses the flow: power moves from secondary (low voltage) to primary (high voltage), and the secondary wave leads. The output power depends on voltage ratio, inductor, switching frequency, and phase shift [6].

$$P_{out} = \frac{nV_{pri}V_{sec}}{2L_K f_{SW}} \phi\,(\phi\ - 1) \qquad \textbf{(Eq II. 2)}$$

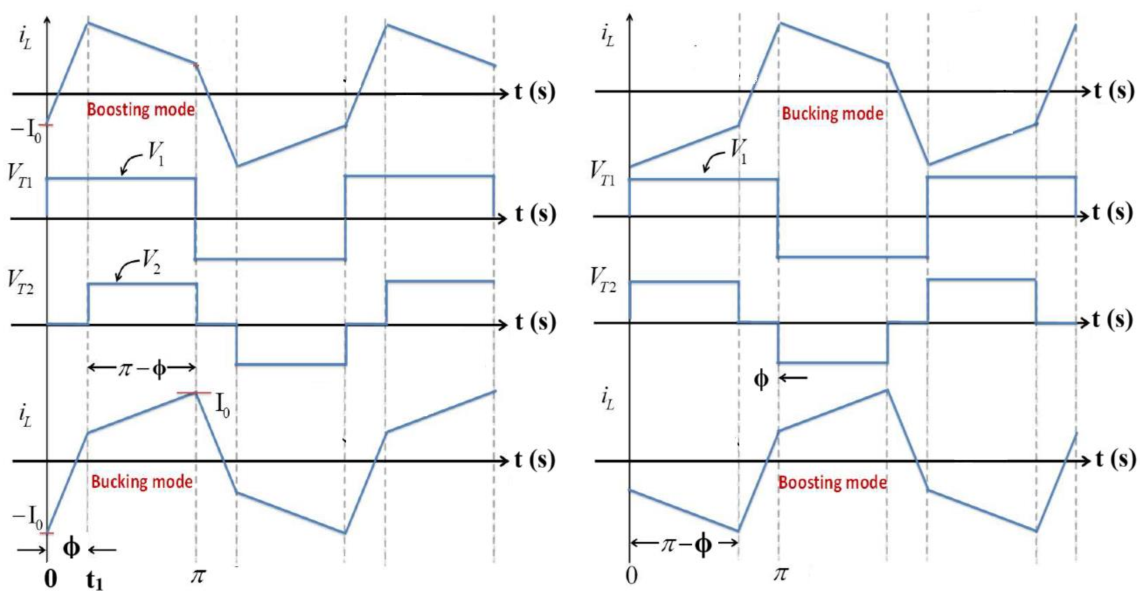

Figure II. 2: The primary, secondary and the leakage inductance current

II.7. Inductor Characteristics

One of the most important elements in a Dual Active Bridge (DAB) converter is the leakage inductance, as it directly governs power transfer. The power flow is controlled by the current through this inductor, which is determined by the voltage difference between V_1 and V_2. The leakage inductance also dictates the maximum power that can be transferred from one side of the converter to the other.

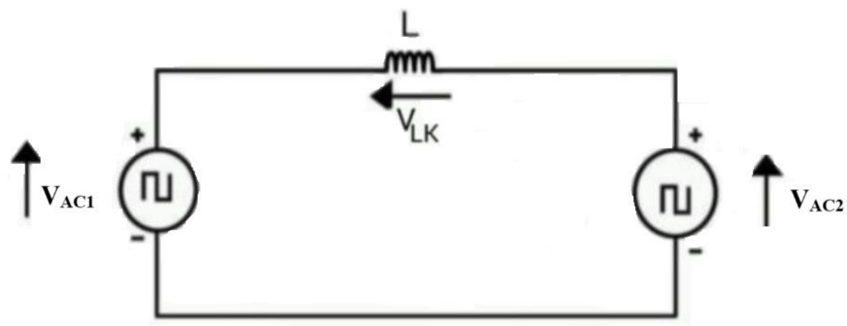

Figure II. 3: Simplified equivalent circuit diagram DAB

The current through the leakage inductor denoted i_L is calculated by integrating the voltage over the inductor, as shown in the equation. Where $i_L(t_0)$ is the initial current, L_K is the inductor and V_{LK} is the voltage over the inductor.

$$i_L(t) = i_L(t_0) + \int_{t_0}^{t_1} V_L dt \qquad \text{Eq (II. 3)}$$

The inductor voltage is a function of the rate of current change through it and its self-inductance expressed in the following equation:

$$V_L(t) = L\frac{d_{iL}(t)}{dt} \qquad \text{Eq (II. 4)}$$

$$L\frac{d_{iL}(t)}{d_t} = V_1(t) - V_2(t) \quad \forall \quad 0 < t < \frac{T_s}{2} \qquad \text{Eq (II. 5)}$$

As the voltage spikes, the current follows its lead, rising in sync. The relationship between them flips depending on which way power flows. By breaking this into time segments, we can describe each phase of current with clear equations that capture how the inductor responds to changing voltage

$$i_L(t_{0-1}) = i_L(t_0) + \frac{V_{ac1}+nV_{ac2}}{L_K}(t - t_0) \qquad \text{Eq (II. 6)}$$

$$i_L(t_{1-2}) = i_L(t_1) + \frac{V_{ac1}-nV_{ac2}}{L_K}(t - t_1) \qquad \text{Eq (II. 7)}$$

$$i_L(t_{2-3}) = i_L(t_2) - \frac{V_{ac1}+nV_{ac2}}{L_K}(t - t_2) \qquad \text{Eq (II. 8)}$$

$$i_L(t_{3-4}) = i_L(t_4) - \frac{V_{ac1}-nV_{ac2}}{L_K}(t - t_3) \qquad \text{Eq (II. 9)}$$

In other hand and due to the symmetry of the current waveform in a Dual Active Bridge, the current at time t_0 is the negative of the current at t_2, and the same applies for t_1 and t_3. This pattern repeats every switching cycle, meaning values at t_4 mirror those at t_0. The timing of t_1 is determined by the phase shift (ϕ) and switching frequency f_{sw}. Meanwhile, t_2 is fixed at half the switching period because each voltage pulse has a 50% duty cycle. By combining these relationships, the inductor current i_L simplifies to a function of just the phase shift and switching frequency, making it easier to analyze power transfer in the DAB converter.

$$t_1 = \frac{\phi}{2\pi f_{sw}} \quad \textbf{Eq (II. 10)}$$

$$t_2 = \frac{1}{2 f_{sw}} \quad \textbf{Eq (II. 11)}$$

$$i_L(t_0) = \frac{(nV_2 - V_1)\pi - nV_2 . 2\phi}{4\pi L_K f_{sw}} \quad \textbf{Eq (II. 12)}$$

II.8. The average power

We can calculate the system's average power flow using the current i_L, as explained below, Where Ts represents the period time, which is inversely related to the operating frequency which we previously mentioned as $T_s = {}^{1}/_{f_{sw}}$:

$$P1 = \frac{1}{T_{s1}} \int_0^{T_{s1}} P_1(t) dt = \frac{1}{T_{s1}} \int_0^{T_{s1}} V_{pri}(t). i_L(t)\, dt \quad \textbf{Eq (II. 13)}$$

$$P2 = \frac{1}{T_{s2}} \int_0^{T_{s2}} P_2(t) dt = \frac{1}{T_{s2}} \int_0^{T_{s2}} V_{sec}(t). i_L(t)\, dt \quad \textbf{Eq (II. 14)}$$

Due to the half-wave symmetry, we can thus express the average power as:

$$P1 = \frac{2}{T_s} \int_0^{\frac{T_s}{2}} V1. i_L(t)\, dt = \frac{2V1}{T_s} \int_0^{\frac{T_s}{2}} i_L(t) dt \quad \textbf{Eq (II. 15)}$$

II.9. Phase shift

The secret to controlling power transfer in these converters lies in one key component: the leakage inductor. Think of it like this: the inductor's size directly affects the amount of phase shift required for efficient energy transfer which is given by the equation below:

$$\phi = \frac{\pi}{2}\left(1 - \sqrt{1 - \frac{8 f_{sw} L_K |P|}{n V_1 V_2}}\right) \quad \text{for} \quad |P| < |P_{max}| \qquad \text{Eq (II. 16)}$$

II.10. Duty cycle

Is the fraction of a period that a signal or system is active. It is usually expressed as a percentage or ratio. A period is the time it takes for a signal to complete an on/off cycle. Duty cycle is the ratio of the time a load or circuit is ON to the time the load or circuit is OFF. It is expressed as a percentage of the ON time. Duty cycle is an important concept that describes the proportion of time a signal spends in the active state compared to its total period. And it's given by the equation:

$$D = \frac{T_{on}}{T_{tot}} \times 100\% \qquad \text{Eq (II. 17)}$$

Here we can get the equation of the power transferred depending on the duty cycle:

$$P_{out} = \frac{n V_1 V_2}{2 L_K f_{SW}} D(D-1) \quad \forall \quad 0 \leq D \leq 1 \qquad \text{Eq (II. 18)}$$

So, the maximum power that can be transferred is when the duty cycle is equal to $|D| = 0.5$ for that we get this power equation:

$$P_{max} = \frac{n V_1 V_2}{8 L_K f_{SW}} \qquad \text{Eq (II. 19)}$$

In this way we can get the equation of the duty cycle from (1) and (2):

$$D = \frac{1}{2}\left(1 - \sqrt{1 - \frac{8. f_{sw}. L. |P|}{n. V_{prim}. V_{sec}}}\right) \quad \forall \qquad P \leq |P_{max}| \qquad \text{Eq (II. 20)}$$

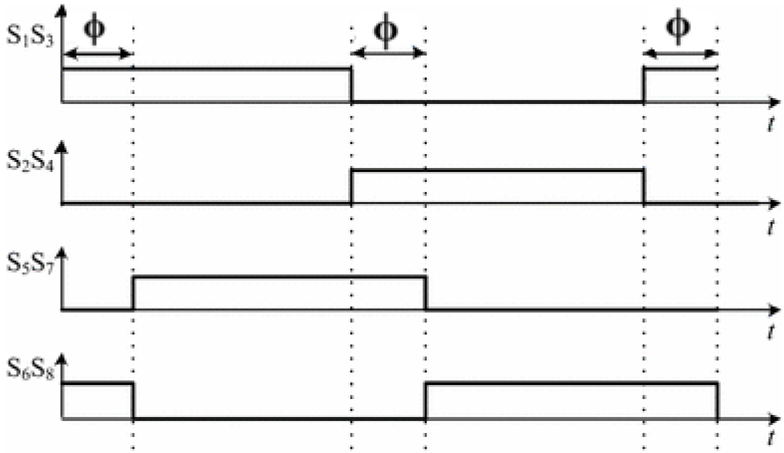

Figure II. 4: Square waves forms with phase shift ϕ

II.11. Soft switching

The DAB converter cleverly switches its IGBTs at just the right moment when voltage across them drops to zero thanks to built-in diodes and internal capacitance. At turn-off, current keeps flowing briefly, nearly eliminating losses (pseudo-ZVS). But true zero-voltage switching happens at turn-on, where stored energy from the inductor charges/discharges the IGBTs' internal capacitors, allowing clean, efficient switching. For this to work smoothly, the converter needs enough current flowing through its inductor a value engineers can calculate to ensure soft switching every time.

The DAB's soft-switching ability depends on the energy stored in the primary side inductor and the output capacitance of the IGBTs shown in the following equations. The amount of energy in the inductor must be able to fully charge/discharge both output capacitors

$$E_L = \frac{1}{2} L . i_L^2 \qquad \text{Eq (II. 21)}$$

$$E_C = \frac{1}{2} C_S V_{DS}^2 \qquad \text{Eq (II. 22)}$$

By combining these two equations we will get the minimum inductor current required to achieve soft switching

$$i_{L\_min} = \sqrt{\frac{2C_S V_{DS}^2}{L}} \quad \text{Eq (II. 23)}$$

II.12. Switching frequency

The converter's performance depends on the switching frequency. Higher frequencies reduce component sizes but boost switching losses and resistance due to skin and proximity effects where current accumulates and densify near conductor surfaces, raising heat and cutting efficiency. While faster switching improves battery response, it also decreases output power. Stabilizing size, efficiency, and power. In our case we chose 10 kHz as the optimal point.

II.13. Leakage inductance

Leakage inductance (L_K) is key in DAB converters, working with the transformer to control power transfer between bridges. Its size depends on switching frequency where higher frequencies allow smaller inductors. It must handle the maximum power at the specific phase shifts, peaking at 90° (0.5π radians). However, since the transformer introduces an additional element so the external inductor should be slightly lower. This relationship is captured by the following equation:

$$L_K = \frac{V_{pri} V_{Sec}}{2 f_{Sw} n P_{out}} \phi \left(\pi - \phi\right) \quad \text{Eq (II. 24)}$$

II.14. Capacitors

The DAB model uses input and output capacitors to reduce voltage ripple to acceptable levels. The current through the output capacitor (iC_2) depends on both the battery current (i_2) and the switching current (Iac_2), as it shown in the following equation. The exact ripple tolerance required varies depending on the design and application. Some systems need tighter control, while others can handle a bit more fluctuation.

$$i_{C2} = I_{ac2} - i_2 \quad \text{Eq (II. 25)}$$

II.15. Battery

Electric vehicles (EVs) rely on batteries that present trade-offs in terms of energy density, cost and lifespan. Lithium-ion batteries lead the way thanks to their balance of power and compact size, but challenges relating to overheating and degradation persist. New chemistries aim to increase range and reduce charging times, but recycling efforts are struggling to keep pace with demand. The future of EVs hinges on the development of cheaper, safer, faster-charging technology that does not compromise durability [17].

II.16. Characteristic

The following figure illustrates the discharge of a Li-ion battery over time. The voltage drops quickly at first (the exponential zone), then stabilizes within the ideal nominal range, where the battery should mostly operate. After that, it enters the depleted zone, where the voltage drops sharply. Staying within the middle range helps to avoid damage and extends battery life, whereas extreme highs or lows wear it out faster. For optimal performance, we must maintain the battery's charge within its nominal range in order to avoid both extreme high and low states of charge.

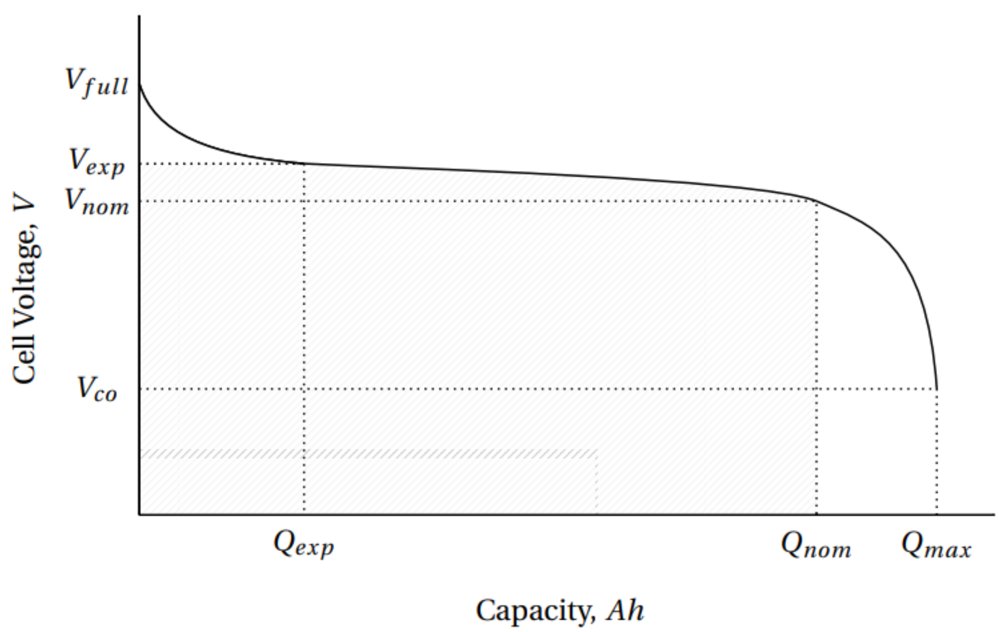

Figure II. 5: Discharge characteristic of a Li-ion battery

II.18. Charging method

Li-ion batteries require a smart charging approach to prevent damage. The standard method involves first applying a constant current (CC), followed by a constant voltage (CV). First, a steady current charges the battery while the voltage rises. Once the voltage peaks, it is held steady while the current drops until the battery is fully charged. While this protects the battery, it also slows charging, so sometimes the CV phase is shortened to speed up the process. The goal? A full charge without overcharging [17].

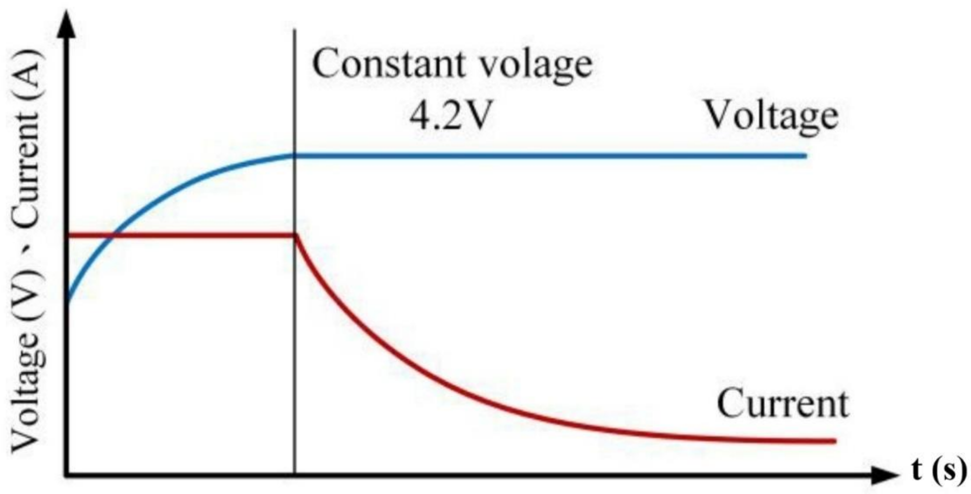

Figure II. 6: Battery current and voltage characteristic during cc/cv charging mode.

II.18.1. State of charge

The SOC (State of Charge) indicates how much battery power is remaining. It is important to get this right overcharging or draining the battery can damage it. There are two main ways to measure SOC: direct and indirect. The simplest method, such as coulomb counting and open circuit voltage (OCV), tracks physical changes in the battery. Coulomb counting is popular because it is straightforward it adds up the current over time but you need to know the initial SOC value since it only tracks changes.

$$SOC(t) = SOC(t_0) + \Delta SOC(t) \qquad \text{Eq (II. 26)}$$

$$SOC(t) = SOC(t_0) + \frac{1}{C_{batt}} \int_{t_0}^{t_0+t} i_2 . 100\% dt \qquad \text{Eq (II. 27)}$$

There are trade-offs when estimating battery charge (SOC). Simple current based method ($SOC(t_0)$ + ΔSOC) accumulate errors over time. Voltage based method (OCV) are straightforward, but require resting periods, which makes them impractical for active use. Indirect methods, such as model-based or adaptive filters, improve accuracy, but also introduce complexity. AI solutions are sophisticated, but they are often impractical. The best method strikes a balance between precision and practicality by factoring in battery health and real-world conditions. No single approach is perfect.

II.19. Conclusion

This chapter explored the Dual Active Bridge (DAB) converter, detailing its operational principles, power flow control via phase-shift modulation, and key components like the leakage inductor and high-frequency transformer. We analysed its bidirectional power transfer (buck/boost modes), soft-switching mechanisms, and design trade-offs (for example switching frequency vs losses). The DAB's efficiency and versatility make it ideal for applications like EV charging, where dynamic control and minimal losses are critical. Understanding these fundamentals lays the groundwork for optimizing DAB performance in real-world systems.

CHAPTER III:

Simulation results and discussion

III.1. Introduction

As discussed in the previous chapter, the Dual Active Bridge (DAB) converter is especially suitable for bidirectional battery charging in electric vehicles. This suitability arises from its galvanic isolation, which ensures electrical safety and noise immunity, its ability to allow power flows in both direction charging and discharging, its precise power control via phase-shift modulation. This chapter focuses on the practical operation of the DAB in charging mode, analyzing principal signals and clarifying the control conditions that govern efficient energy transfer.

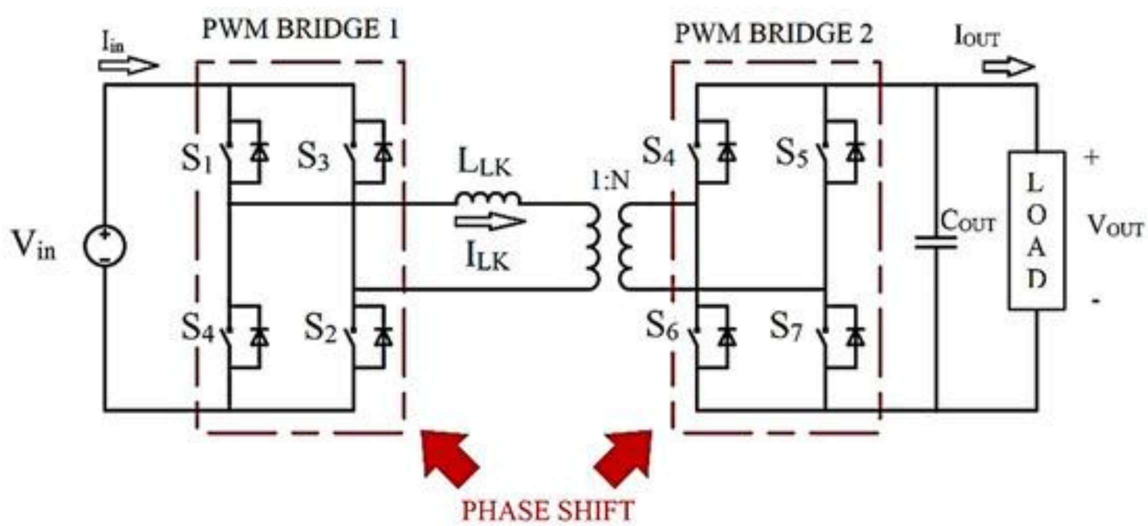

Figure III. 1: Dual active bridge diagram

III.2. The principle of battery charging with a DAB converter

The DAB converter consists of two symmetrical full-bridge circuits connected by a high-frequency transformer. One side, often called the source side, interfaces with the DC bus or the AC/DC charger and provides the input power. The other side, the battery side, connects to the battery through appropriate filtering components and sensors that measure voltage and current to enable closed-loop control.

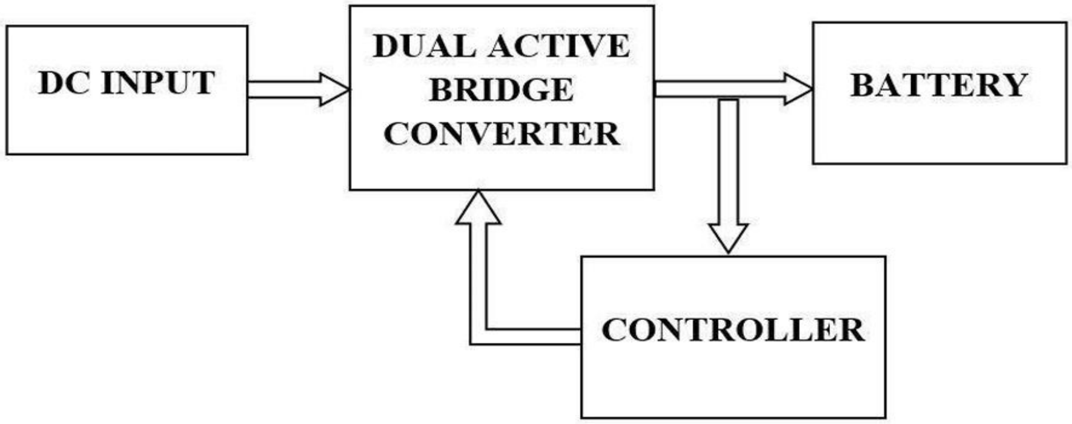

Figure III. 2: Block diagram for the DAB

Energy transfer between these two sides is controlled by adjusting the phase shift between the PWM signals driving the two bridges. Both bridges operate at a fixed switching frequency, typically 10 kHz, with a 50% duty cycle. The key control variable is the phase difference (angle) between the two PWM signals. By increasing or decreasing this phase shift, the DAB regulates the power flow.

The direction of power flow depends on the sign of the phase shift: a positive phase shift transfers energy from the source to the battery (charging), while a negative phase shift reverses the flow, enabling battery discharge back to the source or grid (Vehicle-to-Grid operation). This bidirectional capability is essential for modern electric vehicle systems that may support grid services.

III.3. The regulation loop in the DAB

The regulation loop ensures that the output (current or voltage) follows a reference value, despite disturbances or changes in load and battery state.

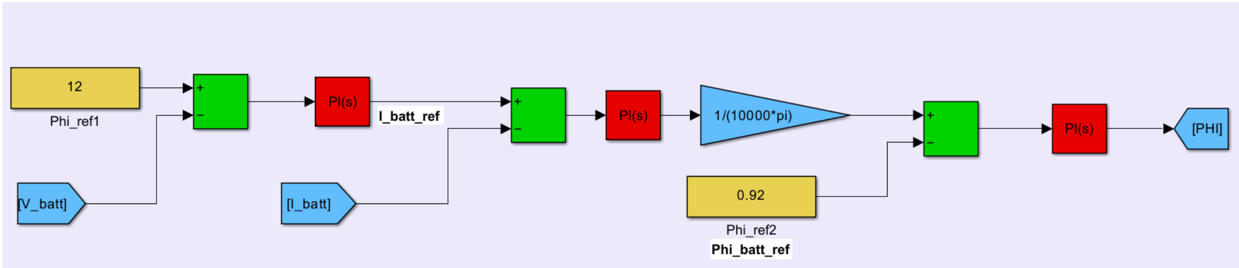

Figure III. 3: The DAB regulation's loop

Sensor continuously measures the output variable of interest, commonly the battery current and voltage. This measured value is compared to a reference value provided by the battery management system or user settings.

The difference between the reference and measured value (the error) is processed by a controller, typically a PI (Proportional integral) regulator. This controller computes the necessary adjustment to the phase shift to minimize this error.

III.4. Battery parameters

This battery model is configured for a high-capacity, fast-responding Lithium-Ion cell, ideal for testing DAB converters in energy storage systems, EV charging, or renewable integration. The absence of temperature and aging effects simplifies the model but may limit realism for long-term or thermal stress simulations.

- **Nominal voltage: 12 V**
- **Rated capacity: 150 Ah**: This is a large capacity, indicating the battery is suitable for high energy storage and extended operation under load
- **Initial state-of-charge: 70%**
- **Battery response time: 1e-4 s**: A very fast response time (100 µs) enables the battery to react quickly to load or control changes

III.5. Stages of battery charging

To ensure safety and longevity, the battery charging follows a well-established profile that the DAB serves through its control strategy:

III.5.1. Constant Current (CC) Phase

At the start of charging, the battery is often deeply discharged, requiring a stable current to safely replenish its capacity. During this phase, the DAB regulates the output current to a fixed reference by adjusting the phase shift, ensuring the battery receives a steady current even as its voltage rises.

III.5.2. Constant Voltage (CV) Phase

Once the battery voltage reaches its nominal maximum the charging strategy switches to maintaining this voltage constant. The DAB then reduces the charging current progressively by decreasing the phase shift, preventing overcharging and thermal stress.

III.5.3. Charge Completion

When the current drops below a predefined threshold or the battery is fully charged, the system automatically stops charging or switches to a maintenance mode. A fundamental aspect of the Dual Active Bridge (DAB) converter's operation is the use of phase-shift modulation to control power flow between its two ports. Both the primary and secondary sides of the DAB are driven by full-bridge inverters generating high-frequency square-wave voltages, typically with a 50% duty cycle.

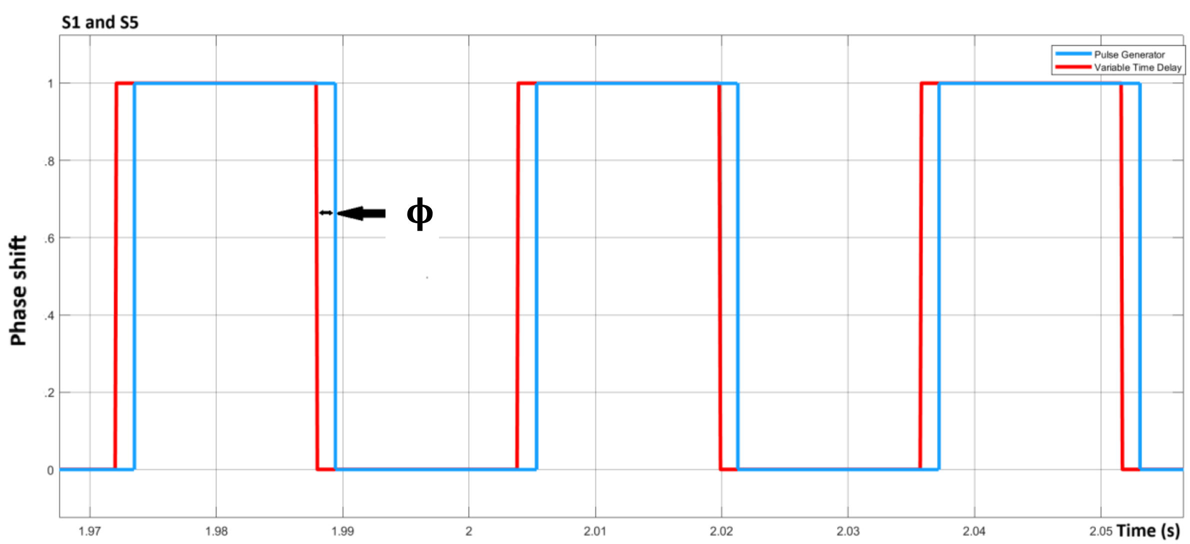

Figure III. 4: Phase shift modulation's waves

The phase shift (ϕ) between these two sets of PWM signals is the main control variable and is responsible for determining both the magnitude and direction of power transfer.

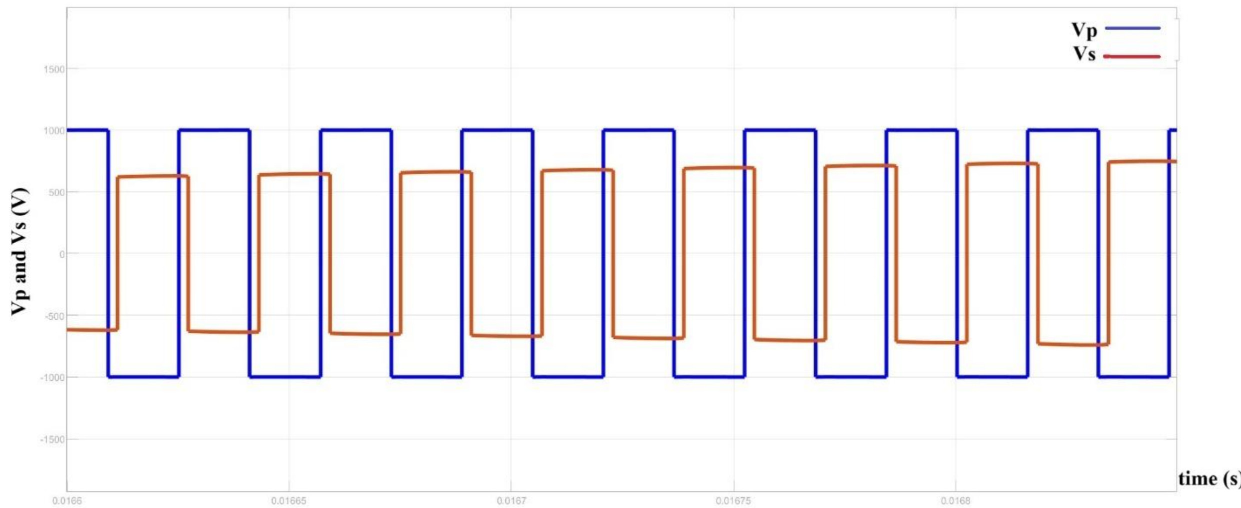

Figure III. 5: Primary and secondary voltage curves

A closed-loop control system continuously monitors battery voltage and current, dynamically adjusting the phase shift to follow this charging profile. This regulation ensures optimal charging speed while protecting battery health.

III.6. Control of the DAB during the charging

The DAB's power transfer is governed by the phase shift between the two full-bridge PWM signals. The power transferred P can be approximated by the well-known equation:

$$P = \frac{V_1 V_2 \phi \left(1 - \frac{\phi}{\pi}\right)}{2\pi f L} \qquad \text{Eq (III. 1)}$$

This nonlinear relationship shows that power increases with phase shift up to a maximum, then decreases, allowing fine control of the charging power by modulating the phase angle. The converter typically operates at 50% duty cycle on both bridges, and the phase shift is the sole control input.

Moreover, the DAB achieves Zero Voltage Switching (ZVS) by ensuring that the voltage across the IGBTs switches is zero at the instant they turn on, significantly reducing switching losses and improving efficiency. This is achieved by carefully managing the current in the leakage inductance during switching dead times.

III.7. Signal analysis

Understanding the DAB operation during battery charging requires analyzing key waveforms:

III.7.1. PWM signal

Both the high-voltage (primary) and low-voltage (secondary) bridges generate square-wave PWM signals at the switching frequency (in our case 10 kHz) with a 50% duty cycle. The phase shift between these signals controls the power flow. Graphs of these PWM signals clearly show the relative timing difference that modulates energy transfer.

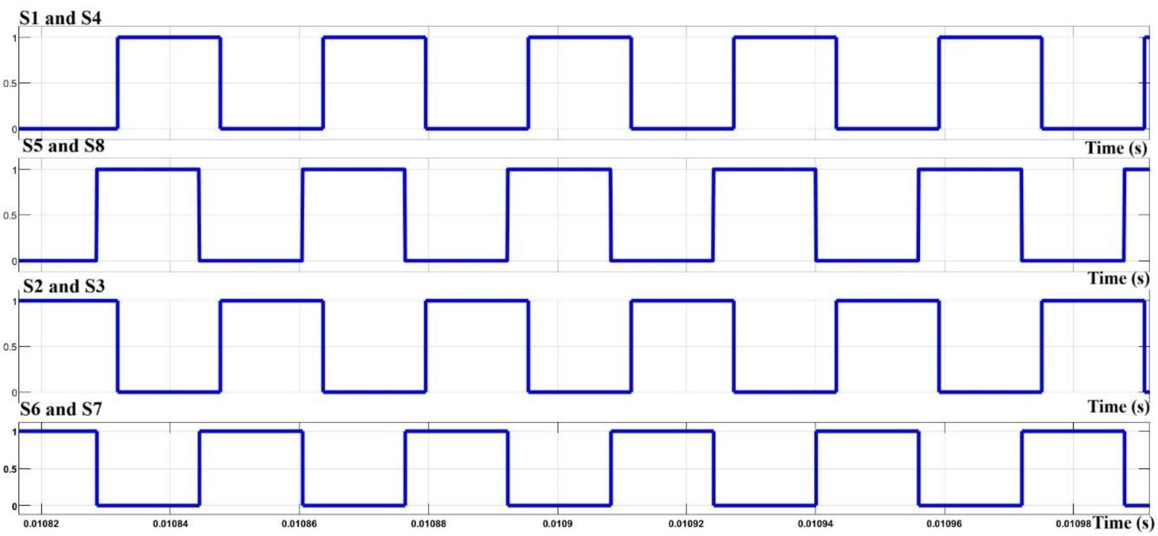

Figure III. 6: Switch gate signals

III.7.2 Transformer current

The current flowing through the transformer's leakage inductance typically has a triangular or trapezoidal shape due to the energy storage and release in the inductance during each switching cycle. The magnitude and shape of this current vary with the phase shift and directly relate to the instantaneous power transferred as shown in this figure**:**

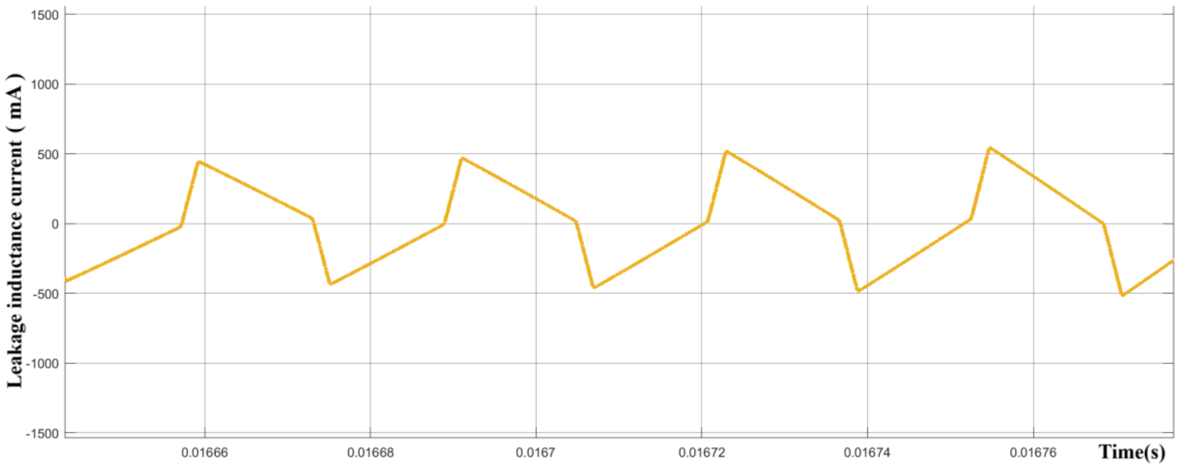

Figure III. 7: leakage inductance current's wave

III.8. Battery terminal voltage

This voltage increases during the CC phase and stabilizes during the CV phase. Monitoring this voltage is crucial for safe charging.

Th charging current is controlled by the phase shift, the current remains constant during the CC phase and decreases during the CV phase, matching the battery's charging profile. as shown in the following figure:

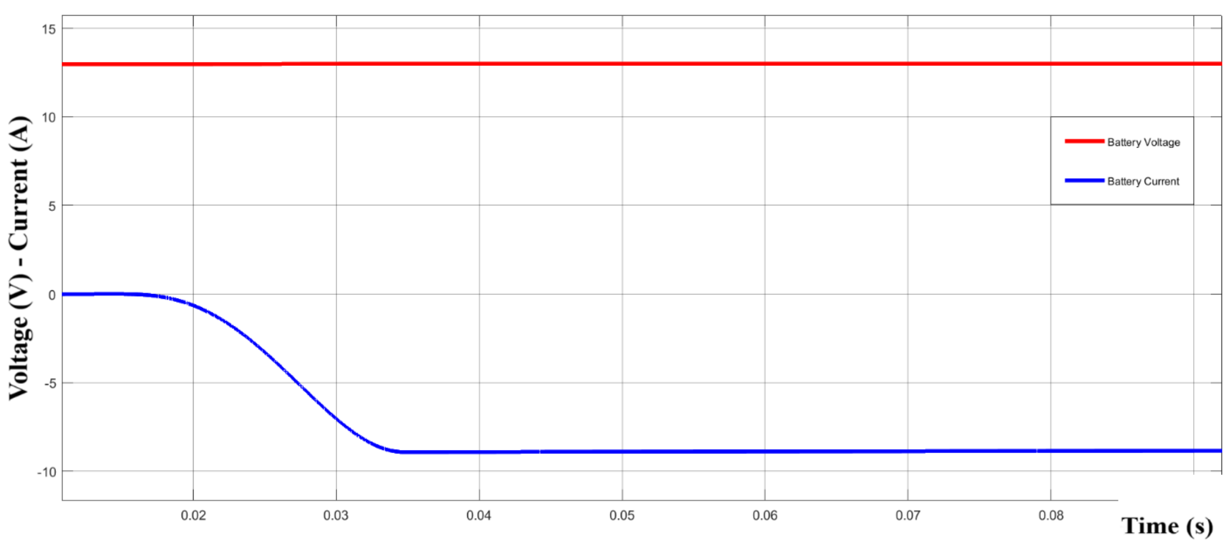

Figure III. 8 : Terminal voltage and the charging current

III.9. State of charge

SOC or state of charge of the battery is the main parameter that influence the dual active bridge's operation during charging and discharging cycle. The SOC represent the current energy level of the battery as a percentage of its total capacity; it's also the permissible current and voltage limits that the management system set.

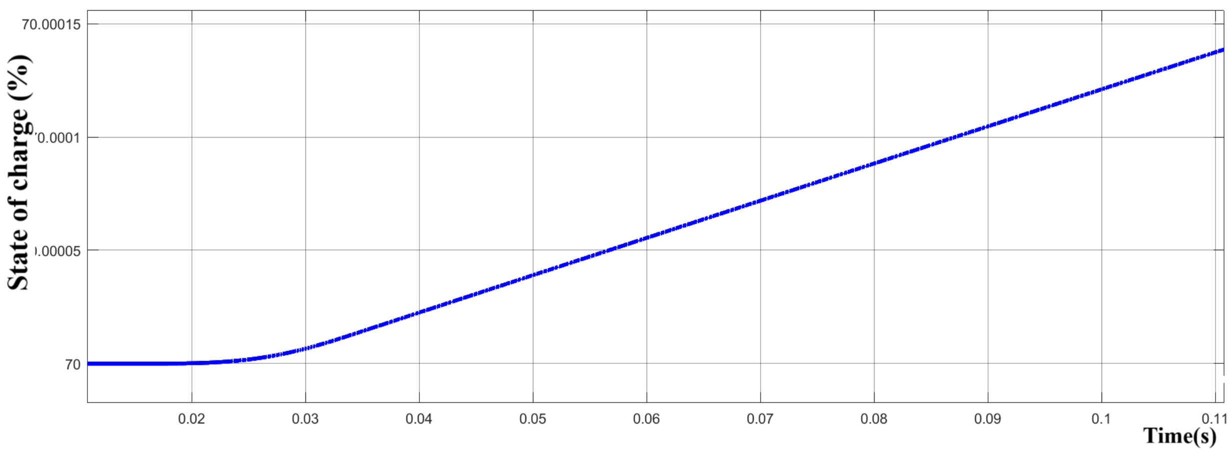

Figure III. 9: State of charge of the battery's

As we see in the previous picture, during the charging, when the battery is at a low SOC, we can observe that the DAB operates in constant current (CC) mode. In this phase the DAB adjusts the phase shift to regulate the output current, ensuring it does not exceed the safe limit for the battery. As the SOC increases and the battery voltage approaches its upper threshold, the charging strategy transits to constant voltage (CV) mode. Here the DAB reduces the charging current by decreasing the phase shift, maintaining the battery voltage at its maximum safe value until the current naturally tapers off.

III .10. Conclusion

The Dual Active Bridge (DAB) converter proves to be a robust solution for bidirectional battery charging, combining galvanic isolation, precise phase-shift control, and high efficiency. Its ability to seamlessly transition between constant-current and constant-voltage modes ensures safe and optimal charging while supporting advanced features like Vehicle-to-Grid (V2G). Through dynamic regulation of the phase shift and Zero Voltage Switching (ZVS), the DAB minimizes losses and adapts to the battery’s state of charge, making it ideal for modern electric vehicle applications.

Conclusion

Global conclusion

In this end of studies project, we started with a thorough review of various DC-DC converter topologies to build a solid foundation for a deeper look into Dual Active Bridge (DAB) converters. These converters stand out because they allow for bidirectional power flow and ensure galvanic isolation thanks to a high-frequency transformer. Operating at high switching frequencies makes it possible to use smaller and lighter magnetic components and filters, which ultimately boosts system efficiency.

The objective is to control the charger's operation to address the power management issues required for each battery charging and discharging operating mode while minimizing power losses. It was found that the dual active bridge converter topology is currently the most efficient product of research for energy storage systems and motor drives.

One of the main advantages of the DAB converter is its ability to use the transformer's leakage inductance, combined with Zero Voltage Switching (ZVS), to improve performance. In systems using IGBTs, ZVS is achieved by carefully controlling the switching transitions so that the voltage across the device drops to zero before it turns on, minimizing switching losses. Although IGBTs generally have slower switching speeds and higher conduction losses compared to MOSFETs, they are often preferred in higher power applications due to their robustness and cost-effectiveness at those levels.

We achieved an average model of the single-phase DAB, presenting its operating principle and switching characteristics. The average model was followed by a steady-state study, which subsequently yielded the linear model of the single-phase DAB.

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Abstract

This project explores the Dual Active Bridge (DAB) converter, which is an efficient, bidirectional DC-DC converter that is used for charging electric vehicle (EV) batteries. Thanks to zero-voltage switching (ZVS), it combines galvanic isolation, bidirectional energy flow and high efficiency. Operating at a high frequency enables the use of compact components. This study analyses the operating principles of the DAB, including phase-shift keying (PSK) and soft-switching techniques, which reduce losses. The DAB can adapt to both constant current (CC) and constant voltage (CV) modes to optimise energy transfer. It is ideal for embedded systems and fast charging and represents a flexible and sustainable solution for electromobility and future energy networks.

Résumé

Ce projet explore le convertisseur Dual Active Bridge (DAB), un convertisseur DC-DC bidirectionnel efficace, appliqué à la charge des batteries de véhicules électriques (VE). Il combine isolation galvanique, flux d'énergie bidirectionnel et haute efficacité grâce à la commutation à tension nulle (ZVS). Fonctionnant à haute fréquence, il permet des composants compacts. L'étude analyse ses principes de fonctionnement, incluant la modulation par déphasage (PSM) et les techniques de commutation douce pour réduire les pertes. Le DAB s'adapte aux modes courants constant (CC) et tension constante (CV), optimisant le transfert d'énergie. Idéal pour les systèmes embarqués et charge rapide, il représente une solution flexible et durable pour l'électromobilité et les réseaux énergétiques futurs.

الملخص

هذا يعتمد .الكهربائية المركبات بطاريات شحن لأنظمة مبتكر كحل المزدوج النشط الجسر محول الدراسة هذه تستعرض
كلا في الطاقة نقل على فريدة قدرة مع ،98% إلى تصل عالية تشغيل كفاءة لتحقيق الطور إزاحة في التحكم مبدأ على المحول
توفر بينما ،الآمن الكهربائي العزل لضمان العالي التردد محول في التسرب حث ملفات باستخدام التصميم يتميز .الاتجاهين
.ملحوظ بشكل الطاقة فقدان من يقلل ممتازاً أداءً صفري جهد مستوى عند التشغيل تقنية

الجهد مرحلة إلى ووصولاً الثابت التيار مرحلة من بدءاً ،المختلفة الشحن متطلبات مع التكيف على النظام قدرة النتائج تثبت
ليقدم والوظيفية الهيكلية المزايا بين المحول هذا يجمع .الذكية والأنظمة السريع الشحن لمحطات مثالياً خياراً يجعله مما ،الثابت
.مضغوط وتصميم عالية موثوقية على الحفاظ مع ،المعاصرة الطاقة أنظمة تحديات يواجه متكاملاً حلاً