Chapter 1

Introduction

1.1 Background

The global shift toward sustainable energy systems has positioned Electric Vehicles (EVs) as a transformative solution to pressing environmental and energy challenges [1]. EVs have garnered widespread attention for their potential to significantly reduce greenhouse gas emissions, enhance urban air quality, and decrease the world's reliance on depleting fossil fuel reserves. Despite higher initial CO_2 emissions during production, EVs achieve“carbon parity” with internal combustion Engine vehicles (ICEV) after approximately one year of operation. Beyond 24,000 km of driving, gasoline vehicles surpass EVs in total emissions [2]. However, the parity period varies depending on the energy source: it extends to over five years with coal-fired electricity but shortens to six months with hydroelectric power. Another study comparing the life cycle emissions of Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), and ICEVs indicates that BEVs have 40% higher production emissions than HEVs and ICEVs, primarily due to battery manufacturing. However, by the end of life, BEVs emit 18% less tons of CO_2 equivalent (tCO_2e) than HEVs and 29% less than ICEVs as shown in Fig. 1.1. Despite the higher initial impact, BEVs achieve lower total emissions, especially when powered by cleaner electricity sources [3].

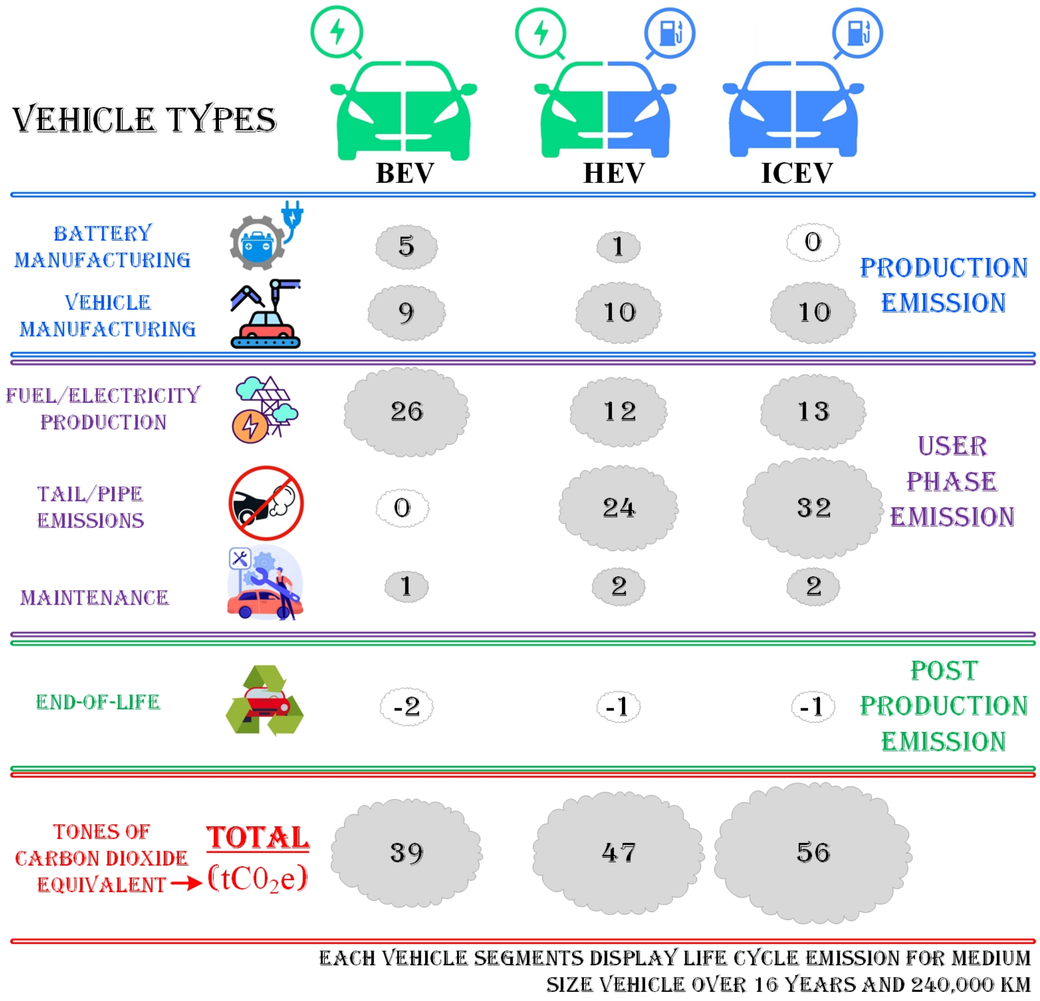
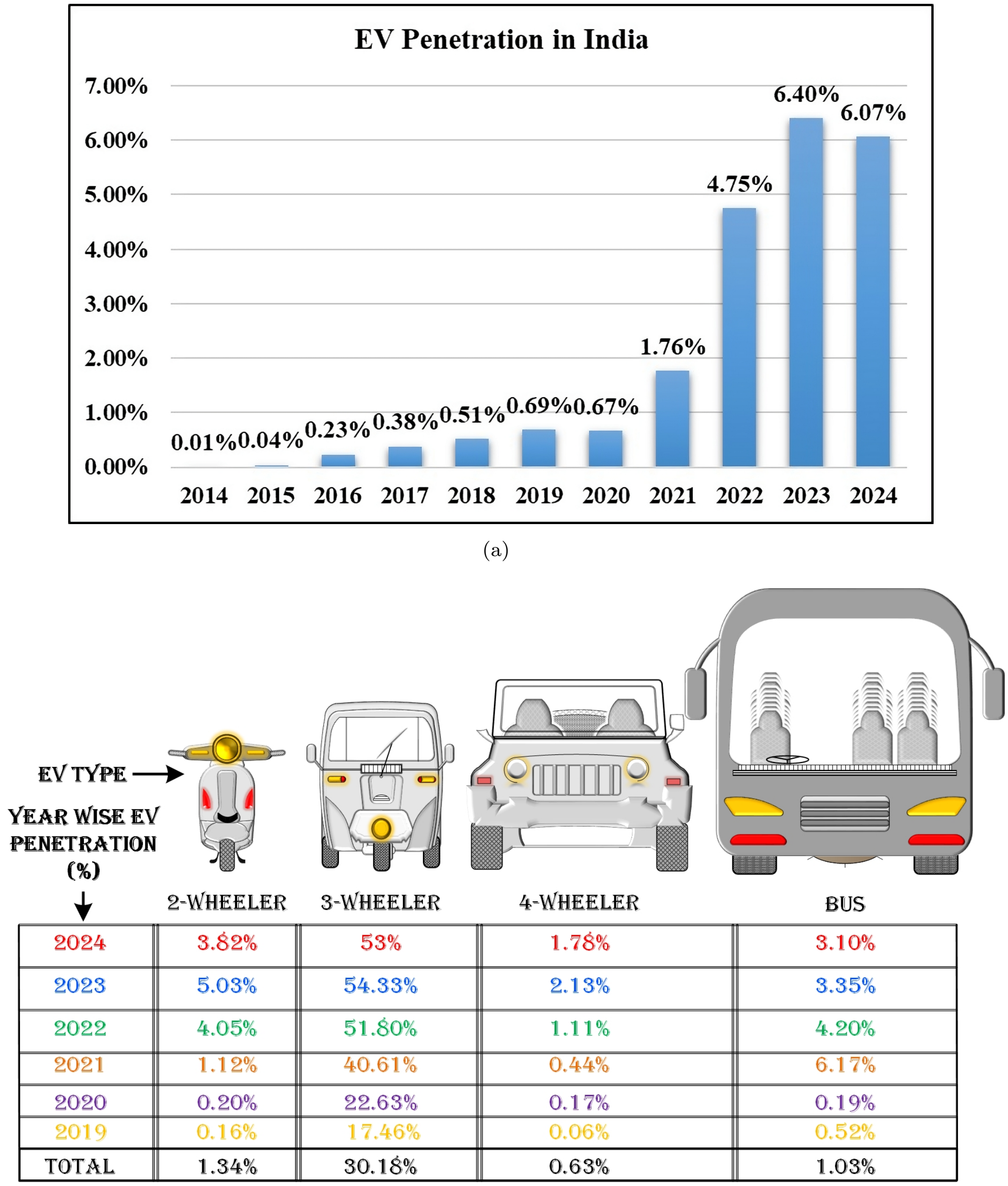


Figure 1.1: Life cycle emission of Battery Electric Vehicle, Hybrid Electric Vehicle, and Internal Combustion Engine Vehicle.

From Fig. 1.1, it can be observed that the integration of EVs into modern transportation systems aligns with global efforts to combat climate change and achieve net-zero carbon targets. With advancements in battery technologies and supportive policies, governments and industries worldwide are making significant investments in EV infrastructure to accelerate this green transition [4].

Another graph shown in Fig. 1.2(a) illustrates EV penetration in India, covering electric two-wheelers (2W), three-wheelers (3W), four-wheelers (4W), and buses. As of October 2024, EV penetration in India stands at approximately 6%, with projections indicating that this figure will surpass 30% of the total vehicle market by 2030. Mean-



YEAR WISE EV PENETRATION (%)	2-WHEELER	3-WHEELER	4-WHEELER	BUS
2024	3.82%	53%	1.78%	3.10%
2023	5.03%	54.33%	2.13%	3.35%
2022	4.05%	51.80%	1.11%	4.20%
2021	1.12%	40.61%	0.44%	6.17%
2020	0.20%	22.63%	0.17%	0.19%
2019	0.16%	17.46%	0.06%	0.52%
TOTAL	1.34%	30.18%	0.63%	1.03%

(a)

(b)

Figure 1.2: India's EV penetration till October 2024. (Source: Vahan Dashboard via clean mobility shift)

while, Fig. 1.2(b) presents vehicle-wise EV penetration trends between 2019 and 2024. This surge reflects not only a shift in transportation preferences but also a broader transformation in how energy is stored and managed.

As the adoption of EVs accelerates, they are poised to become more than just a cleaner alternative to traditional vehicles. Instead, they represent a paradigm shift, evolving into mobile energy assets capable of playing a dynamic role within modern power systems. Their high-capacity batteries hold immense potential for energy storage and management, unlocking opportunities for innovative solutions that blend transportation with energy infrastructure. At the core of this revolution are bidirectional converters, which enable EVs to interact seamlessly with the grid, supporting advanced energy applications and redefining the way energy systems operate [5, 6].

These converters serve as the critical interface between EV batteries and the power grid, enabling energy flow in both directions. This functionality goes beyond mere charging transforming EVs into mobile energy hubs that interact dynamically with the grid [7]. For instance, Vehicle-to-Grid (V2G) applications empower EVs to stabilize grid operations by returning stored energy during peak demand or integrating surplus energy from renewable sources like solar and wind. Imagine a future where parked EVs collectively form a vast, decentralized energy storage network, ensuring that no solar ray or gust of wind goes to waste.

However, achieving this vision in India isn't without challenges. Bidirectional converters must meet stringent standards for energy efficiency, minimize power losses, and ensure seamless synchronization with grid parameters. Modern designs incorporate advanced control strategies and soft-switching techniques to address issues like harmonic distortion, realization complexity reduction and thermal management, making them indispensable to the EV ecosystem.

This thesis presents an opportunity to explore this emerging field, examining the challenges, solutions, and immense potential of integrating bidirectional power flow into modern energy systems. Specifically, it focuses on the development of a novel switching technique and the realization of an advanced modulation strategy for a bidirectional converter, utilized as an on-board charger. Additionally, these modulation techniques are tested for a DC-DC DAB converter in a hybrid energy source-integrated DC charging system, incorporating an efficient power management scheme. These innovations enable improved soft-switching characteristics and significantly enhance converter performance, ensuring greater efficiency and reliability for diverse energy applications.

1.2 Research Motivation

Energy storage systems are essential for achieving net-zero carbon emissions. They support sustainability by efficiently storing renewable energy and meeting the growing demand for clean power, ensuring a reliable and greener future. Among various energy storage solutions, batteries have emerged as the most widely used technology due to their versatility and efficiency. However, the effective utilization of batteries heavily depends on bidirectional converters [8, 9, 10, 11], which enable seamless energy flow in both directions. By enhancing converter performance, transformative applications such as renewable energy integration, V2G, and vehicle-to-home (V2H) systems become feasible. Embracing advanced bidirectional converter technology is a step toward innovation, empowering sustainable energy solutions and driving progress toward a cleaner, greener future.

As the global push for V2G technologies continues to gain momentum, significant initiatives are being introduced to harness the potential of bidirectional energy transfer. Various applications, including V2G, V2H, Vehicle-to-Load (V2L), and Vehicle-to-Building (V2B), are being explored to enhance energy management and grid resilience [12], a typical example is shown in Fig. 1.3. In 2017, Nuvve, a V2G technology provider, launched the INVENT pilot program at the University of California San Diego, funded by the California Energy Commission. This involved installing 50 V2G bidirectional charging stations on campus [13]. In November 2018, Toyota Tsusho Corporation and Chubu Electric Power Co., Inc. initiated V2G demonstrations with electric vehicles in Toyota City, Aichi Prefecture, Japan [14]. Additionally, in May 2016, Nissan and Enel Power Company announced a collaborative V2G trial in the United Kingdom, utilizing

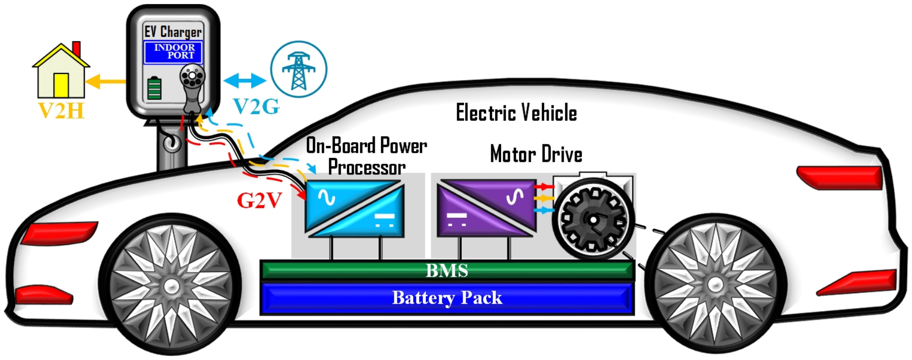


Figure 1.3: Typical operating modes of an EV in V2G, G2V, and V2H scenarios.

100 V2G charging units with Nissan Leaf and e-NV200 electric vans [15]. On September 29, 2022, Solaris inaugurated a Charging Park in Bolechowo, Poland, designed to test the charging and discharging capabilities of electric vehicles [16].

The Government of India has actively embraced the development of EV charging infrastructure that supports V2G technology, demonstrating a strong commitment to advancing sustainable energy solutions [17]. In alignment with this initiative, Tata Power-Delhi Distribution Limited has signed a Memorandum of Understanding (MoU) with the Indian Smart Grid Forum (ISGF) to showcase innovative V2G technology in North Delhi [18, 19]. Furthermore, Sheru, an energy software company, is developing a V2G bidirectional battery-swapping system aimed at balancing demand, addressing the increasing pressure on the country's electrical grid [20]. Furthermore, several EVs in India are now equipped with bidirectional charging capabilities [21].

These initiatives highlight the growing demand for reliable, efficient, and flexible bidirectional power transfer solutions. Among the different bidirectional converter topologies, the AC-DC DAB converter stands out due to its high power density, galvanic isolation, and efficient bidirectional energy transfer capability. These characteristics make it an ideal candidate for battery charging applications, where efficiency, control flexibility, and grid integration are crucial.

However, the effectiveness of an AC-DC DAB converter heavily depends on its modulation strategy, which directly impacts soft-switching capability, power factor correction (PFC), and overall system performance. Despite extensive research, existing modulation techniques face several challenges, particularly in:

- Ensuring soft-switching operation under wide battery voltages, varying grid-side conditions, and throughout line frequency operation.
- Minimizing power losses, pseudo soft-switching, and current stress to enhance system performance.
- Improving power factor correction for seamless grid integration without additional circuitry.
- Reducing computational complexity for real-time modulation control in practical implementations.
- Poor light load performance during battery charging, especially in CV operation.

While various modulation strategies—such as trapezoidal modulation (TZM), triangular modulation (TRM), a combination of TRM and TZM with variable frequency modulation, as well as unipolar and bipolar sinusoidal modulation have been explored, each presents trade-offs in terms of efficiency, control complexity, and suitability for battery charging applications. Despite these advancements, a critical research gap remains in identifying an optimized modulation scheme that effectively balances soft-switching, PFC, and efficiency for AC-DC DAB converters. Addressing this gap is essential for enhancing the performance and reliability of battery charging systems, thereby contributing to the advancement of sustainable energy solutions.

These challenges have inspired the pursuit of a novel modulation technique for bidirectional AC-DC DAB converters, specifically designed for battery charging applications. The research aims to address critical issues such as non-linear power relationships, soft-switching performance, realization complexities, improving light load performance, and natural PFC, contributing to improved system efficiency and reliability. By developing and validating an innovative modulation approach, this thesis aspires to provide meaningful contributions to energy storage technologies, ultimately driving progress toward a sustainable energy future. Finally, a DC charging system capable of multi-mode operation is presented, offering enhanced flexibility and performance. This application-oriented chapter of the thesis aims to support the Government of India's e-AMRIT scheme by contributing to advanced and sustainable EV charging solutions.

1.3 Literature Survey

The field of bidirectional converters is vast and diverse, with a range of solutions explored in existing literature [8, 22, 23, 24]. Among these, one of the most prominent and widely adopted configurations is the single-phase, single-stage bidirectional AC-DC DAB converter [25, 26]. These converters have seen a surge in popularity, positioning themselves as a top contender in the future of power electronics design. With a host of notable advantages, such as galvanic isolation between input and output, a streamlined compact design, and a single-stage configuration, the DAB converter has earned its place in the spotlight. Inherently soft-switching and devoid of the need for electrolytic capacitors, it proves both efficient and reliable. These outstanding characteristics make it ideal for an expansive array of applications, including onboard battery chargers [27, 28, 29, 30, 31], microinverters [32, 33, 34, 35], hybrid AC/DC microgrids [36, 37], traction systems [38, 39, 40], and Vehicle-to-Grid (V2G) applications [41, 42].

Focusing specifically on battery charging, the DAB converter stands out by offering essential features such as grid and battery-side terminal isolation, support for both constant current (CC) and constant voltage (CV) charging modes, and AC-side PFC or unity power factor operation (UPF). These robust capabilities, combined with its innate advantages, make the DAB converter an indispensable tool for advancing energy systems that prioritize both efficiency and sustainability. This unique combination not only solidifies its place in modern energy technologies but also fuels further exploration and innovation in the field.

A key factor driving the DAB converter's remarkable performance is its sophisticated modulation technique, which significantly enhances both operational efficiency and control precision. By carefully managing switching patterns, this technique facilitates zero-voltage and/or zero-current switching, drastically reducing switching losses and minimizing thermal stress on the system's components. Furthermore, this modulation approach optimizes RMS current levels, leading to a substantial reduction in conduction losses while boosting overall energy efficiency. With its ability to maintain stable operation over a broad voltage range, the DAB converter shines in high-demand applications such as electric vehicle charging, renewable energy integration, and grid management systems. Despite these important benefits, several challenges remain, including the complexity of non-linear control variables (also referred to as degree of Freedom (DoF)) and power relationships, maintaining optimal soft-switching performance under varying input and output voltages, managing the computational load of advanced switching techniques, and enhancing inherent PFC capabilities.

As mentioned earlier, one of the key challenges tied to the AC-DC DAB modulation technique is the non-linear power relationship with the control variable. Even a small change in the control variable can result in a non-linear shift in output power, complicating control design [43]. This non-linearity often leads to oscillations before the system reaches a steady state, ultimately degrading the converter's performance. These oscillations, while temporary, can undermine the efficiency and reliability of the system, requiring additional stabilization efforts.

To address these challenges, a deeper understanding of bidirectional AC-to-DC DAB converters and their limitations is essential. This section is divided into three parts: first, an analysis of single-stage, single-phase converters, focusing on their design and implementation challenges; second, a review of soft-switching techniques to improve converter efficiency; and finally, an evaluation of modulation strategies to optimize power transfer, reduce losses, and overcome operational constraints.

Furthermore, as the number of control variables increases, the computational load on microcontrollers becomes heavier, often necessitating advanced multi-architecture controllers. Systems such as Digital Signal Processors (DSPs), renowned for their sequential processing capabilities, and Field-Programmable Gate Arrays (FPGAs), which excel at parallel processing, are often employed to manage this complexity. However, a thought-provoking question arises: Is it possible to achieve similar performance with fewer control variables, utilizing just a single microcontroller architecture? Delving into this possibility could open the door to simpler, more cost-effective control designs that maintain high performance, leading to more efficient converter systems.

This section is structured into three distinct parts. The first part provides an in-depth analysis of single-stage, single-phase bidirectional AC-to-DC DAB converters, delving into their design aspects, as well as exploring the challenges and limitations that accompany their implementation. The second part examines various soft-switching techniques, discussing their core principles, benefits, and practical applications in enhancing converter efficiency. Finally, the third part focuses on different modulation techniques employed in DAB converters, evaluating their effectiveness in optimizing power transfer, reducing losses, and addressing operational constraints.

1.3.1 Bidirectional AC-DC DAB Converters

The AC-DC DAB converter has gained significant popularity, driven by its remarkable advantages over traditional converters. With bi-directional power flow capability, high power density achieved through the absence of electrolytic capacitors, and galvanic isolation, it stands as a preferred solution for modern applications [25, 44, 45, 46]. Its soft switching transitions and compact structure further enhance its efficiency and versatility, making it well-suited for a wide range of applications and power ratings [47, 48]. These features not only elevate its performance but also ensure its place as a preferred choice in industries such as renewable energy, EV charging, and grid integration

[8, 26, 49, 50]. The non-resonating AC-DC bidirectional DAB converter is an evolution of the DC-DC DAB converter, retaining its core advantages while extending its capability to handle both AC and DC power. In these converters, power transfer between the input and output is governed by the phase shift between the bridges, ensuring efficient bidirectional energy transfer. Based on their structural and operational characteristics, these single-stage, single-phase converters are typically classified into three categories: the Matrix-Type AC-DC DAB converter, the Quasi Single Stage (Q1S) AC-DC DAB converter with an intermediate capacitor, and Quasi Single Stage (QS^2) AC-DC DAB converter without an intermediate capacitor.

All above mentioned topologies used a modulation technique which at least one control variable called phase-shift to regulate the quantity and direction of power flow, making them suitable for regulating power. Furthermore, there exist other DAB topologies that utilize unipolar and bipolar PWM techniques for power conversion. A detailed discussion of some of these PWM-based DAB topologies will be presented later in this section. Please note that throughout this thesis, the term Q1S refers to AC-DC DAB converters with an intermediate capacitor, while QS^2 refers to AC-DC DAB converters without an intermediate capacitor. Additionally, these quasi-single-stage AC-DC DAB converters are also referred to as full-bridge type AC-DC DAB converters, and the intermediate capacitors are non-electrolytic. The Matrix-Type AC-DC DAB converter is discussed in detail below.

1.3.1.1 Bidirectional AC-DC Matrix Type Dual Active Bridge Converter

As discussed above, the bidirectional AC-DC DAB converter is an evolution of the DC-DC DAB converter, preserving its fundamental advantages while enhancing its ability to handle both AC and DC power. One of the most widely used configurations is the matrix-type DAB converter, which was first presented in [51, 52], which combines two DC-DC DAB converters—one operating at positive voltage and the other at negative voltage, as shown in Fig. 1.4. The matrix-type converter is named as such because the AC-side bridge converts line-frequency AC into high-frequency AC at the switching frequency. This converter can also be perceived as a configuration where each DAB device is replaced by bidirectional switches. Devices labeled as S_{xa}, where $x = 1$ to 4, operate during the positive half-cycle, while devices labeled as S_{xb}, function during the negative half-cycle. When the converter operates for the positive half-cycle, all devices S_{xb} remain on, making it function as a DC-DC DAB operating on pulsating unipolar DC voltage, and vice versa for the negative half-cycle of the grid voltage.

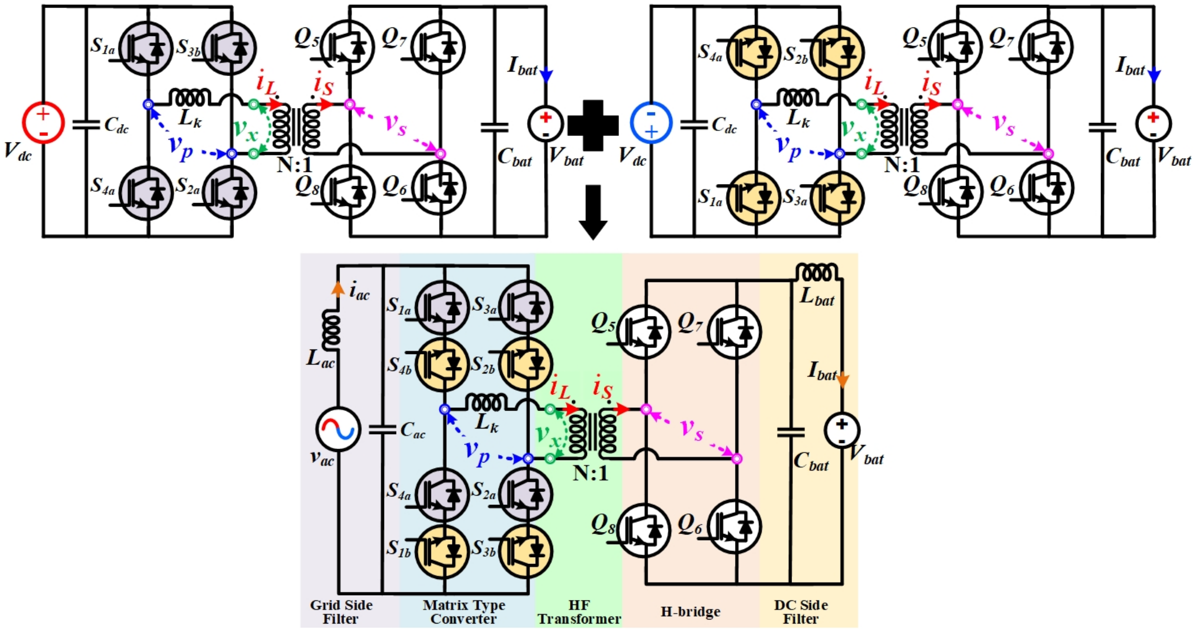


Figure 1.4: Bidirectional AC-DC Matrix Type Dual Active Bridge Converter.

Similar to the DC-DC DAB converter, the leakage inductance (L_k) acts as the energy storage element and is typically the natural leakage inductance of the high-frequency transformer used for this purpose. For non-resonating DAB operation, the magnetizing inductance is much greater than the leakage inductance. Both the grid and DC sides include LC filters, and the capacitors used are typically non-electrolytic. As a result, the entire converter is considered an electrolytic-less system. The matrix-type converter can operate in either boost or buck mode, depending on the modulation technique employed, which will be discussed in the later subsections.

1.3.1.2 Q1S AC-DC Dual Active Bridge Converter

If a DC-DC DAB converter is designed to handle a pulsating unipolar DC input and is operated to draw a current that follows the voltage waveform, it can be adapted for AC-DC conversion as shown in Fig. 1.5. Building on this concept, another popular AC-DC DAB converter is derived, known as the bidirectional Q1S AC-DC DAB, also referred to as the full-bridge AC-DC DAB converter with an intermediate capacitor. This concept was first introduced in [53], where a diode bridge rectifier was employed at the front end, followed by a half-bridge configuration for the DAB. The term "Quasi" signifies "Pseudo," reflecting the presence of an intermediate high-frequency capacitor in the converter [25, 54]. However, the primary role of this intermediate capacitor is to maintain a constant DC link voltage. If the high-frequency capacitor is used solely for filtering high-frequency ripples rather than sustaining a constant DC link, it cannot be classified as a DC-link capacitor. Consequently, the converter shown in Fig. 1.5 is referred to as a Q1S AC-DC DAB converter due to its incorporation of a pseudo DC-link (C_1). Nevertheless, it is still categorized as a single-stage design, as the low-capacitance, non-electrolytic DC capacitor is exclusively intended for filtering high-frequency ripples, as previously mentioned [55, 56, 57].

In Fig. 1.5, the grid-side devices S_1 to S_4 operate at the grid frequency as a synchronous rectifier (SR). Specifically, devices S_1 and S_4 remain ON during the positive half-cycle of the grid voltage, while S_2 and S_3 remain ON during the negative half-cycle. The Q1S AC-DC DAB converter operates similarly to the matrix-type AC-DC DAB converter, as it perceives the incoming grid voltage as a pulsating unipolar DC signal over the line frequency. The modulation technique plays a critical role in ensuring that a sinusoidal current with THD is drawn from the grid with near-unity PFC. Unlike the AC-DC Matrix-Type DAB converter, this configuration requires only eight switches to operate at high frequency throughout the line frequency cycle. Therefore, the devices S_1 to S_4, which operate as synchronous rectifiers, only experience conduction losses. This distinguishes them from the rest of the high-frequency devices, which are subject to both conduction and switching losses.

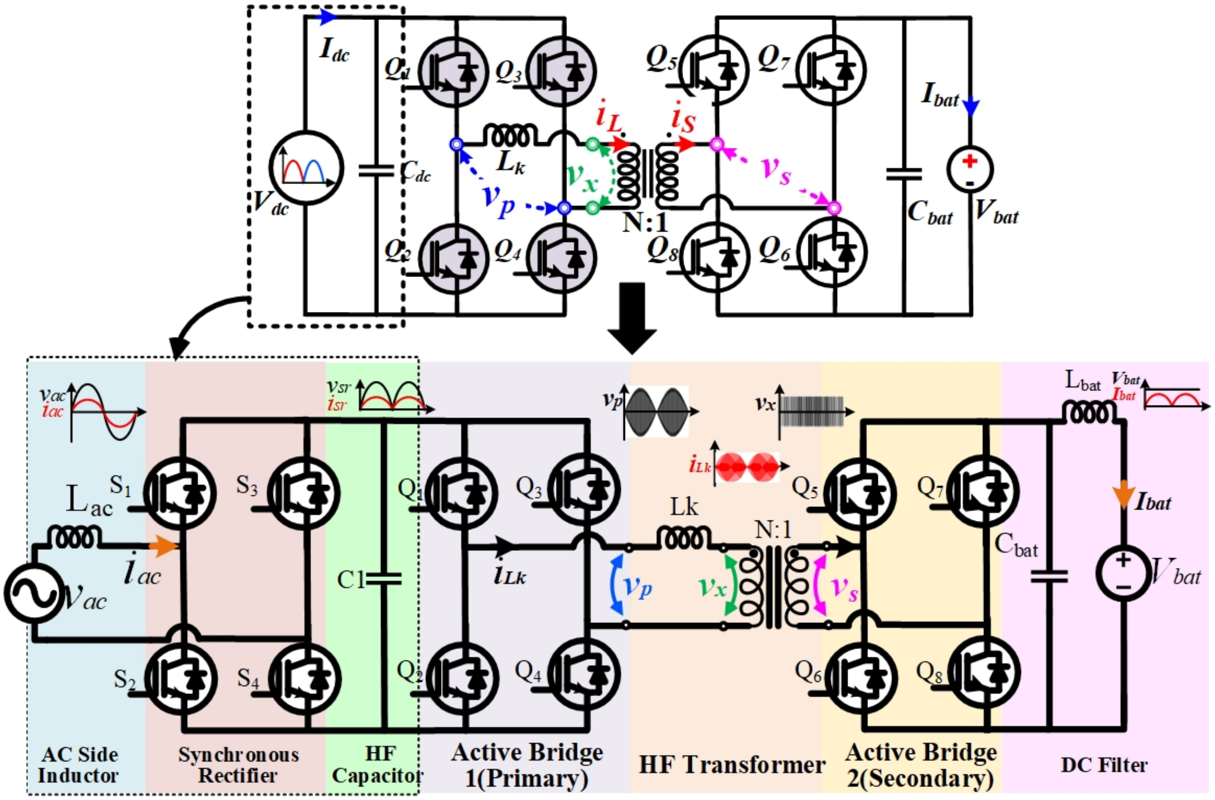


Figure 1.5: Bidirectional Quasi Single Stage (Q1S) AC-DC Dual Active Bridge Converter with Intermediate Film Capacitor.

1.3.1.3 QS^2 AC-DC Dual Active Bridge Converter

Similar to the Q1S AC-DC DAB, another popular AC-DC DAB topology is the QS^2 AC-DC DAB, which operates without an intermediate capacitor [58, 59, 60, 61, 62]. The intermediate DC capacitor shown in Fig. 1.5 is shifted to the grid side and presented as an AC capacitor in Fig. 1.6. In this topology, the input to the primary active bridge is directly supplied with a high-frequency current at the switching frequency. Consequently, the synchronous rectifier (SR) folds the input voltage, and due to the switching of the high-frequency bridge, the input of the primary bridge transforms into a high-frequency current, as depicted in Fig. 1.6. As a result of this switching, both the diode and the device in the SR conduct; however, it still operates as a synchronous rectifier. Consequently, the conduction loss of the SR is distributed between the switch (MOSFET or IGBT) and the diode. The QS^2 AC-DC DAB is particularly favored for modulation techniques that lead to a discontinuous input current [63]. In comparison to the Q1S AC-DC DAB, the QS^2 AC-DC DAB offers additional advantages due to the inclusion of the filter inductor L_{ac} and filter capacitor C_{ac}. These filtering elements, positioned before the synchronous rectifier (SR), effectively mitigate the issue of inrush current, which is commonly encountered in other topologies lacking such filters. This results in more stable and efficient operation, especially during the initial power-up or cold start conditions. The disadvantage of this topology, from a design perspective, is that, unlike the Q1S AC-DC DAB, it does not have the folded grid current available at the end of the SR, which can also be used to regulate the grid current during DC-AC operation. Therefore, an additional conditioning circuit is required for sensing the AC grid current for the analog-to-digital converter (ADC) of the MCU.

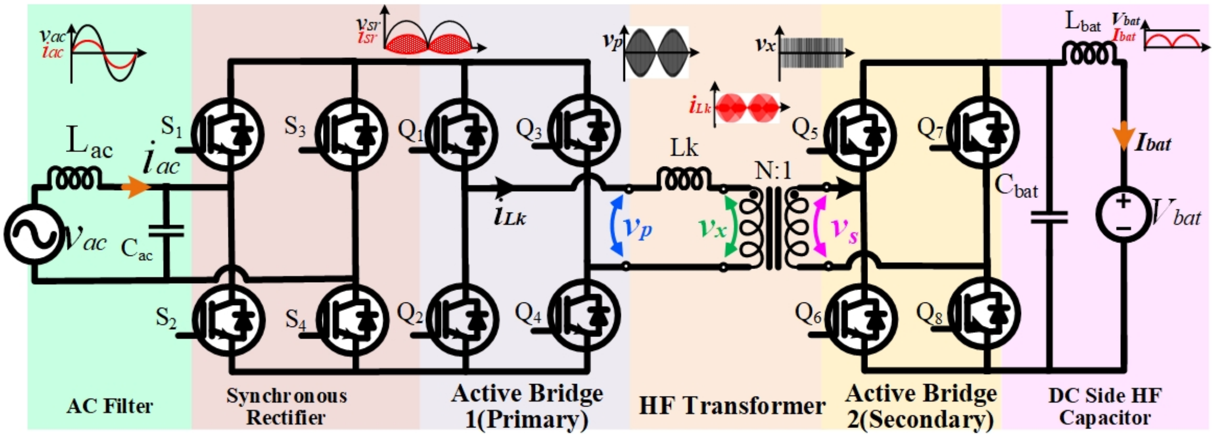


Figure 1.6: Bidirectional Quasi Single Stage (QS^2) AC-DC Dual Active Bridge Converter without Intermediate Film Capacitor.

1.3.1.4 Bidirectional AC-DC Indirect Matrix Type DAB Converter

Fig. 1.7 illustrates the circuit configuration of an AC-DC Indirect Matrix Type DAB converter [54, 64, 65, 66], which consists of a matrix, a full-bridge (FB) converter, and a high-frequency transformer (HFT). The FB converter is connected to a DC bus for AC-to-DC conversion, while the matrix, which uses bidirectional switches similar to Fig. 1.4, is connected to the grid for AC-to-AC conversion. These two converters are linked by the high-frequency transformer. The converter is referred to as an Indirect Matrix Type due to the interconnection of the matrix-type converter with the source and the high-frequency transformer in comparison with Fig. 1.4.

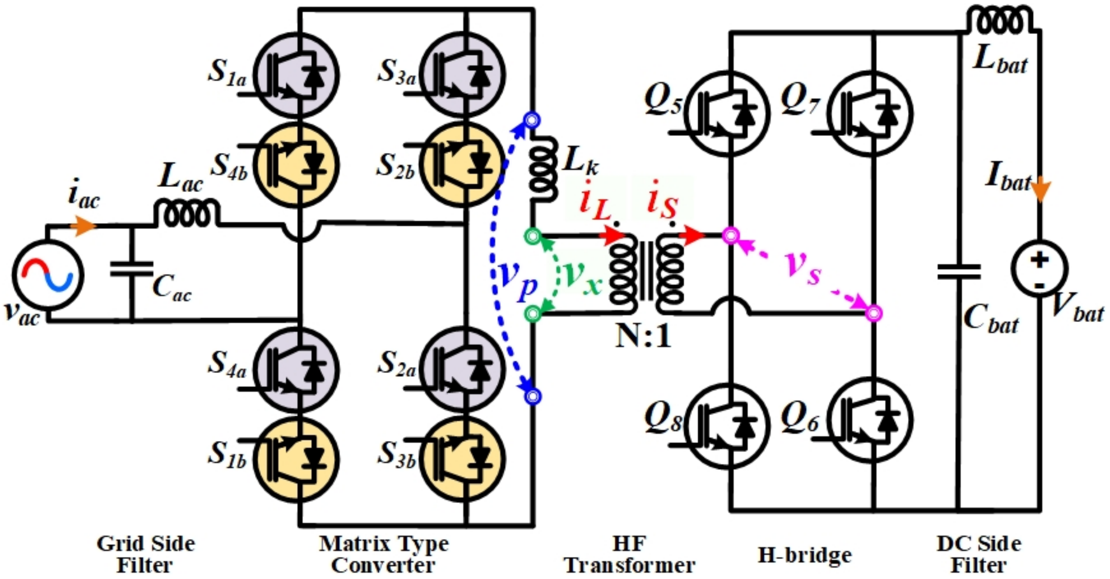


Figure 1.7: Bidirectional AC-DC Indirect Matrix Type Dual Active Bridge Converter.

One of the undesirable conditions of this structure is that both the high-frequency transformer leakage inductor and the filter inductor function as current sources, creating a series connection during intermediate switching states. This condition causes an abrupt rise in the high-frequency transformer leakage current during the AC-to-AC conversion process, leading to high-voltage spikes across the power devices [54, 66, 67, 68]. These spikes can significantly affect the efficiency and reliability of the Indirect Matrix Type converter system. Further, the converter suffers from distortion near the zero crossing of the grid current.

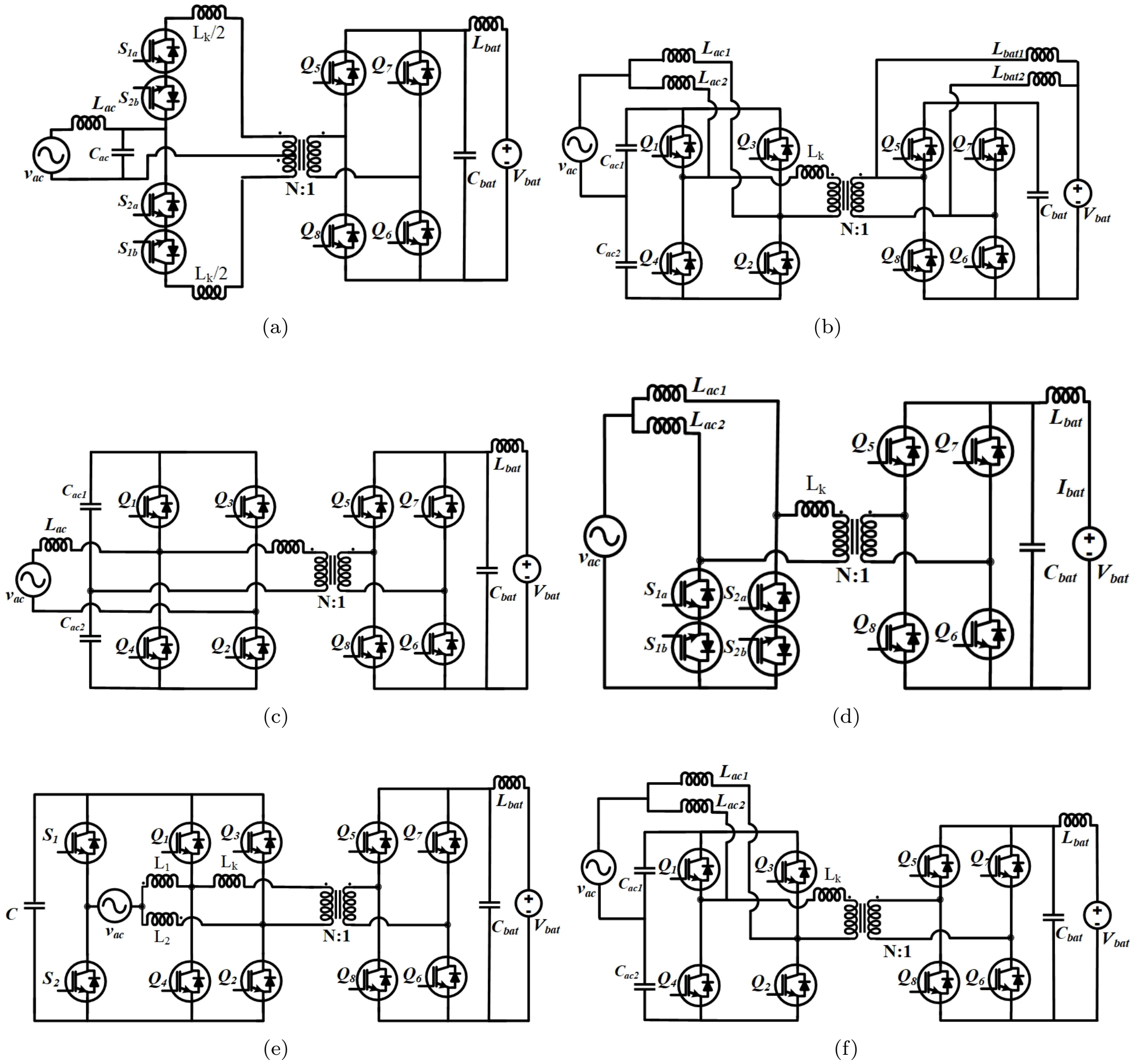
Additionally, this converter does not rely on phase-shifted power flow for AC-to-DC or DC-to-AC conversion. Instead, it depends on unipolar or bipolar sinusoidal PWM control, necessitating a separate switching sequence, which adds to the complexity of its operation. However, one key advantage of this topology is its ability to achieve a boosted DC output due to the presence of the boost inductor L_{ac} on the grid side. This inductor facilitates energy storage during the AC-to-DC conversion process, effectively raising the DC output voltage. As a result, the system can efficiently operate in scenarios where a higher DC voltage is required for subsequent DC stages.

1.3.1.5 Other Single-Stage AC-DC DAB Topologies

Several recent bidirectional AC-DC converters, derived from the basic DAB topology (Fig. 1.8), use phase-shift or sinusoidal PWM modulation. Some key configurations are discussed below.

Topology 1:- The topology 1, as shown in Fig. 1.8(a) [47, 69], features a transformer with primary windings connected in a push–pull configuration to a single-phase AC source v_{ac} using switches S_{xa} and S_{xb} (x=1 and 2). Each four-quadrant switch is implemented with an IGBT, with a body diode that acts as a natural rectifier. On the primary side, the transformer is linked to a matrix-type converter through a split inductor L_K, representing both the transformer's leakage inductance and any additional inductance. The H-bridge consists of four switches Q_5 to Q_8 and is connected to a DC link with voltage V_{bat}.

Topology 2:- The topology of the multiphase boost AC–DC DAB converter is shown in Fig. 1.8(b) [70]. The converter consists of two full-bridge circuits linked by a high-frequency transformer, similar to a conventional DAB converter. The inductor L_{Lk} includes the transformer leakage inductance, and the converter incorporates multiphase



(a) (b) (c) (d) (e) (f)

Figure 1.8: Other AC-DC DAB based topologies; (a) Push-pull DAB Topology 1 [47, 69]. (b) Multiphase Boost Type DAB Topology 2 [70]. (c) Reconfigured AC-DC DAB Topology 3 [71, 72]. (d) Current Source DAB Topology 4 [73, 74]. (e) Interleaved Inversely Coupled Inductor DAB Topology 5 [75, 76]. (e) Single-Phase Boost Type DAB Topology 6 [77].

boost interfaces at both input and output ports. On the AC side, the DC bus is established by two series-connected capacitors. Each leg of the AC-side bridge, along with its capacitive DC bus leg, forms two separate half-bridge inverter units. On the DC side, each leg of the full-bridge, along with the boost inductor connected to its switch node, forms a boost phase unit. The inverter phase units are connected to the load through filter inductors L_{bat1} and L_{bat2}, respectively. The interleaved operation of the phase units at both input and output sides reduces input and output current ripple, minimizing the filter capacitor requirement. Since the phase units share the input and output currents, smaller inductors can be used for current source interfacing at both ports. Additionally, the interleaved operation reduces the effective input and output inductance of the system, improving its dynamic response. This converter utilizes only eight switching devices; however, it requires a large number of passive components, which decreases the overall power density.

Topology 3:- The eight-switch DAB converter can be reconfigured to function as a DC-AC converter instead of a DC-DC converter, as illustrated in Fig. 1.8(c) [71, 72]. In the conventional DAB converter, two full-bridge converters are linked through a high-frequency transformer (HFT). In this topology, the secondary-side converter remains a full-bridge, where all the switches operate at the switching frequency. On the primary side, the bridge consists of two switch sets: Q_1, Q_4, and Q_2, Q_3. One switch set, Q_1, Q_4, operates at the switching frequency, while the other switch set, Q_2, Q_3, operates at the grid frequency. The Primary-side terminals of the high frequency transformer are connected between the midpoints of switch set Q_1, Q_4, and the split capacitor C_{ac1}, C_{ac2}. The positive and negative terminals of the input voltage v_{ac} are connected to the midpoints of the two switching sets, Q_1, Q_4, and Q_2, Q_3, respectively. This configuration allows the converter to perform efficient AC-DC conversion while leveraging the benefits of the DAB topology supports phase-shift modulation. This converter supports phase-shift modulation as well; however, it suffers from high current stress, which can impact the overall efficiency and reliability of the system.

Topology 4:- The converter topology, as shown in Fig. 1.8(d) [73, 74], is capable of operating in all four quadrants of voltage and current. The topology consists of a current-fed bidirectional half-bridge converter on the primary side, while the secondary side features a full-bridge topology interfacing with the battery through a filter inductor. Power transfer between the primary and secondary sides is facilitated by a high-frequency transformer. The equivalent series inductance, denoted as leakage inductance of the transformer, is represented by an external series inductance if the inherent leakage inductance is insufficient. During battery charging, the converter functions as a two-phase boost converter, whereas in reverse power flow conditions, it operates as a full-bridge converter with a current doubler configuration.

Topology 5:- Fig. 1.8(e) shows the AC–DC DAB converter based on an inversely coupled inductor [75, 76]. The primary full bridge (Q_1–Q_4) is connected with the secondary full bridge (Q_5–Q_8) via a high-frequency transformer with an equivalent leakage inductance. The inversely coupled inductor (L_1, L_2) is connected to the midpoint of two bridge arms of the primary full bridge, respectively. The auxiliary fundamental frequency half bridge (S_1, S_2) is connected last. The two full-bridge circuits operate in a bidirectional phase-shift pattern to achieve the sine half-wave pulse width modulation, while the auxiliary fundamental frequency half-bridge enables DC to AC sine conversion. Compared with a single inductor, the interleaved parallel configuration significantly reduces the ripple in the output current and increases the equivalent switching frequency, thereby eliminating the need for an additional filter inductor in this topology. Considering that the volume of magnetic components increases as the number of cores grows, this converter integrates magnetic technology with an inversely coupled inductor. This design not only retains the advantages of the interleaved parallel configuration but also addresses the associated challenges effectively.

Topology 6:- This topology consists of an AC-side bridge, a capacitive leg, and a

DC-side full-bridge circuit. On the AC side, the AC source v_{ac} is connected to the switch nodes of the AC-side bridge through the filter inductors L_{ac1} and L_{ac2}, which help in smoothing current and mitigating switching-induced distortions as shown Fig. 1.8(e) [77]. The neutral of the AC source is connected to the midpoint of the capacitive leg, allowing for a balanced voltage reference. Each leg of the AC bridge, along with the capacitive leg, forms two separate half-bridge inverter units, contributing to the generation of AC voltage waveforms required for modulation. On the DC side, a full-bridge converter is used, which is responsible for processing the DC input and enabling bidirectional power transfer. This converter supports phase-shift modulation as well; however, it suffers from high current stress, which can impact the overall efficiency and reliability of the system.

1.3.2 Fundamentals of Soft Switching

Soft switching has emerged as a critical advancement in power electronics, aimed at addressing the inefficiencies associated with traditional hard-switched converters. In conventional PWM converters, significant energy losses occur during switching transitions due to factors such as diode reverse recovery, semiconductor output capacitance, and current tailing in IGBTs. These losses not only reduce overall system efficiency but also increase thermal stress on the components, necessitating advanced cooling mechanisms and potentially reducing the lifespan of the converter.

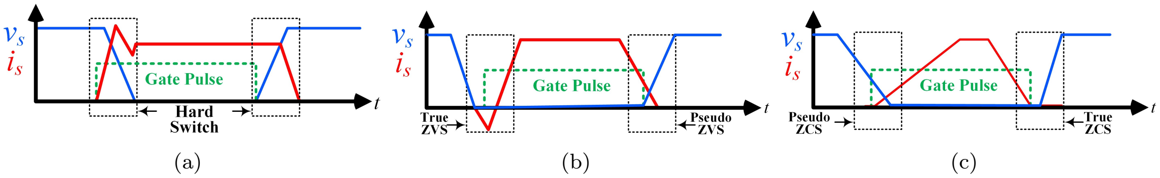
Soft switching refers to the mitigation or elimination of these switching loss mechanisms by ensuring that semiconductor devices transition under favorable conditions, such as zero voltage or zero current. By recovering the energy that would otherwise be lost, soft-switching techniques transfer it to the source or load, enhancing the overall efficiency of the system. The primary classifications of soft switching include ZVS and Zero Current Switching (ZCS). ZVS ensures that MOSFETs or other transistors switch on when the voltage across them is near zero, thereby reducing turn-on losses, while

ZCS minimizes losses during transitions by ensuring that the current through the device is near zero.

Switching transitions are typically categorized into hard, soft, and pseudo-switching, as shown in Fig. 1.9. The need for soft switching arises from the growing demand for high-efficiency and high-frequency power converters. In Fig. 1.9(a), voltage and current overlap during transitions, leading to significant switching losses, EMI, and voltage or current spikes, which are characteristic of hard switching. In Fig. 1.9(b), soft switching is depicted, where the voltage across the switch is reduced to zero before turn-on, significantly lowering turn-on losses result in true ZVS. However, turn-off losses may persist in devices with current tails, such as IGBTs. In Fig. 1.9(c), True ZCS is illustrated, where the current through the switch is reduced to zero before turn-off, effectively minimizing turn-off losses. Nonetheless, turn-on losses may still occur due to capacitive effects. Similarly, Fig. 1.9(b) and Fig. 1.9(c) show the waveform that partially reduces the voltage-current overlap but does not completely eliminate losses due to parasitic effects or imperfect circuit switching, resulting in pseudo-soft switching.

As switching frequencies increase to enable smaller transformers and filter components, the losses associated with hard-switched converters become more significant, making soft switching an essential design consideration. While soft-switching techniques are commonly implemented in resonant converters through the integration of resonant elements, they can also be achieved using advanced modulation schemes. Such schemes optimize the switching transitions to minimize energy dissipation without relying solely on resonant components. Converters like the DAB have become widely adopted in this context, as they employ advanced modulation strategies to achieve soft switching, offering a practical and efficient solution for modern power conversion needs [78, 49, 79].

The advantages of soft switching are manifold. It reduces switching losses, leading to improved efficiency and reduced heat generation. This, in turn, lowers cooling requirements, thereby reducing the size and cost of thermal management systems [80, 81].



(a) (b) (c)

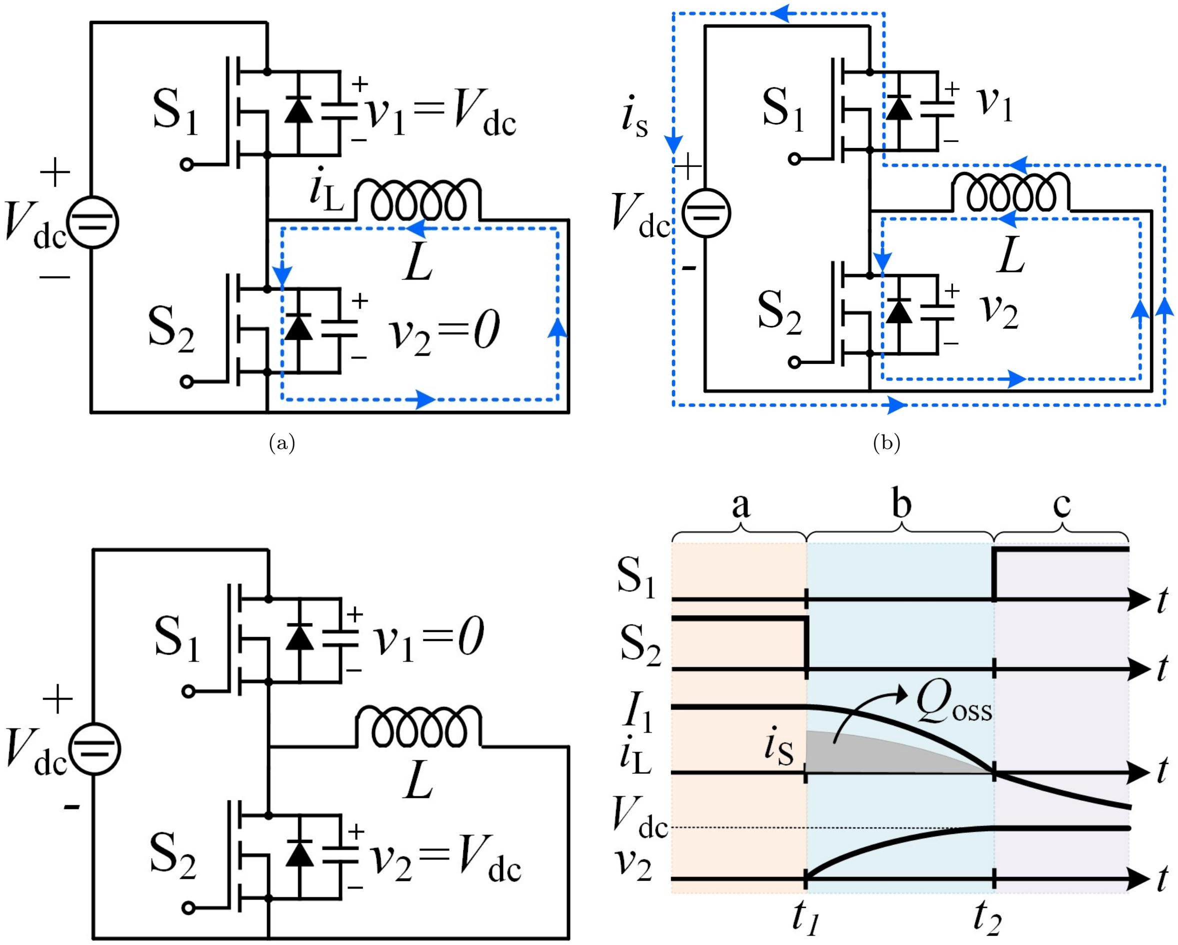
Figure 1.9: Switching waveform of device (a). Hard Switching. (b). True and pseudo ZVS (c). True and pseudo ZCS.

Furthermore, soft-switching converters exhibit enhanced electromagnetic compatibility (EMC) due to smoother voltage and current transitions, which help minimize high-frequency noise [82, 83, 84, 85]. Despite these benefits, resonance-based soft switching may introduce additional conduction losses due to the resonant elements. However, modulation-based soft switching offers an advantage by effectively addressing these limitations.

1.3.2.1 Zero Voltage Switching

To achieve ZVS, a semiconductor half-bridge configuration is typically utilized, incorporating an inductive element connected to the midpoint. This arrangement is common in topologies such as DAB converter [86]. As depicted in Fig. 1.10, ZVS operation is enabled by employing an inductive component to store energy, facilitating a resonant transition within a MOSFET bridge leg. Each MOSFET has a parasitic output capacitance (C_{oss}) that varies non-linearly with the drain-source voltage (V_{DS}). Consequently, the charge stored in the parasitic capacitance, represented as Q_{oss}, is also voltage-dependent. To simplify MOSFET modeling, a linear charge-equivalent capacitance ($C_{\text{Q,eq}}$) can be introduced, which corresponds to the same amount of stored charge as the non-linear capacitance at a specific V_{DS} [87].

Initially, during the free-wheeling interval shown in Fig. 1.10(a), the inductor current flows through the conducting MOSFET S_2, while the output capacitance $C_{\text{oss},1}$ of the non-conducting MOSFET S_1 is charged to the supply voltage V_{DC}. When S_2 turns



(a) (b) (c) (d)

Figure 1.10: Zero voltage transition of MOSFET Leg (a). Free-wheeling state (i_L=I_1). (b). Device S_2 turns off, and the resonant transition starts with the additional current path through the DC source during the dead time between two pulses (c). End of transition when the drain–source voltage of S_2 has reached the source voltage. (d). Waveform of various voltages and currents during all three states.

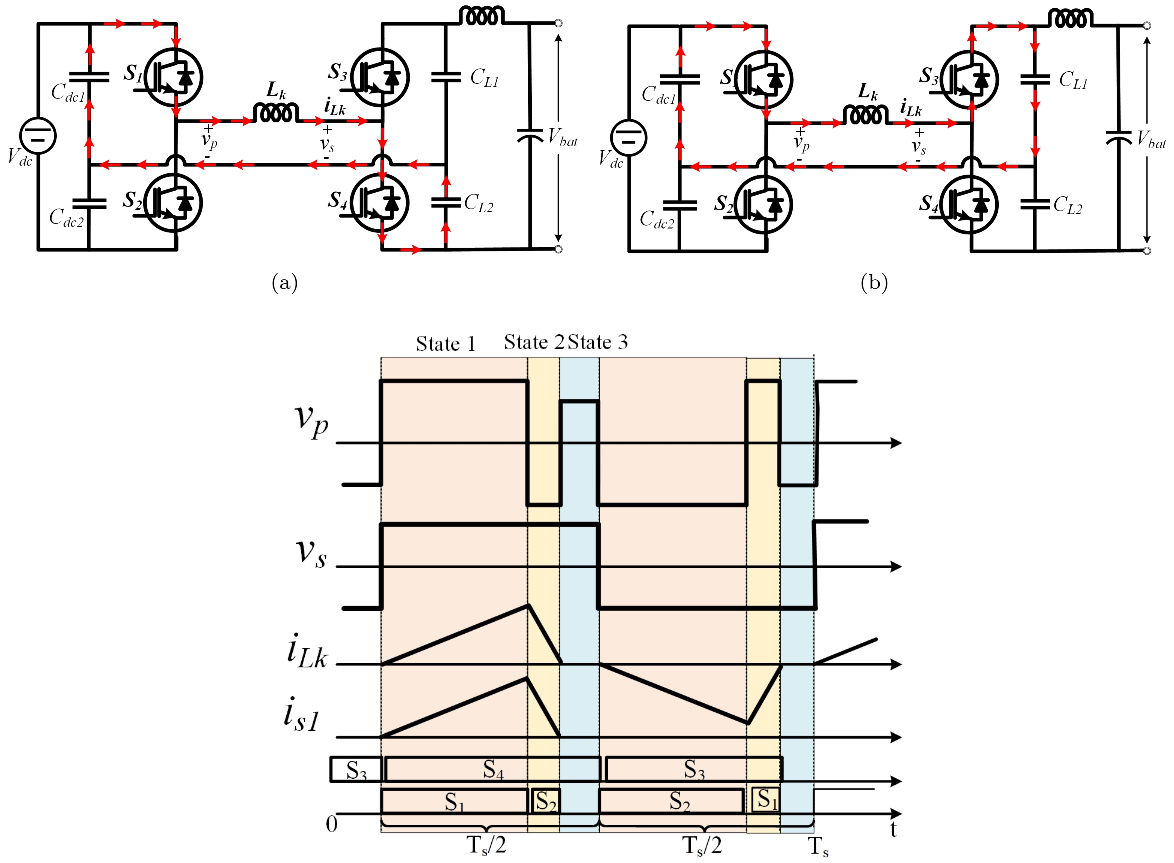
off, the energy stored in the inductor creates a resonant transition during dead time, discharging $C_{\mathrm{oss},1}$ and charging $C_{\mathrm{oss},2}$, as shown in Fig. 1.10(b). This transition ensures that the voltage across S_1 reaches zero before it is turned on. At the end of the transition shown in Fig. 1.10(c), when the drain-source voltage of switch S_2 reaches the source voltage (i.e., $v_2 = V_{\mathrm{DC}}$), switch S_1 turns on at zero voltage. This transition results in the movement of the charge Q_{oss} from switch S_1 to the DC source, while the energy stored in the inductor L becomes zero. Despite this, the total energy stored in the MOSFET bridge leg remains constant. The condition for achieving complete soft switching is satisfied when the energy stored in the inductor is greater than or equal to the energy required to transfer the charge from switch S_1 to the DC source. This condition is mathematically expressed as $\frac{1}{2}LI^2 \geq Q_{\text{oss}}(V_{\text{DC}}) \cdot V_{\text{DC}}$. This ensures that ZVS occurs effectively, minimizing switching losses. The various waveforms are presented in Fig. 1.10(d), highlighting different states. In conclusion, for ideal operation, if the body diode conducts before the switch within the same packaging, the switch is said to be undergoing ZVS turn-on once it starts conducting.

ZVS in a MOSFET ensures its body diode also operates under ZVS, eliminating switching losses from reverse recovery and enhancing efficiency in circuits where the diode is forward-biased. It also addresses over-voltage issues caused by transformer leakage inductance, removing the need for voltage-clamped snubber circuits and improving reliability [88].

1.3.2.2 Zero Current Switching

ZCS is achieved by controlling the current path during specific operational phases of the circuit. To illustrate ZCS operation, Fig. 1.11 depicts three distinct states. Each switching cycle consists of these states, as shown in Fig. 1.11 (a)-(c). By carefully managing these states, the converter ensures that the switches operate under zero-current conditions [89, 90]. ZCS is particularly effective in reducing switching loss for power devices such as IGBT with large tail current in the turn-off process and typically has a switching frequency in a few kHz [91, 92]. Typically, in ZCS, both the device and its body diode switch ON and OFF under zero current conditions.

In State A, the switches S1 and S4 are turned on, initiating current flow in the circuit. During this phase, the current i_L begins to rise from zero, influenced by the voltage difference between the input voltage V_{dc} and the reflected output voltage v_s. The precise timing of this state ensures that i_L reaches the required level without overshooting or



(a)

(b)

(c)

Figure 1.11: Zero current transition of IGBT Bridge (a). Current path during positive half cycle resulting in ZCS turn ON of S_1. (b). Current path during positive half cycle resulting in ZCS turn OFF of S_1 (c). Waveform of various voltages and currents during all three states.

crossing zero prematurely. In State B, after S4 is turned off and S3 is turned ON, current flow is positive but the slope is now negative, allowing i_{Lk} to naturally return to zero. By carefully controlling the duration of this state, the current trajectory avoids crossing zero during the switching transitions. This ensures that when S1 is turned OFF at zero current, there is no residual current, maintaining zero-current conditions. In this same discontinuous nature of i_{Lk} current repeat in the negative half, and the device current for the S1 is i_{s1} appears for only one half to ensure ZCS ON and OFF. The waveform of the various currents and voltages is shown in Fig. 1.11(c), illustrating that S1 turns ON and OFF at ZCS where i_{s1} is device current.

1.3.3 Modulation Techniques

The modulation techniques for the DAB converter represent a highly interesting area of research, as they enhance the converter's adaptability across a wide range of applications. Interestingly, similar to the DAB converter topology, the modulation techniques for the AC-DC DAB converter are also derived from various modulation strategies used in the DC-DC DAB [78, 93]. These techniques primarily rely on phase-shift control to regulate power transfer and optimize converter performance across different operating conditions.

The major difference between the modulation techniques of the DC-DC DAB converter and the AC-DC DAB converter lies in the nature of the AC grid voltage. In the AC-DC DAB converter, the input AC grid voltage varies continuously from zero to its peak value. Therefore, the modulation technique for AC-DC DAB is designed to ensure that at each switching instance, in reference to the changing grid voltage, soft switching is maintained throughout the grid frequency. Additionally, the current drawn from the grid must achieve a near-unity power factor.

To accomplish this, at least one control variable must vary throughout the grid frequency. Compared to a conventional two-stage battery charger [9, 10, 94, 95, 96], where PFC is managed solely by the switching of the grid-side converter, in the AC-DC DAB converter, the DC side bridge or both bridges contribute to maintaining PFC through their switching actions. This integrated approach enhances overall efficiency and simplifies the power conversion process.

These phase-shift-based modulation techniques for the AC-DC DAB converter are typically categorized into trapezoidal modulation (TZM) and triangular modulation (TRM) [8, 58, 59], as shown in Fig. 1.12. These modulation techniques are further classified into three categories: Single Phase Shift (SPS), Dual Phase Shift (DPS), and Triple Phase Shift (TPS) control, which are further divided into fixed-frequency, semi-variable frequency, and variable-frequency modulation. Fixed frequency means the switching frequency remains constant throughout the operating range, while semi-variable frequency allows the switching frequency to vary with loading conditions. In contrast, variable frequency implies that the switching frequency changes at each switching instance. In the literature, both individual and combined modulation techniques are widely used [71, 97, 98]. Hence, in Fig. 1.12, some modulation techniques share common references. In combined approaches, different modulation techniques are switched throughout the line frequency to leverage their respective advantages. A brief discussion of these TZM techniques is provided below.

1.3.3.1 Trapezoidal Modulation Techniques

As the name suggests, TZM arises when the DAB converter switches in a manner that shapes the current through the transformer's leakage inductance into a trapezoidal waveform. This characteristic is achieved when the non-resonating voltages of the transformer, along with both its rising and falling edges, are out of phase. In other words, for AC-DC power flow, the rising and falling edges of the primary voltage lag behind those of the secondary voltage, as illustrated in Fig. 1.12, and vice versa for DC-AC power flow.

Typically, TZM focuses on minimizing turn-on loss by enabling ZVS and has a circulating current, resulting in active power issues. In an AC-DC DAB with a turns ratio of unity, TZM can achieve both buck and boost modes. However, achieving a wide voltage range while maintaining soft switching requires additional control variables. To illustrate this, a flowchart is presented in Fig. 1.12, showing the increasing number of control variables from left to right. Furthermore, TZM is classified into three categories: SPS, DPS, and TPS control, which are further divided into fixed-frequency, semi-variable frequency, and variable-frequency modulation, adding frequency as an extra control variable. The SPS is further detailed below.

1. Single-Phase Shift (SPS) Control:- As the name suggests, SPS control has only one control variable: the phase shift. SPS was first introduced in [99] for DC-DC

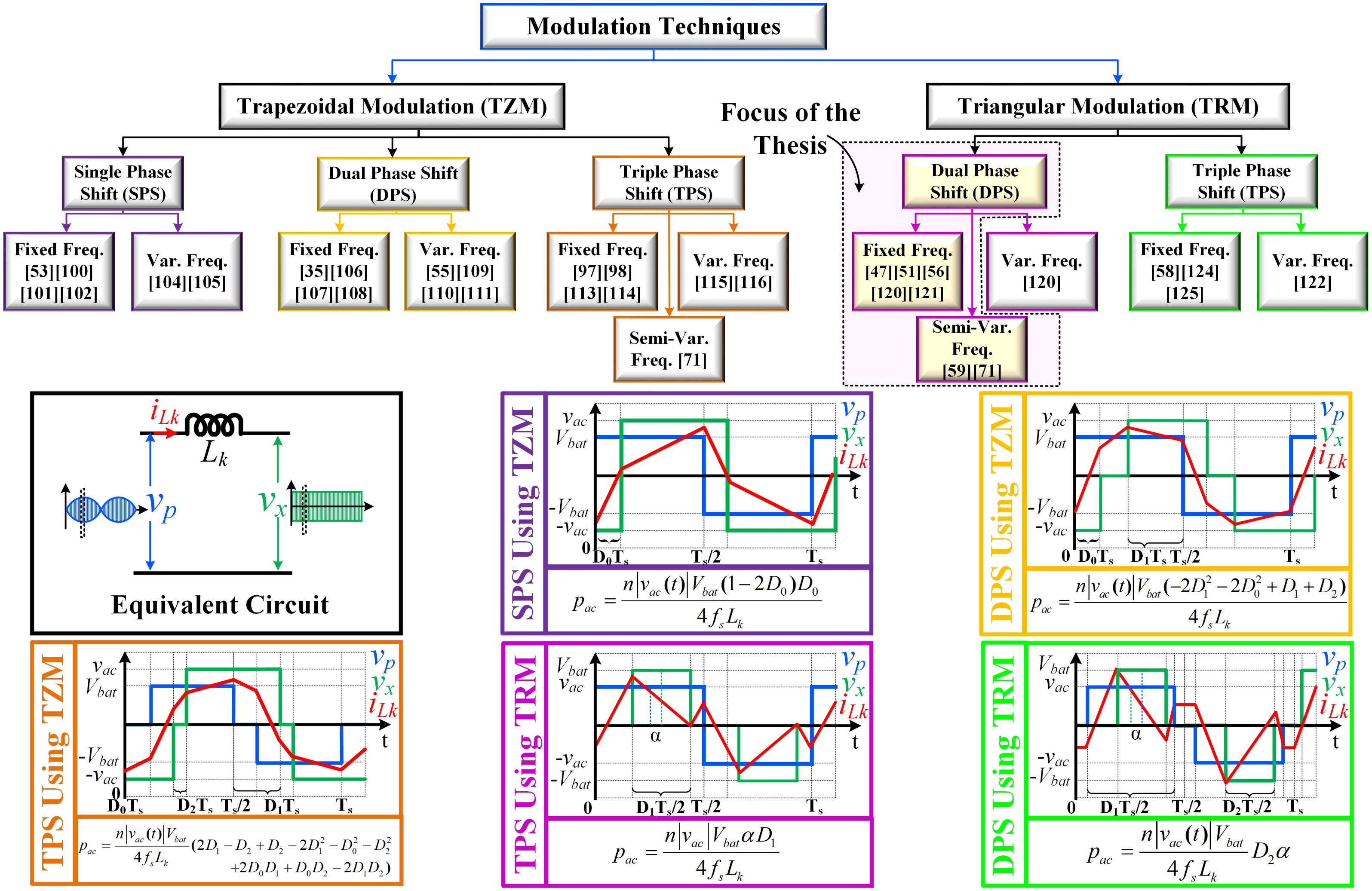


Figure 1.12: Categorization of various modulation techniques for AC-DC DAB with waveforms and their power relationship with control variables.

DAB and later studied in [53, 100, 101, 102, 103] for AC-DC DAB. The phase shift (D_0) measured from edge to edge of the is solely used to regulate the voltage. The equivalent waveforms for the AC-DC side are shown in Fig. 1.12. As illustrated, both the primary voltage (v_p) and the secondary voltage reflected to the primary side (v_x) are square waves. The waveform of v_x lags behind v_p, resulting in power flow from the AC to the DC side and vice versa. Typically, the D_0, measured from edge to edge of v_p and v_x, alone is not capable of maintaining PFC, soft switching, and voltage regulation. Therefore, it is not widely popular and leads to a loss of power factor, high THD, zero crossing distortion in grid current and soft switching. To address this, variable frequency SPS introduces frequency as an additional control variable, achieving a linear power relationship [104, 105], yet it still suffers from the loss of soft switching. Despite its simplicity, fixed-frequency SPS exhibits a non-linear power relationship, as shown in Fig. 1.12.

2. Dual-Phase Shift (DPS) Control:- In DPS, compared to SPS, an additional control variable is introduced through the duty width of v_x, which provides another degree of flexibility in modulation. While SPS relies solely on the phase shift of the voltage waveforms and uses only one control variable, DPS incorporates both phase shift and the duty cycle of v_x (or duty cycle of v_p), thus adding an extra degree of freedom to the control process [35, 106, 107, 108] as shown in Fig. 1.12. This additional control variable improves the modulation technique's ability to fine-tune power transfer, enhancing performance, especially in systems where load variations or efficiency are critical. By adjusting the duty cycle of v_x, DPS allows for more precise regulation of power flow, offering better control over the converter's operation and potentially improving soft-switching characteristics and distortion near zero crossing. However, this increased control introduces a non-linear power relationship and adds complexity to the modulation.

Despite these challenges, DPS provides significant benefits in operational flexibility and performance optimization compared to SPS. It also represents a tradeoff between complexity and performance when compared to SPS and TPS. The variable frequency version of DPS, widely used in AC-DC DAB applications, further improves performance but adds an additional layer of complexity [55, 109, 110, 111]. Overall, DPS strikes a balance between the simplicity of SPS and the advanced capabilities of TPS, making it an attractive option in certain applications.

2. Triple-Phase Shift (TPS) Control:- As the name suggests, TPS involves three control variables: phase shift (D_0), and the width/duty of v_p and v_x. Under TZM, it features six unique modes [112], with one of the power equations shown in Fig. 1.12. It is important to note that the edges of v_x lag behind v_p for it to be classified as TZM. The interesting aspect of TPS is that the generalized formula for power, with its three control variables, can also be applied to SPS and DPS. Therefore, TPS serves as a superset of these SPS modulation techniques. This is why TPS is widely accepted; the inclusion of three control variables enhances both the soft-switching range, voltage range, RMS current reduction [97, 98, 113, 114]. However, this modulation technique is more complex due to the need for numerical methods to evaluate the control variables and their realization, considering the number of variables involved. It also has a non-linear power relationship with the control variable, with three control variables.

The addition of frequency as a control variable further complicates TPS by introducing another dimension of control [115, 116], requiring more intricate calculations and modeling. A few modulation techniques also use semi-variable frequency as well [71]. This increased complexity demands advanced numerical methods and precise control strategies to manage the multiple variables effectively, making the implementation and optimization more challenging. Despite these challenges, the inclusion of frequency allows for finer control over the system's performance, but it adds to the overall complexity of the modulation technique.

1.3.3.2 Triangular Modulation Techniques:-

The TRM is another category of modulation techniques, sometimes considered a special case of TZM [59, 117, 118] as shown in Fig. 1.12. In TRM, the modulation ensures that $v_p < v_x$, and v_x remains within the edges of v_p, as shown in Fig. 1.12. As a result, the current through the transformer's leakage inductance takes a triangular shape. Therefore, to achieve TRM, the DC-side bridge cannot be configured as a half-bridge. The phase shift α, measured from the center of v_p to the center of v_x, determines power transfer. If the center-to-center (C2C) phase shift α is positive, power flows from AC to DC, and vice versa. TRM is particularly interesting as it is capable of enabling both soft turn-on, turn-off through ZCS and does not have an active power issue [119]. However, it suffers from high peak current, leading to increased conduction losses. For a turns ratio of 1:1, this modulation always operates in boost mode, meaning the DC voltage remains higher than the peak grid voltage. Furthermore, this modulation is categorized into DPS and TPS and further classified based on operating frequency.

1. Dual-Phase Shift (DPS) Control:- DPS based on TRM was first introduced in [119], originating from the duty modulation of the DC-side H-bridge. In this modulation, v_p is a square wave voltage, while v_x is a quasi-square wave voltage. The scheme involves two key variables: the phase shift α, which serves as the control variable, and the duty ratio D_1 ($D_1 = v_p/v_x$), which is an independent variable. The power relationship with the control variable is typically proportional to both variables, making it linear with only one control variable and well-suited for open-loop PFC and simplified control design as shown in Fig. 1.12.

Another key advantage of TRM is its capability to achieve both soft turn-on and turn-off through ZCS. However, it suffers from pseudo-soft switching due to the utilization of three carriers [57]. Several types of TRM have been proposed, each exhibiting different soft-switching characteristics [44, 47, 51, 56, 120, 121]. While some variants are designed to achieve ZVS [44, 51], which is preferred for MOSFETs, others prioritize ZCS, which is more suitable for IGBTs [91, 92].

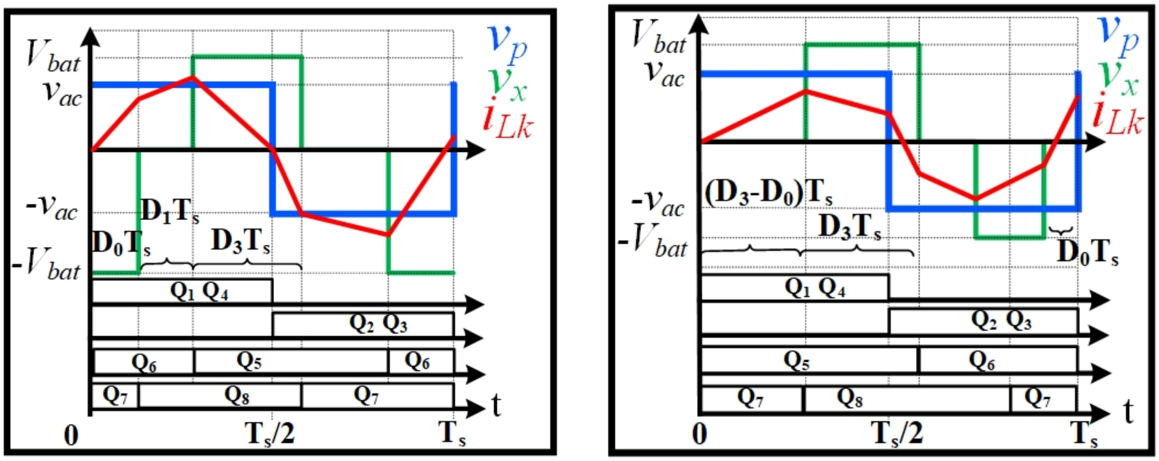
To further enhance performance, semi-variable frequency [59, 71] and variable frequency [122] DPS under TRM have been introduced in the literature. These modulation techniques are applied in different modes at various moments throughout the line frequency cycle, adapting to changing operating conditions. Improving these modulation techniques will remain a key research focus throughout this thesis.

2. Triple-Phase Shift (TPS) Control:- TPS under TRM introduces an additional control variable compared to DPS under TRM, and it has five different types as presented in [123]. This modulation technique is based on the duty regulation of both the H-bridge, where both v_p and v_x are quasi-square waveforms [58, 124, 125], as shown in Fig. 1.12. It involves three variables: the width of v_p (D_1), the width of v_x (D_2), and the C2C phase shift α. In Fig. 1.12, D_2, is again a non-linear function of D_1, therefore, it also has a non-linear power relationship.

This TRM also has a variable frequency operation, adding another control variable in the form of frequency [122]. This makes it suitable for reducing conduction losses at each switching instance.

1.3.3.3 Asymmetric Modulation Strategies

Asymmetric Modulation Strategies warrant a distinct classification, as they can operate in both TZM and TRM within a single cycle [59, 126, 127, 128, 129]. These strategies are further categorized into two types. In Type 1, the modulation resembles TRM and TZM, but the positive and negative pulses of either v_P, v_X, or both are asymmetrical in transformer current. The modulation ensures inductor voltage balance to account for leakage inductance, following the waveform pattern in Fig. 1.13. In Type 2, the bridges switch with a varying duty cycle, deviating from the conventional 50% operation; however, the transformer current maintains symmetry across both the halves.



(a) (b)

Figure 1.13: Asymmetric Modulation Strategies shown for one cycle of switching frequency [127] (a). Asymmetric TZM. (b). Asymmetric TZM+TRM.

1.4 Research Gap and Challenges with Existing Literature

Based on the insights gathered from the above literature survey, numerous unexplored areas exist in the field of bidirectional AC-DC DAB converters and their modulation techniques, offering significant scope for research and innovation. Despite advancements in efficiency and control, key challenges persist, particularly in optimizing modulation strategies, addressing non-linear power relationships, and improving control complexity. The following research gaps summarize these issues:

1. **Non-Linear Power Relationship**:- Modulation techniques with a non-linear power relationship to the control variable, particularly when measured over the line frequency, complicate controller implementation and hinder effective parameter optimization. Notably, some modulation methods face this issue even with a single control variable [104]. A linear power relationship is vital in bidirectional AC-DC DAB converters, simplifying control design and enhancing performance. Linearizing the power transfer equation removes non-linear complexities, enabling simpler control and real-time implementation [43, 130, 120]. This reduces computational

demands and improves dynamic response under varying loads. Furthermore, it ensures predictable, proportional power flow, maintaining stability and optimizing performance, especially in precision applications. Numerous studies emphasize the importance of linear power relationships and their advantages [43, 130, 124].

2. **Number of Control Variables**:- The number of control variables plays a critical factor in its modulation technique. While additional control variables can enhance performance by extending the voltage and soft-switching ranges, they also introduce significant complexity [113, 116, 131]. For instance, while four control variables are required in [110], five are needed in [128], and six are needed in [126], further complicating control realization, particularly due to the non-linear power relationship. Each variable requires precise calculation and optimization at every switching instance to maintain PFC and soft-switching across the entire line frequency. This significantly increases the computational burden and implementation complexity, particularly for resource-constrained MCUs. Some techniques also rely on off-line calculations and optimizations stored in look-up tables [106, 116, 110, 132], adding memory demands and reducing flexibility. Balancing the benefits of additional control variables with hardware limitations is essential to ensure efficient, practical, and robust DAB converter design.
3. **Complex Control**:-The DAB converter is widely recognized for its bidirectional nature. However, certain modulation techniques presented in [54, 64, 65, 68, 66] necessitate different switching schemes for power transfer between the AC-DC sides and vice versa. This results in varying numbers of modes of operation within a single switching cycle for each direction. Consequently, it can be concluded that two distinct modulation schemes are required to accommodate both directions of power flow effectively.
4. **Close-Loop Power Factor Correction**:- Modulation techniques that mandate closed-loop PFC methods often involve intricate control loops utilizing grid current

sensors and advanced controllers. While these approaches are effective in regulating grid-side current and achieving high power factor, they tend to complicate the design process, increase system costs, and may contribute to elevated THD [43, 75, 133]. In contrast, natural PFC in AC-DC DAB converters simplifies control by eliminating grid current sensors and complex loops [89, 106, 120, 134]. It ensures sinusoidal grid current and high power factor without relying on variable frequency control or phase-shift methods to linearize control variables [43, 75, 133]. Moreover, natural PFC mitigates phase drift and hard switching in DCM under low voltage or light load conditions [135], reduces current stress, and ensures reliable performance, making it a cost-effective solution with a wide soft-switching range [106], highlighting the need for efficient and robust modulation techniques.

5. **Multi-Architecture Microcontroller**:- Modulation techniques with multiple carriers and/or control variables demand advanced MCUs due to their complexity and computational load [54, 68, 136, 137]. Hybrid architectures, combining DSPs for sequential computations and FPGAs for parallel switching state generation [137, 138], address these challenges but increase converter costs. Simplifying modulation by reducing carriers minimizes computational demands, enabling efficient implementation on DSP-based systems. Therefore, further research is required to develop simple modulation techniques that can be effectively realized using a single MCU.
6. **Multiple carrier/Counter**:- Carrier/Counter reduction is an active area of research and has been widely explored, particularly in topics like inverters and matrix-type converter [139, 140, 141]. As the number of carriers increases in modulation schemes, the computational burden also rises significantly. This is due to the need for more complex calculations per switching cycle, which leads to higher processing demands and slower control response times. As a result, optimizing and implementing the control system becomes more challenging. Several AC-DC

DAB modulation techniques continue to use multiple carriers, as demonstrated in works such as [68, 64, 70, 77, 142], while other studies have concentrated on reducing the number of carriers to ease the computational burden [143, 144].

7. **Modulation for Turn-On Loss Reduction Only**:- As highlighted in the sections discussing TZM, modulation techniques primarily focus on minimizing turn-on losses of devices through ZVS. However, there is a limited body of literature addressing the comprehensive elimination of switching losses during the entire switching process. This research gap presents an opportunity to develop a modulation technique aimed at reducing both turn-on and turn-off losses effectively.
8. **Pseudo Soft Switching**:- Some modulation techniques fail to achieve true soft switching due to factors like neglecting parasitic components, parameter variations, control method limitations, and non-ideal switching transitions [120, 130, 145, 146]. Although certain methods may provide soft switching under specific conditions, they often lose this capability in certain regions of the full line frequency range or under certain operating conditions [104]. This inconsistency leads to non-zero switching losses, ultimately reducing efficiency.
9. **Zero Crossing Distortion at Grid Frequency**:- Some modulation techniques suffer from zero crossing distortion at the grid frequency, caused by the loss of soft switching near zero crossing or limitations in the modulation technique. This results in higher THD of the grid current at any loading condition, leading to poor power quality [53, 64, 65, 104, 147].
10. **Light Performance**:- Typically, light load performance in DAB modulation techniques results in a loss of soft-switching, higher conduction losses, and elevated THD (more than 5%) [114, 148]. There are two primary types of losses in the devices: switching losses and conduction losses. Some modulations based on TRM suffer from relatively high conduction losses compared to the processed output power under light load [44, 51, 58, 56, 120], while others experience losses in

soft-switching or both under the same conditions [104, 149, 150].

1.5 Objective of the Thesis

Several key issues in existing modulation techniques, as discussed above, impact both the realization and performance of bidirectional AC-DC DAB converters. This thesis aims to develop and optimize a triangular modulation (TRM) technique to improve performance while reducing implementation complexity. Realization challenges include non-linear power relationships, numerous control variables, complex control strategies, and the need for closed-loop power factor correction, all of which increase computational and hardware complexity. The use of multiple microcontroller architectures and carrier signals further complicates the system. On the other hand, performance limitations such as pseudo-soft switching, zero-crossing distortion at grid frequency, and degraded light-load performance adversely affect the overall efficiency and reliability of the system.

By addressing both realization and performance challenges, this thesis seeks to enhance the efficiency and practicality of bidirectional AC-DC DAB converters, particularly for battery charging applications. These improvements are extended later in the thesis to an application-oriented DC charging system. The work is guided by the following key objectives:

1. Analyzing the limitations of existing modulation techniques and their impact on converter efficiency and power quality.
2. Proposing an optimized modulation strategy that ensures improved soft switching, higher efficiency, and enhanced natural PFC performance.
3. Developing a control framework that minimizes computational complexity while maintaining robust performance across varying load and grid conditions, with benchmark realizations to evaluate and compare the performance with conventional modulation.
4. Development of renewable integrated hybrid input-based bidirectional DC charging

system for E-Rickshaws.

5. Validating the proposed approach through simulation and experimental studies to demonstrate its practical feasibility.

To meet these objectives, the thesis progresses through several stages:

Firstly, this thesis develops an innovative triangular modulation technique (TRM) for a DC-AC bidirectional matrix-type DAB converter to address challenges such as the need for multiple control variables, reliance on multiple carriers, pseudo soft switching, and non-linear power relationships. The proposed method uses a sinusoidally modified variable frequency PWM, enabling true soft-switching with a single carrier and simplifying implementation on the F28335 MCU. By eliminating complex calculations, the TRM ensures soft-switching and open-loop power factor correction across the converter's entire operating range.

Secondly, the application of the proposed TRM technique is explored on a 500 W Quasi Single Stage (Q1S) bidirectional AC-DC DAB converter with an intermediate capacitor. This investigation focuses on maintaining performance while further reducing computational complexity by minimizing the number of district PWMs required. The method, implemented on the TMS320F28335 microcontroller, shows soft-switching performance and power quality, setting a new benchmark in TRM design.

Thirdly, this research addresses the challenge of high RMS current and increased conduction losses under light load conditions, which negatively impact the efficiency of TRM techniques in battery charging applications. The study investigates the non-linear reduction in RMS current as the phase-shift ratio decreases, affecting both the transformer and devices. It explores solutions to mitigate the conduction losses caused by the RMS current under under CV mode of charging. An improved modulation method is proposed to enhance performance under light load conditions, reducing total harmonic distortion and current stress, thereby improving overall converter efficiency.

Finally, this research explores an adaptive optimal power management scheme for a hybrid energy input-based DC charging system. The scheme optimizes power distribution among different energy sources, enhancing system efficiency and performance. It focuses on optimizing photovoltaic (PV) power to reduce grid consumption, ensures seamless transitions between modes, and supports DC fast charging for E-rickshaw batteries with rapid dynamic control and high-quality power. Future work will focus on integrating the AC-DC DAB converter with the proposed modulation technique to further enhance the performance and efficiency of the DC charging system.

1.6 Organization of the Thesis

The thesis is structured into six chapters. Chapter 1 covers the background, research motivation, literature review, research gap, along with challenges with existing literature, and objectives of the study.

Chapter-2: This chapter introduces a novel TRM technique for a DC-AC bidirectional matrix-type DAB converter, which can be implemented in two distinct ways. This technique modulates one leg of the H-bridge using a sinusoidally modified variable frequency PWM, also referred to as an asymmetrical switching sequence, ensuring true soft switching by precisely shaping the transformer current and controlling the transformer voltage. Both methods can be realized using a single carrier, and their digital implementation is presented using the F28335 MCU to highlight the simplicity and practicality of the approach. Additionally, the TRM eliminates the need for complex analytical methods, improving efficiency and soft-switching performance across the converter's operational range while maintaining an open-loop power factor. Experimental results are discussed exclusively for Method 1 for V2G and G2H applications using a 500 W prototype.

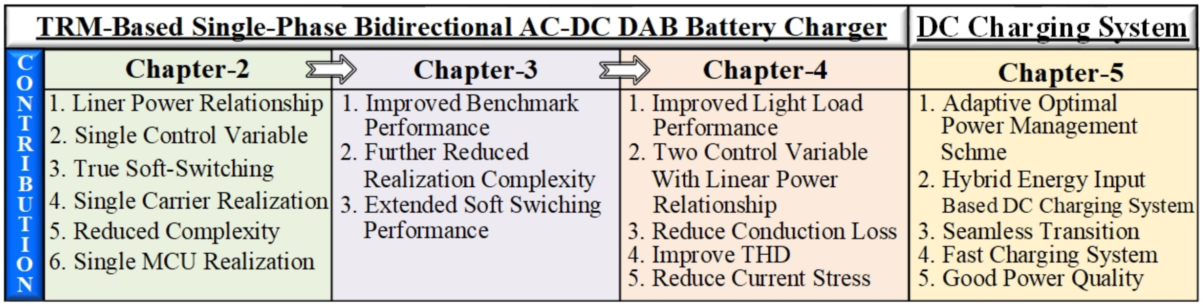
Chapter-3: This chapter examines the application of the proposed TRM technique to a different converter topology, focusing on maintaining performance while further reducing computational complexity. It explores how minimizing the number of distinct

PWM signals can be achieved by implementing an asymmetrical switching sequence-based TRM in a Q1S bidirectional AC-DC DAB converter with an intermediate capacitor. The study emphasizes that selecting the right modulation techniques in accordance with the chosen topology can optimize control performance and achieve better benchmarks using the Texas Instruments TMS320F28335 microcontroller, without compromising key performance factors such as soft switching performance and power quality.

Chapter-4: This Chapter addresses a significant issue present in both the proposed TRM and other existing TRM modulation techniques, focusing on the high RMS current that contributes to increased conduction losses, particularly under light load conditions that appear during CV mode of the battery charging applications. While the phase-shift ratio maintains a linear relationship with power transfer, the RMS current decreases non-linearly as the phase-shift ratio is reduced to supply power at light loads. This non-linear decrease results in higher conduction losses relative to the output power being processed at that phase shift, negatively impacting converter efficiency, especially in battery charging applications. Despite achieving soft-switching during both turn-on and turn-off operations, the TRM modulation scheme experiences reduced efficiency at light loads due to non-linear conduction losses. This chapter investigates this challenge and explores potential solutions to improve performance under light load conditions, including reducing conduction losses, improving THD, and minimizing current stress, by utilizing the proposed improved Method 1.

Chapter-5: This chapter is application-focused, addressing a DC charging system developed at TRL 6 with a 10 kVA prototype. It introduces a proprietary adaptive optimal power management scheme for a hybrid energy input-based DC charging system capable of bidirectional power flow. The chapter explores how various energy sources are integrated and describes how the proposed scheme optimizes power distribution, improving system efficiency and performance. It also emphasizes the system's ability to optimize photovoltaic (PV) power and reduce grid power consumption, ensuring smooth transitions between different modes without interrupting load demand. Furthermore, the system supports DC fast charging for E-rickshaw batteries, providing fast dynamic control and good power quality. The adaptive optimal power management scheme is independent of the converter topology, and future work will involve replacing the conventional three-phase rectifier with the proposed modulation using AC-DC DAB discussed before.

Chapter-6: Chapter 6 summarizes the key conclusions of the research and outlines the scope for future work, highlighting potential advancements and areas for further improvement in the presented work. Further, the organization of the Chapter and its contributions are shown in Fig. 1.14.



	TRM-Based Single-Phase Bidirectional AC-DC DAB Battery Charger			DC Charging System
	Chapter-2 ⇨	Chapter-3 ⇨	Chapter-4	Chapter-5
CONTRIBUTION	1. Liner Power Relationship 2. Single Control Variable 3. True Soft-Switching 4. Single Carrier Realization 5. Reduced Complexity 6. Single MCU Realization	1. Improved Benchmark Performance 2. Further Reduced Realization Complexity 3. Extended Soft Swiching Performance	1. Improved Light Load Performance 2. Two Control Variable With Linear Power Relationship 3. Reduce Conduction Loss 4. Improve THD 5. Reduce Current Stress	1. Adaptive Optimal Power Management Schme 2. Hybrid Energy Input Based DC Charging System 3. Seamless Transition 4. Fast Charging System 5. Good Power Quality

Figure 1.14: Contributions of the Chapters

1.7 Conclusion

This chapter highlights the recent trends in EVs in India and the growing need for efficient bidirectional power flow in applications such as V2G, V2H, V2L, and along with their global development. A detailed literature review on isolated bidirectional AC-DC DAB topologies, soft-switching techniques, and modulation strategies identifies key research gaps and challenges in the literature. Finally, this chapter outlines the research problems addressed, highlights the key contributions of this thesis in the subsequent chapters, and presents a structured chapter-wise organization of the thesis.