

**POWER FACTOR CORRECTION IN ELECTRIC VEHICLE
BATTERY CHARGING USING INTERLEAVED BOOST
CONVERTER**

A DISSERTATION

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AWARD OF THE DEGREE

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In

POWER ELECTRONICS AND SYSTEM

Submitted by

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I, ANKUSH JHA, Roll No. 2K23/PES/01 student of M.Tech (Power Electronics and Systems), hereby declare that the project Dissertation titled “**Power Factor Correction In Electric Vehicle Battery Charging using Interleaved Boost Converter**” which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in the partial fulfillment of the requirements for the award of degree of Masters of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma, Associateship, fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled “**Power Factor Correction In Electric Vehicle Battery Charging using Interleaved Boost Converter**” which is submitted by ANKUSH JHA (2K23/PES/01), Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfilment of the requirements for the award of the degree of Master of Technology, is a record of project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Electric vehicles(EV's) are becoming popular to achieve goals of sustainable transportation development and rising concerns about climate change and the diminishing nature of fossil fuels. The battery charging system is a crucial component of electric vehicles and has attracted a lot of research interest, particularly in relation to vehicle-to-grid (V2G) power transfer. The primary objectives of vehicle to grid (V2G) are to assist the grid in reaching peak load levelling. This project aims to design , develop and analyse single-phase on-board charger with improved power factor & efficiency as compared to that of conventional EV chargers.

A multi-stage power conversion architecture (AC-DC-AC-DC) is adopted for Grid to vehicles power transfer . The Interleaved Power Factor Correction (PFC) front-end converter provides dc to dc conversion with power factor close to unity. which significantly reduces grid harmonics to less than 5% Total Harmonic Distortion (THD). This approach offers higher efficiency compared to traditional bridge rectifiers and ensures compliance with grid power quality standards.

Further, a Dual Active Bridge (DAB) stage involves an intermediate AC conversion through a high- frequency transformer, which is crucial because direct DC-DC conversion for a battery level voltage would be highly inefficient. Additionally, this stage provides galvanic isolation(Due to transformer), which is vital for protecting both the battery and the user from potential electrical hazards. This multi-stage conversion process ensures optimal performance, safety, and adherence to regulatory standards in the charging system for specially three-wheeler electric vehicles.

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CHAPTER 1

INTRODUCTION

Electric vehicle (EV) battery chargers play a vital role in the broader EV infrastructure by ensuring batteries are recharged reliably, efficiently, and with minimal environmental impact. A key component that supports this functionality is the Power Factor Correction (PFC) circuit, which contributes to improved power quality and better system efficiency.

1.1 General

Power Factor Correction involves strategies used to optimize how electrical systems consume power. In simple terms, the power factor measures how effectively electrical energy is converted into usable work. It's calculated as the ratio of real power (actual usable energy) to apparent power (the total supplied power). When the power factor is low, it means energy is being wasted—often resulting in higher operational costs and greater strain on the electrical grid. PFC circuits are designed to address this by shaping the input current to more closely follow the input sinusoidal voltage. This alignment reduces losses, minimizes harmonic distortion, and ensures more efficient use of power drawn from the source. Basic Architecture of an EV Battery Charger with PFC.

1.2 Basic Architecture of an EV battery Charger

A standard EV charger usually includes two key stages in its power conversion process:

1.2.1 Power Factor Correction Stage:

This front-end stage is responsible for converting alternating current (AC) input into a well-regulated direct current (DC) output. At the same time, it adjusts the power factor, enabling the charger to consume electricity more cleanly and efficiently. By doing so, it minimizes unwanted current harmonics and enhances overall system performance.

1.2.2 DC-DC Conversion Stage:

The second part of the charger refines the DC power received from the PFC stage. It adjusts the voltage to meet the specific charging needs of the battery. This stage can employ different converter designs—such as buck, boost, or resonant converters depending on factors like voltage range, power level, and charger design specifications.

In my project , I have chosen Interleaved Boost PFC ,i.e 2 boost Converters in parallel in order to reduce ripple in input current and also it has the ability to improve Electromagnetic Interference . Interleaved boost PFC is particularly advantageous in applications where minimizing input current ripple and EMI is critical, while also offering flexibility in design and scaling for various power levels.

1.3 Role of PFC in EV Charging

By correcting the power factor , PFC circuits reduce harmonic distortion in the input current , leading to better overall power quality . This is particularly important in modern electrical grids where multiple devices are connected. PFC circuits help minimize energy losses during charging by ensuring that the charger operates at optimal efficiency levels . Higher efficiency translates into less heat generation and reduced operational costs. Many regions have strict regulations regarding harmonic emissions and power quality . Implementing PFC in EV chargers helps manufacturers comply with these standards, facilitating smoother integration into existing electrical infrastructure . By ensuring a more stable and controlled charging process, PFC circuits contribute to healthier battery management. This can lead to longer battery life and improved performance over time . Three common PFC topologies are Boost , Interleaved Boost and Totem-pole . Each has unique advantages and disadvantages that influence their application in EV charging systems.

1.3.1 Boost PFC

Simplicity: The boost PFC topology is straightforward, making it easy to implement and control . It can achieve a power factor of 0.95 or higher, which is beneficial for reducing energy losses .Low Input Current Distortion, Since the boost inductor is on the input side, it helps maintain low distortion in input current . The presence of a diode bridge introduces conduction losses that can reduce overall efficiency .Conventional boost PFCs are not inherently bidirectional, limiting their use in applications requiring energy return to the grid

1.3.2 Interleaved Boost PFC

By using multiple power switches and inductors, interleaved boost PFCs can handle higher power levels efficiently. This topology spreads the switching frequency spectrum over a wider range, which minimizes electromagnetic interference (EMI) peaks. It reduces ripple currents at both input and output, enhancing overall system efficiency . The need for synchronized control of multiple converters can complicate the design and control algorithms .The additional components required for interleaving can increase the overall cost of the system.

1.3.3 Totem-Pole PFC

The totem-pole configuration significantly reduces conduction losses by allowing current to flow through only two switches at a time, improving efficiency up to 98.6% in some designs. This topology is inherently capable of bidirectional operation, making it ideal for vehicle-to-grid (V2G) applications and onboard chargers. By eliminating the diode bridge, it simplifies the circuit design and reduces component count, leading to lower costs and increased reliability. Implementing effective current sensing can be challenging due to the floating nature of the input voltage during operation. When using silicon MOSFETs, reverse recovery losses can be significant if continuous conduction mode (CCM) is employed; however, advancements in silicon carbide (SiC) technology mitigate this issue. In my project, I have chosen Interleaved Boost PFC, i.e. 2 boost Converters in parallel in order to reduce ripple in input current and also it has the ability to improve Electromagnetic Interference. Interleaved boost PFC is particularly advantageous in applications where minimizing input current ripple and EMI is critical, while also offering flexibility in design and scaling for various power levels.

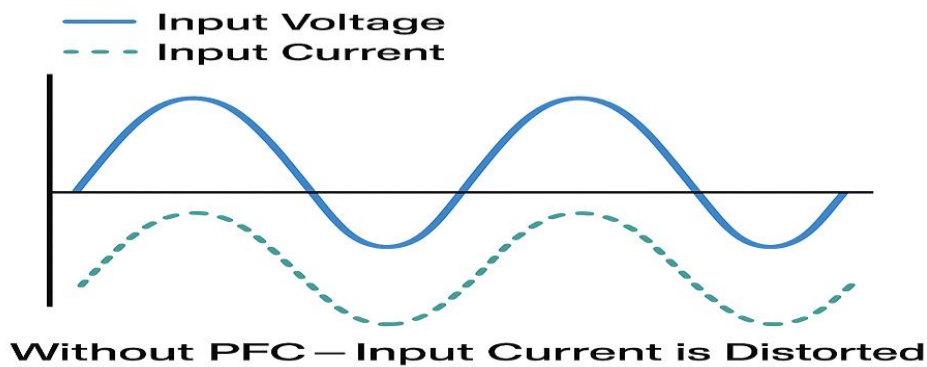


Figure 1.1 Effect of using PFC in Electric Vehicle battery charger .

Above figure shows that, both Input current and input voltage are in same phase while using the Interleaved Boost PFC, which is our required parameter during this project.

1.4 Dual Active Bridge

The Dual Active Bridge (DAB) converter is a highly efficient, isolated bidirectional DC-DC converter that plays a significant role in various applications, particularly in electric vehicle (EV) charging and energy storage systems. Here are the key roles and advantages of the DAB converter. Dual Active Bridge (DAB) converters are becoming a go-to solution in various advanced power applications, particularly in electric vehicles (EVs), renewable energy systems, and energy storage. Their smart design and versatile performance make them especially well-suited for managing energy flow efficiently and reliably. Here's a look at why DAB converters are so valuable:

1.4.1 Power Flow in Both Directions

One of the standout features of the DAB converter is its ability to transfer power in both directions. This is incredibly useful in scenarios like EV charging and vehicle-to-grid (V2G) systems, where energy may need to flow from the grid to the vehicle or back from the vehicle to the grid. This bidirectional capability allows for more flexible and interactive energy systems.

1.4.2 Electrical Isolation for Safety

DAB converters use a high-frequency transformer to separate the input side from the output side. This “galvanic isolation” helps protect critical system components from voltage fluctuations or surges, improving safety and reducing the risk of electrical damage.

1.4.3 High Efficiency Operation

These converters are known for their excellent efficiency, often reaching above 95%. They achieve this through a technique called zero-voltage switching (ZVS), which significantly cuts down on energy lost during the switching process. The result is a more efficient power conversion with less heat and energy waste.

1.4.4 Space-Saving Design

Since DAB converters operate at higher frequencies, the components—especially the transformer—can be made much smaller. This leads to a more compact and lightweight design, which is ideal for applications where space is at a premium, such as onboard EV chargers. The DAB converter stands out because of its combination of efficiency, versatility, and compact form factor. Whether it's used in EV charging systems, energy storage, or renewable energy integration, its ability to move energy back and forth safely and efficiently makes it an essential piece of modern power electronics.

1.5 Type of Chargers for electric vehicle battery

Chargers for EV battery are essential to facilitate the easy and effective recharging of electric vehicles as the world accepts the shift to modern transportation. These chargers which offer a dependable and convenient way to recharge the vehicle's battery, are crucial aspects for electric vehicles' infrastructure. To meet the varied needs of owners of electric vehicles, EV battery chargers are available in a variety of shapes and charging capacities. In their most basic form,

1.5.1 Level 1

chargers fit into a typical household outlet and are intended for residential use. These generally work at 230V 16A and can be connected to wall socket to charge the EVs. Despite having the slowest charging rate, Level 1 chargers are a practical choice for charging overnight, guaranteeing that the car is prepared for everyday use. Adds approximately 50 to 80 km of range when charging for 10hrs.

1.5.2 Level 2

chargers are basically private and charging stations for the general public to provide faster charging. These chargers work at higher power levels and require a dedicated charging unit generally working at 240V 80A. This allows them to dramatically reduce charging times. For regular charging demands, level 2 chargers are the perfect answer because they enable PEV owners to quickly refuel their cars. Adds approximately 65 to 100 km of range when charging for 10hrs.

1.5.3 Level 3

These are the fastest chargers using DC power and are available at public charging stations for even faster and more convenient charging. Direct current (DC) is used by DC fast chargers to quickly charge the car's battery. Working at about 50kW and delivering power to the battery and charging it in from 30 mins to 1 hr. Adds approximately 160 to 320 km of range when charging for 1hrs.

The recharging of battery is necessary in order to start and extract energy from the battery and operate on its full capability. Battery charger's power density, charging time, sustainability, and efficiency are crucial components that set it apart from the competition. These device characteristics are influenced by the controller, switching mechanisms, and component choice. Microcontrollers are used to implement digital control techniques. Figure:- 1.2 shows about the overall architectural block diagram of a charger.

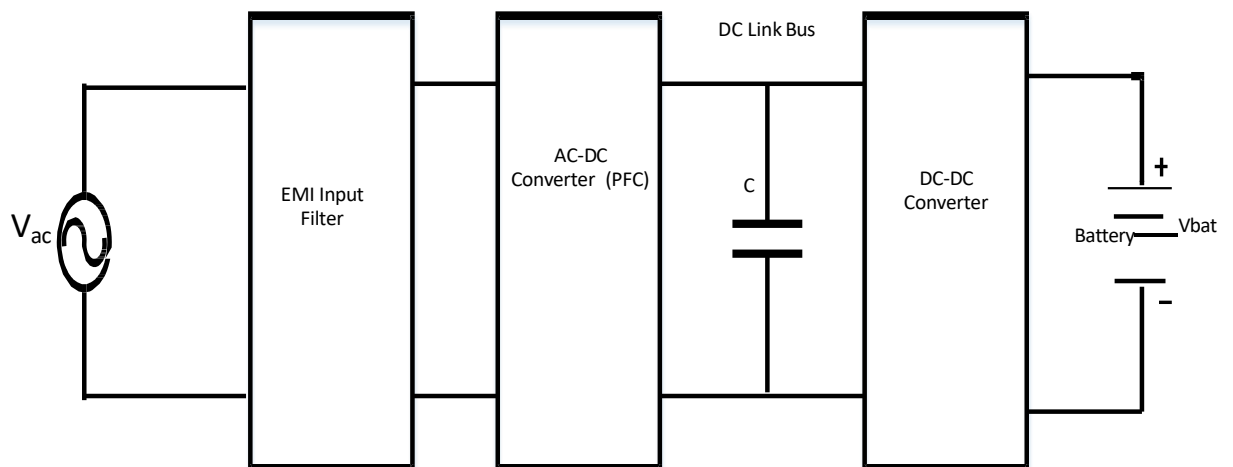


Figure 1.2: Topology of Charger Circuit

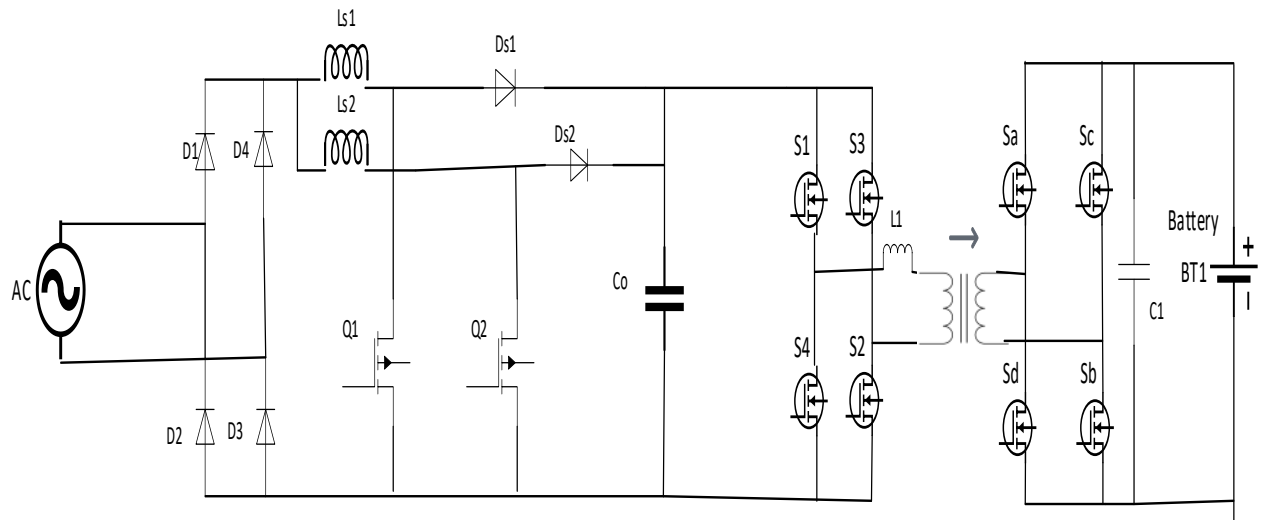


Figure 1.3 :- EV circuit Diagram using Interleaved Boost PFC

1.6 Modelling of Battery

Figure 1.4 shows the analogous circuit model, which is a typical electrical representation of a lithium-ion battery. This model makes up of multiple circuit components that simulate how a Li-ion battery would act in various scenarios. Here is an illustration of a basic electrical circuit circuit :

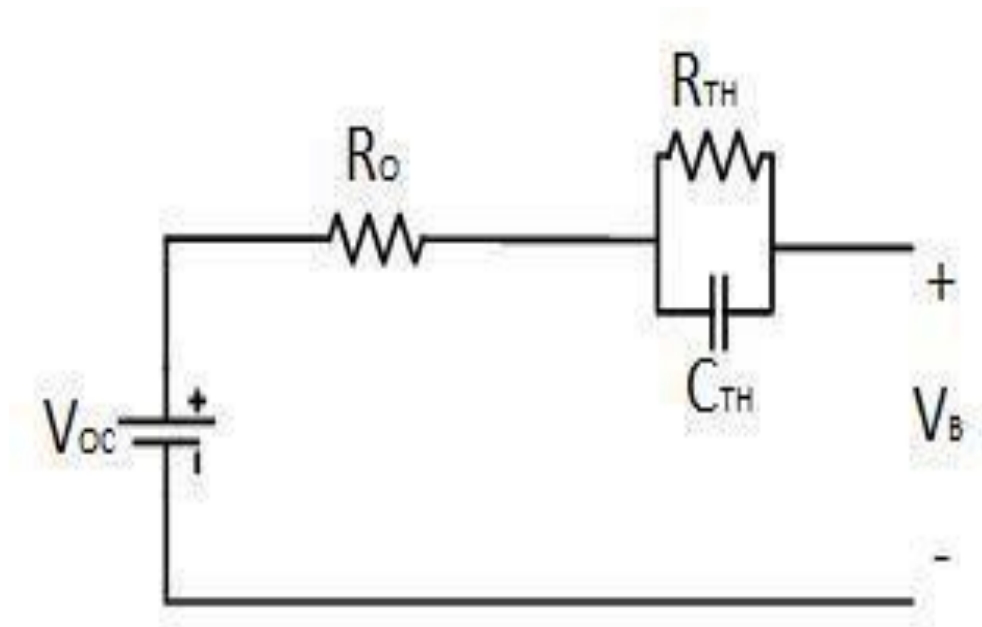


Figure 1.4 Equivalent circuit of a Lithium Ion cell .

Thevenin voltage(V_{oc}) is the voltage of the battery when there is no current flowing through it. The battery's state of charge (SoC), which is frequently determined by measurement or calibration, is crucial. The battery's internal resistance is what stops current from passing through it. Contact resistance, electrode resistance, and electrolyte resistance are only a few of the several resistance sources it includes. Internal resistance in the battery causes voltage drops and power losses. Both the ohmic resistance (R_o) and the polarization resistance (R_{TH}) in this model account for the internal resistance . C_{TH} is Capacitance is a measure of the battery's ability to store and release charge. It provides an explanation of the double-layer capacitance and intercalation capacitance at the electrode-electrolyte interface. V_B indicates the operational voltage of a battery when it is connected to a source or acts as a source. A comprehensive schematic of various battery models, encompassing thermal modelling, (Thevenin, Rint, Dual Polarization). The diagram should display each model's structure with components such as diffusion layers, heat flow, resistors, capacitors, and voltage sources identified.

1.7 Charging and discharging Characteristics of a battery

The main distinctions between constant current (CC) and constant voltage (CV) charging are outlined in the following comparison table:

Feature	Constant Current (CC) Charging	Constant Voltage (CV) Charging
Charging Method	Fixed current, voltage increases	Fixed voltage, current decreases
Phase	First phase of charging	Second phase of charging
Voltage Behavior	Rises gradually	Held constant (e.g., 4.2V for Li-ion)
Current Behavior	Remains constant	Decreases gradually
SOC Range	Charges up to ~70–80%	Charges from ~80% to 100%
Duration	Shorter (faster charging)	Longer (slower top-off)
Purpose	Rapid energy input	Safe full charge without overvoltage
Risk	Risk of overvoltage if not controlled	Risk of overheating if prolonged

Table 1.1 Features of Constant Current and Constant Voltage battery charging

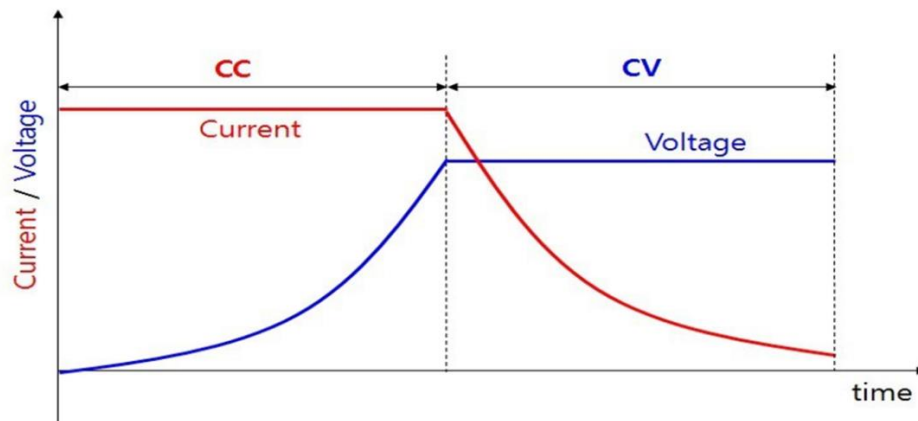


Figure-1.5:- CC-CV charging Methodology

1.8 Objectives of the Present work

This project mainly focuses to design and analyze the following aspects of EV chargers.

- (i) To develop and analyze a 2 phase boost converter based PFC circuits for EV charging with galvanic isolation
- (ii) To design and develop a dual active bridge based bidirectional charger for EV charging .

1.9 Outline of Thesis :

Chapter 1:- In this chapter, a comprehensive overview to Electric Vehicles battery charging , EV battery charger , their specifications , PFC converters have been discussed .

Chapter 2:- An Interleaved Boost Power Factor Correction Circuit (PFC) have been discussed . Although we have lots of PFC's in our hand , like Boost , Totem-pole and Interleaved Boost PFC .

Chapter 3:- The design of a dual active bridge converter operating in single phase shift (SPS) mode is examined in this chapter

Chapter 4:- Application of Constant Current- Constant Voltage Battery Charging

Chapter 5:- Final Conclusions and Future scope of Work .

CHAPTER 2

INTERLEAVED BOOST POWER FACTOR CORRECTION CIRCUIT

2.1 Introduction

This type of converter is developed using the basic boost converter topology but goes a step further by using multiple switching phases (usually two or more) that operate in parallel but out of sync. This technique is known as interleaving. By spreading the power load across multiple phases, interleaved converters: Improve overall efficiency , Minimize current ripple, which reduces stress on components Lower electromagnetic interference (EMI), making the system more compliant with power quality standards .The interleaved boost PFC converters are ideal for applications that require high reliability, clean power, and consistent performance—especially in today’s growing world of high-performance electronics and electric mobility.

2.2 Power Factor Correction (PFC)

The efficiency with which electrical power is being used is indicated by the Power Factor (PF). By ensuring that the input current follows the input voltage's form, a PFC circuit reduces reactive power and harmonics. Because boost converters can shape the input current while controlling the output voltage, they are frequently employed for PFC. Using several converter phases that run out of phase with one another, such as two or more boost converters, is known as interleaving. Better thermal distribution and fewer passive components are made possible by this reduction in input and output current ripple.

Important Elements of an AC-DC Interleaved Boost PFC Rectifier:

- (i) Produces uncontrolled DC from AC mains.
- (ii) Two or more boost stages functioning out of phase are known as interleaved boost converters. Loops of Control:
- (iii) The input current is shaped by the current loop to follow the voltage waveform.
- (iv) The DC output is smoothed by the output capacitor.
- (v) Conducted emissions are decreased by an EMI filter.

Advantages

1.	High Efficiency:	Reduced conduction and switching losses.
2.	Low Input Current Ripple:	Improves EMI performance.
3.	Better Thermal Management:	Heat is distributed across multiple phases.
4.	Scalability:	Easy to scale power by adding more phases.

2.2.1 PFC with Interleaved Boost

Ideal for: Power outputs ranging from 1 to 5 kW. Reduced input current ripple by reducing ripple, several phases make EMI filtering easier. Improved thermal distribution heat is dispersed among several parts. Adding extra phases makes it simple to increase power. Broadly compatible with both digital and analog controllers.

2.2.2 Traditional PFC Boost

Ideal for: Power levels that are low to medium (<1.5 kW) , only a diode, switch, and inductor. Less complicated control and fewer parts. But it has some disadvantages too like increased ripple in input current ,larger EMI filter and more substantial parts, less effective when power levels are higher.

2.2.3 Totem-Pole PFC

Best for: High efficiency and compact designs (especially with GaN/SiC), Uses synchronous rectification, Especially with wide-bandgap devices. But it has also some disadvantages like it requires fast and precise digital control (e.g., MCU or DSP). sensitive to grid conditions: Especially in bridgeless mode. higher cost: GaN/SiC devices and advanced controllers.

2.2.4 A comparison of different PFC topologies

Table 2.1 shows a comparison of all 3 different PFC topologies .

Feature	Interleaved Boost	Conventional Boost	Totem-Pole PFC
Efficiency	High	Medium	Very High
Complexity	Medium	Low	High
Cost	Medium	Low	High
EMI Performance	Good	Poor	Excellent
Scalability	Excellent	Limited	Good

Table 2.1 Difference between all the PFC topologies in tabular form

2.2.5 The advantages of having a high power factor ($PF \approx 1$)

Maintaining a high power factor, close to unity ($PF \approx 1$), offers several significant advantages. It reduces the amount of current required to deliver the same amount of power, which in turn minimizes copper losses and allows for the use of smaller conductors. This efficiency leads to lower energy waste in transmission and distribution systems, enhancing overall productivity. Financially, it helps avoid penalties that utilities often impose for low power factor, resulting in reduced electricity bills. Additionally, equipment such as generators, transformers, and wiring can be more compact and cost-effective due to the lower current demands. Environmentally, improved efficiency means less energy is wasted, contributing to a smaller carbon footprint and supporting sustainability goals.

2.2.6 The drawbacks of having a low power factor ($PF < 1$)

A low power factor can lead to several operational and financial drawbacks. One of the primary issues is the increased current draw required to deliver the same amount of power, which necessitates the use of thicker cables and results in higher energy losses. This inefficiency also reduces overall productivity, as more energy is wasted in the form of heat and reactive power. From a cost perspective, utilities often impose additional charges for low power factor because it places extra demand on the electrical grid. Furthermore, the infrastructure—including transformers, generators, and wiring—must be larger and more robust to handle the elevated current, leading to higher capital and maintenance costs. Environmentally, the increased energy waste contributes to greater fuel consumption and higher emissions, negatively impacting sustainability efforts.

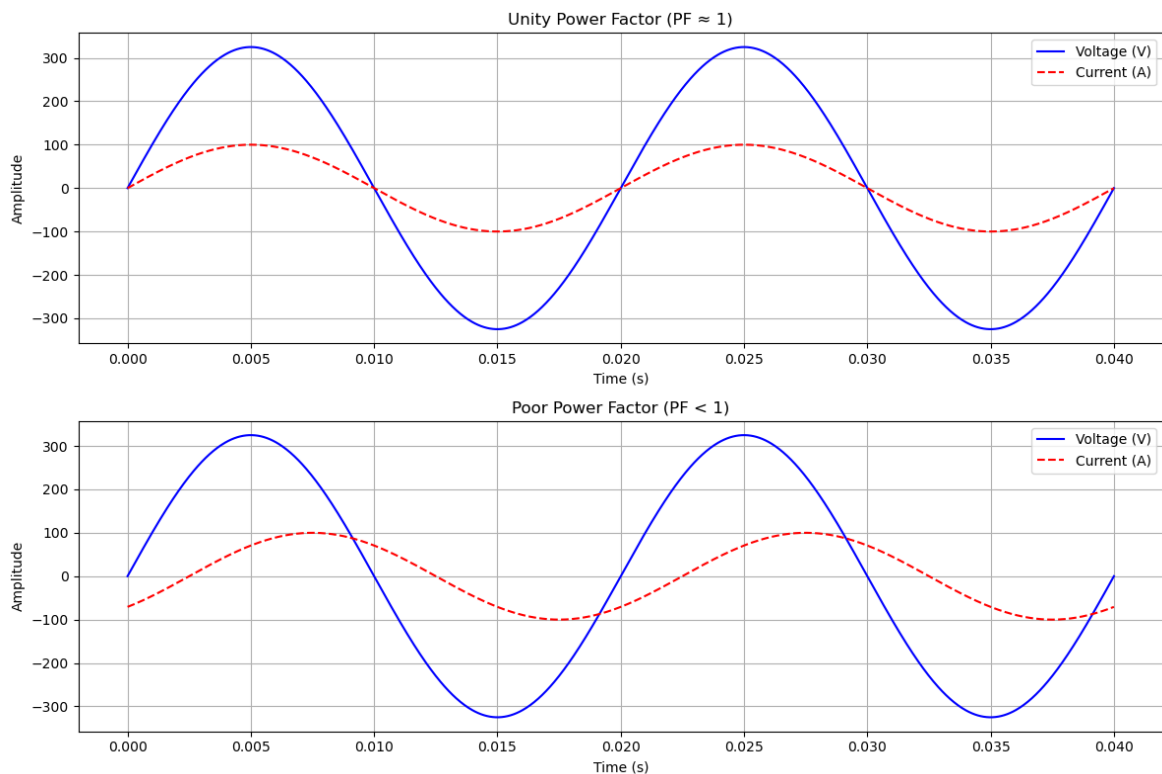


Figure 2.1 Power factor

Highlights:

Top Plot-Unity PF: Power consumption is efficient because voltage and current are exactly in phase.

Bottom Plot: Poor PF: Reactive power and inefficiency are evident as current lags voltage by 45° .

2.3 Effect on Voltage and Current ripple by varying the Duty ratio(D) and Load Resistance (R) :**Combined Effects in Interleaved Boost PFC**

Parameter Change	Output Voltage	Current Ripple	Notes
↑ Duty Ratio	↑	↑ (per phase)	Interleaving helps reduce net ripple
↓ Duty Ratio	↓	↓	Lower stress, but lower voltage
↑ Load Resistance	↑ (slightly)	↓	Light load, less ripple
↓ Load Resistance	↓ (if overloaded)	↑	Heavy load, more ripple

Table 2.2 Effect of Duty ratio(D) and Load resistance® on Output voltage and Current ripple

Above table shows variation of Output voltage and Current ripple , that is V_o and Iripple when , Duty Ratio i.e D changes and also what conclusions that we can draw from above table . (Current ripple is shown in per-phase only)

2.4 Switching Pulses Waveforms :

2.4.1 Here are the switching pulse waveforms for a 2-phase Interleaved Boost PFC Converter

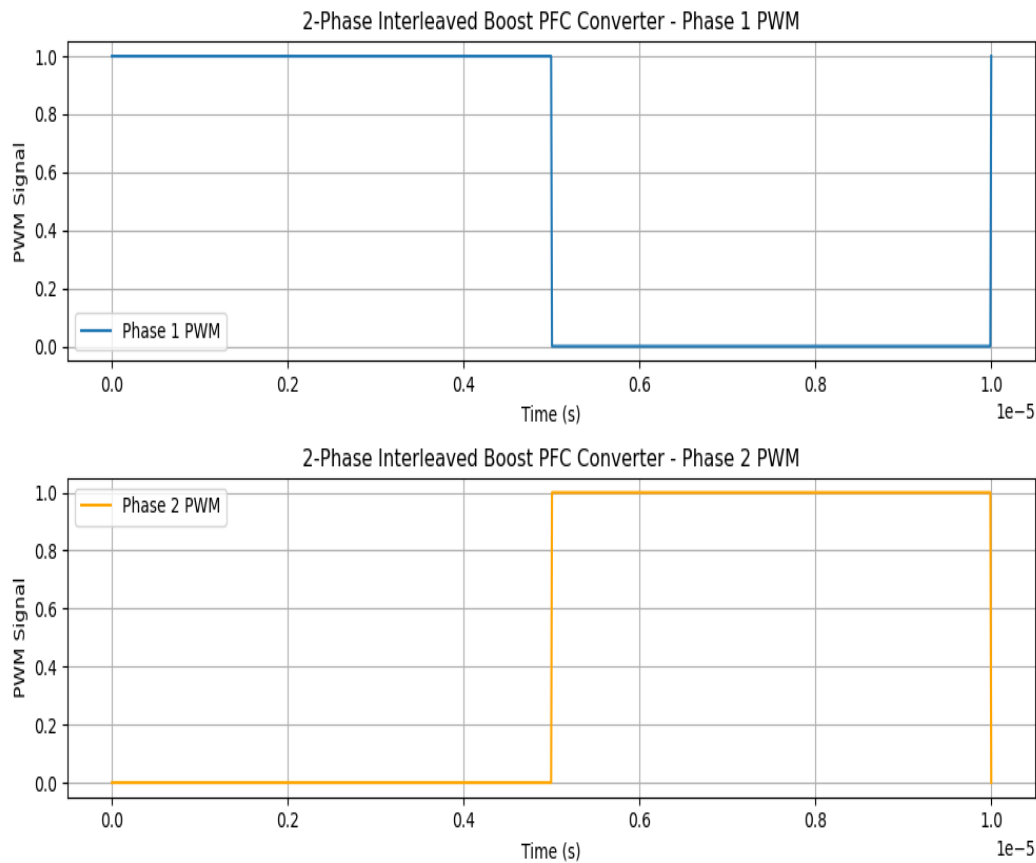


Fig 2.2 Two-phase IBC switching pulses with a 180° phase shift

2.4.2 Here are the switching pulse waveforms for a 3-phase Interleaved Boost PFC Converter

Individual Phase PWM Signals

- Top Plot: Phase 1 PWM (starts at 0°)
- Middle Plot: Phase 2 PWM (shifted by 120°)
- Bottom Plot: Phase 3 PWM (shifted by 240°)

This layout makes it easier to understand the timing and interleaving of each phase.

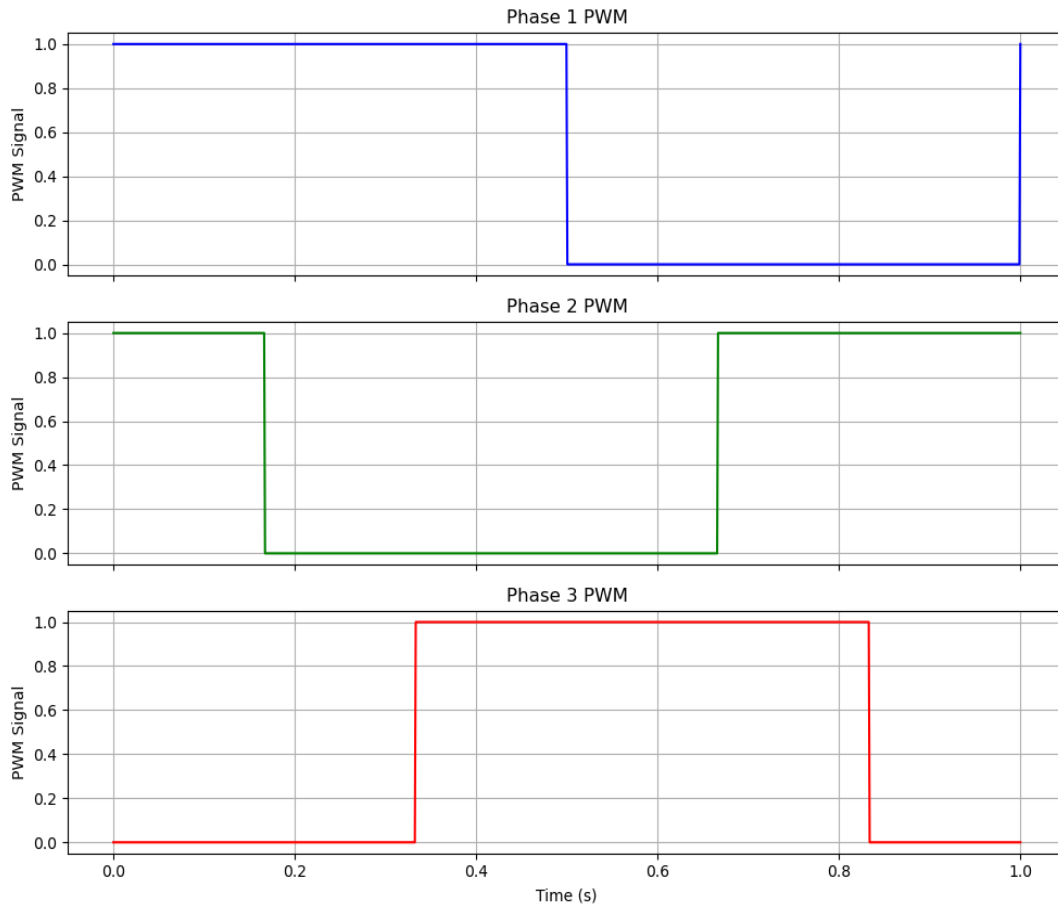


Fig 2.3 Three-phase IBC switching pulses with a 120° phase shift.

2.4.3 Here are the switching pulse waveforms for a 4-phase Interleaved Boost PFC Converter:

Individual Phase PWM Signals

- **Phase 1:** Starts at 0°
- **Phase 2:** Shifted by 90° ($\frac{1}{4}$ of the switching period)
- **Phase 3:** Shifted by 180° ($\frac{1}{2}$ of the switching period)
- **Phase 4:** Shifted by 270° ($\frac{3}{4}$ of the switching period)

Each phase is active for 50% of the switching period, and the interleaving ensures that switching events are evenly distributed, minimizing input ripple and improving efficiency.

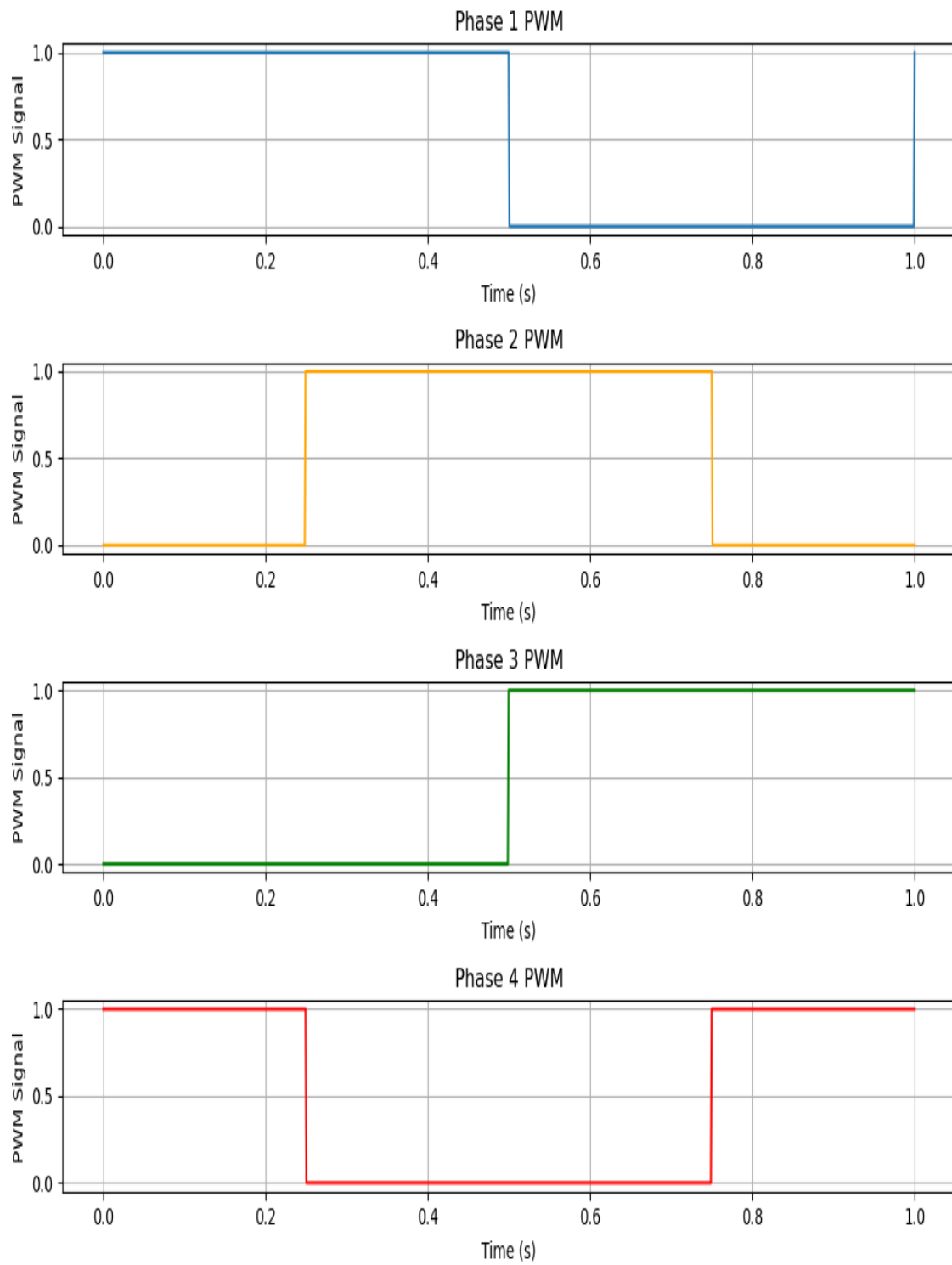


Fig 2.4 Four phase IBC switching pulses with a 90° phase shift.

2.5 Interleaved Boost PFC Circuit Analysis

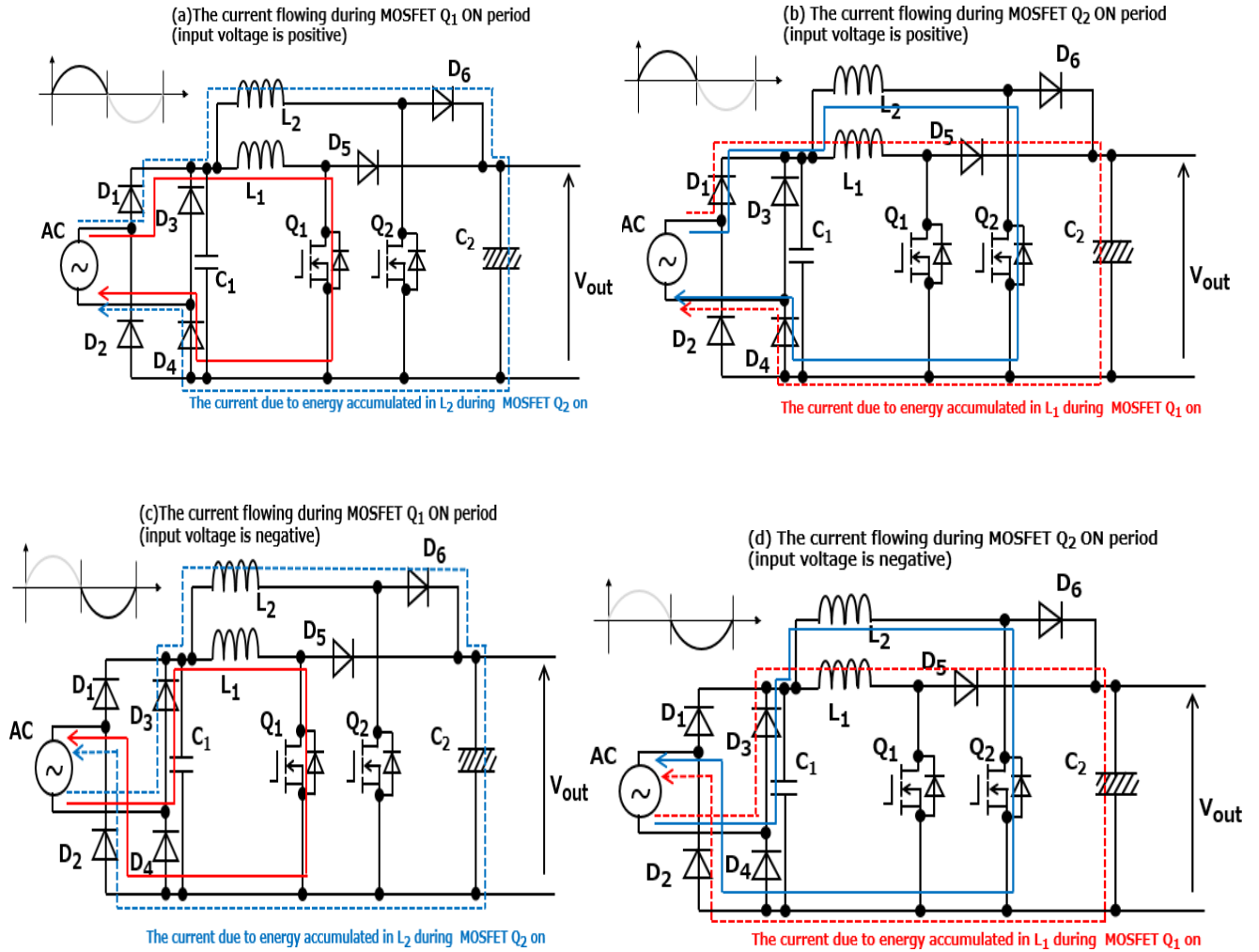


Fig 2.5 :- Circuit analysis and it's operation

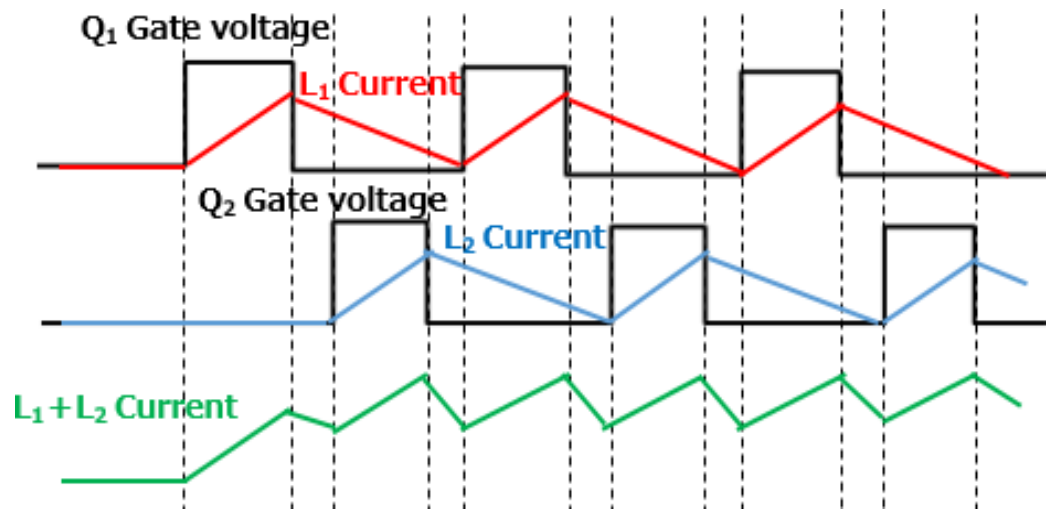


Fig 2.6 :- 2 phase IBC waveform

2.6 Performance of Interleaved Boost PFC

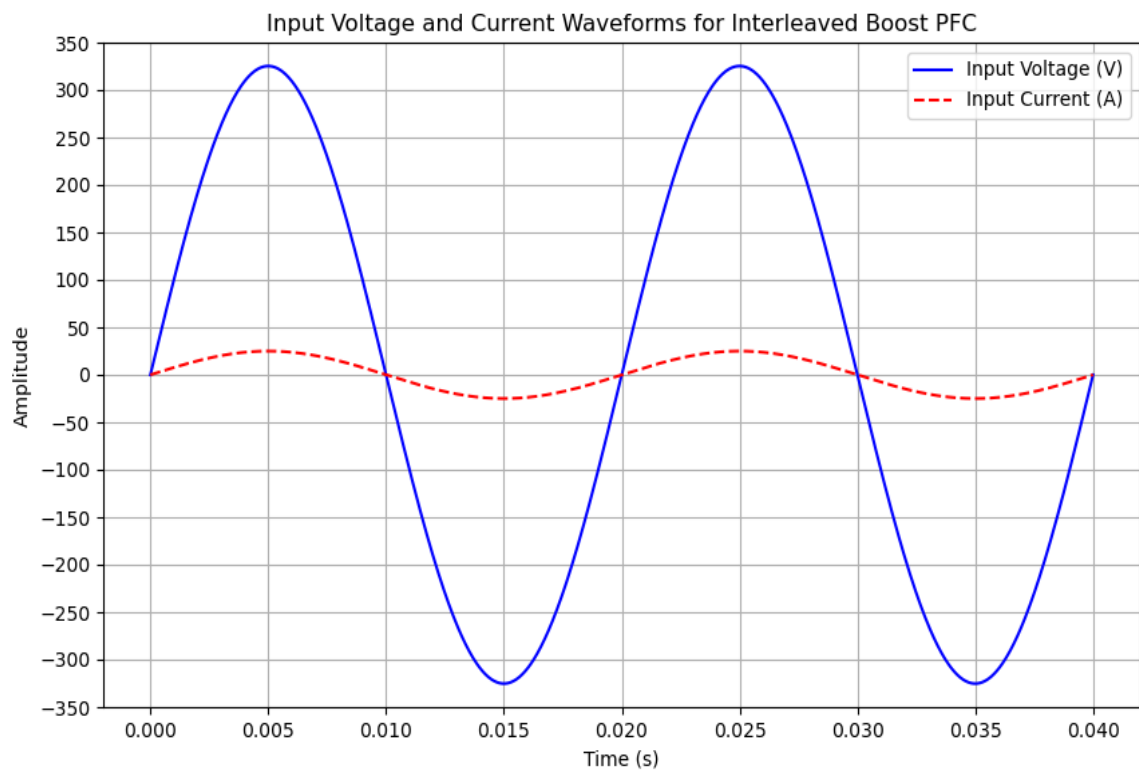


Fig 2.7 Input Current and Input voltage waveform of a IBC (2 phase)

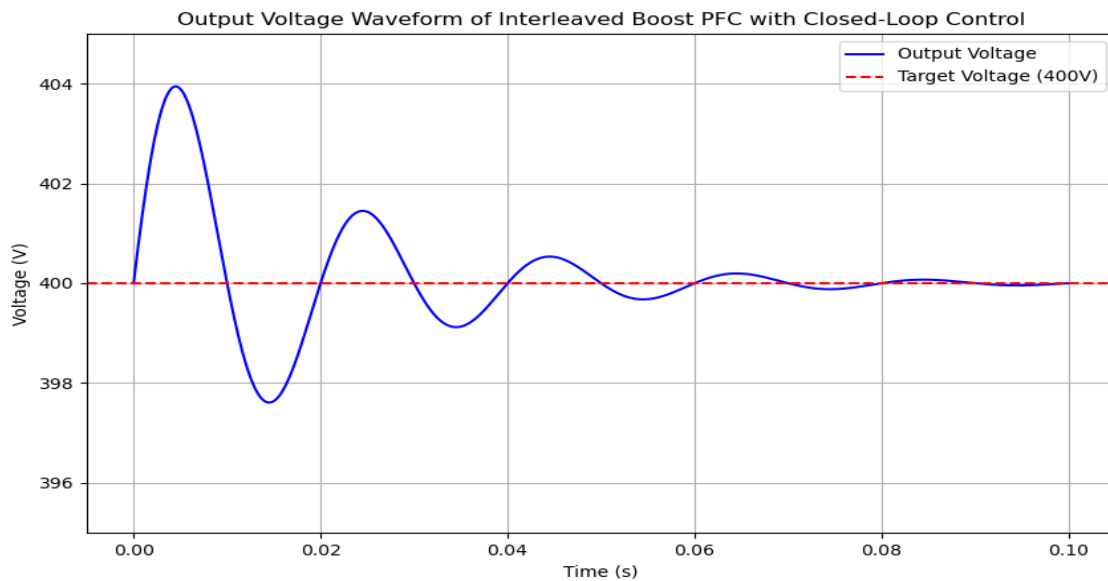


Fig 2.8 Output voltage waveform of a IBC (2 phase)

2.7 Simulation and Results of 2 Phase Interleaved Boost PFC

In a two-phase interleaved boost converter (IBC), both phases are connected to the same input source, meaning each phase receives an identical input voltage. The voltage stress experienced by the switches and diodes is governed by the output voltage rather than the input, although the input voltage still influences the required duty cycle for voltage boosting. The total input current is shared equally between the two phases, ideally splitting the load to enhance efficiency. Additionally, when the phases operate 180 degrees out of phase, input current ripples are significantly reduced. This phase shift smooths the input current waveform, minimizing electromagnetic interference (EMI) and improving overall system performance.

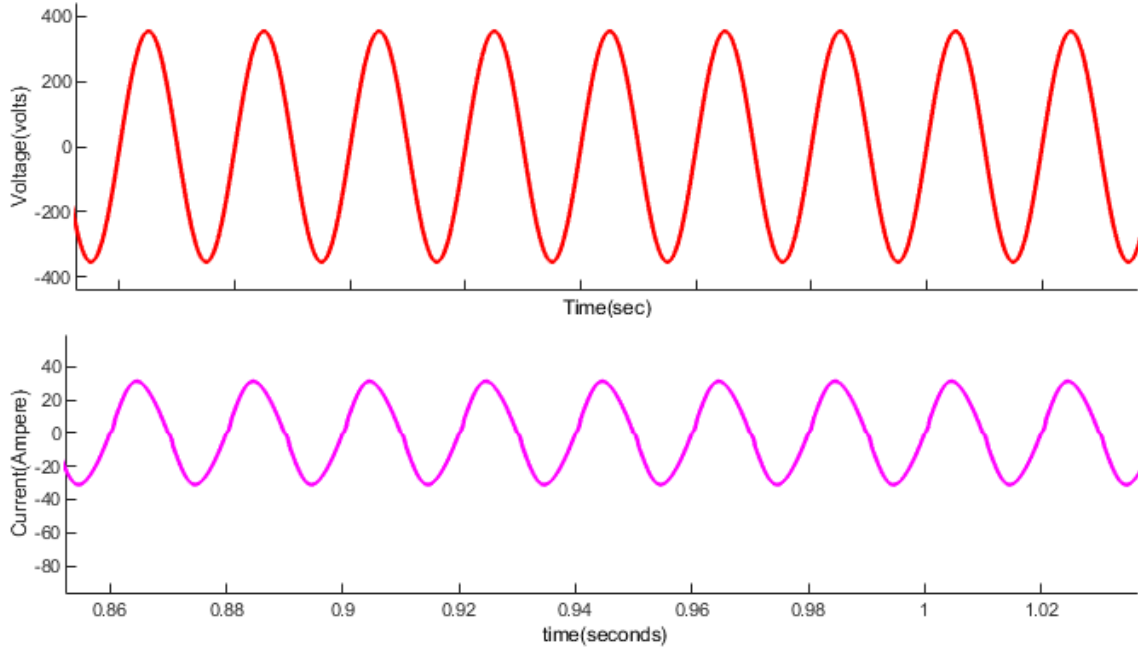


Fig 2.9 Simulation Result of 2 Phase IBC(input V & I)

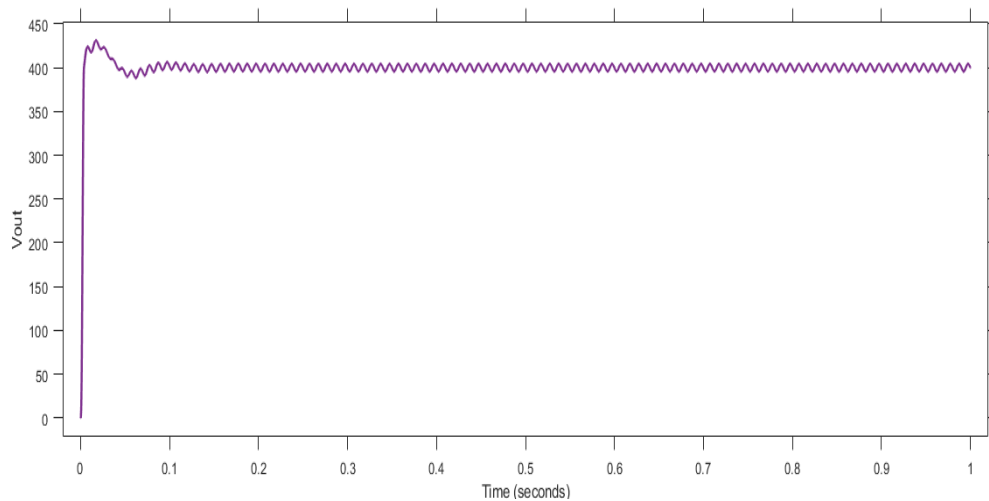


Fig 2.10 Simulation Result of 2 Phase IBC(Vo)

2.8 Conclusion

By operating two converters with a 180-degree phase shift, interleaved systems effectively minimize input current ripple, enhancing overall efficiency and promoting even heat distribution across components. This not only improves thermal management but also extends the hardware's operational life. The interleaved control approach ensures a more continuous and less distorted current flow, which helps improve the power factor—an essential criterion for adhering to global power quality standards. Since both phases draw from the same input voltage, their operation remains synchronized and stable. Thanks to their modular and scalable nature, interleaved converters are ideal for high-power applications such as industrial power systems, renewable energy setups, and electric vehicle charging infrastructure.

CHAPTER 3

DUAL ACTIVE BRIDGE CONVERTER FOR BIDIRECTIONAL CHARGING

3.1 Introduction

The Dual Active Bridge (DAB) converter is a widely adopted solution in modern power systems due to its ability to efficiently manage bidirectional DC-DC power transfer. Its design supports high performance and adaptability, making it ideal for advanced energy applications. With built-in galvanic isolation and strong energy conversion efficiency, the DAB is commonly used in electric vehicles, renewable energy platforms, and grid-integrated energy storage systems.

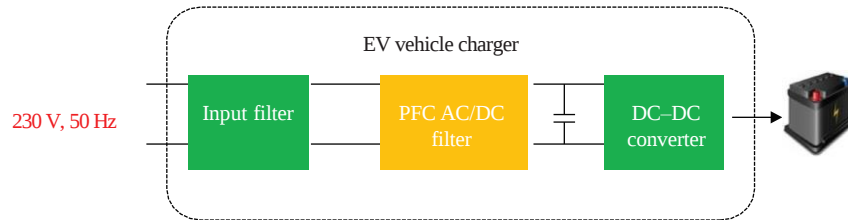


FIGURE 3.1: Schematic of on-board charger.

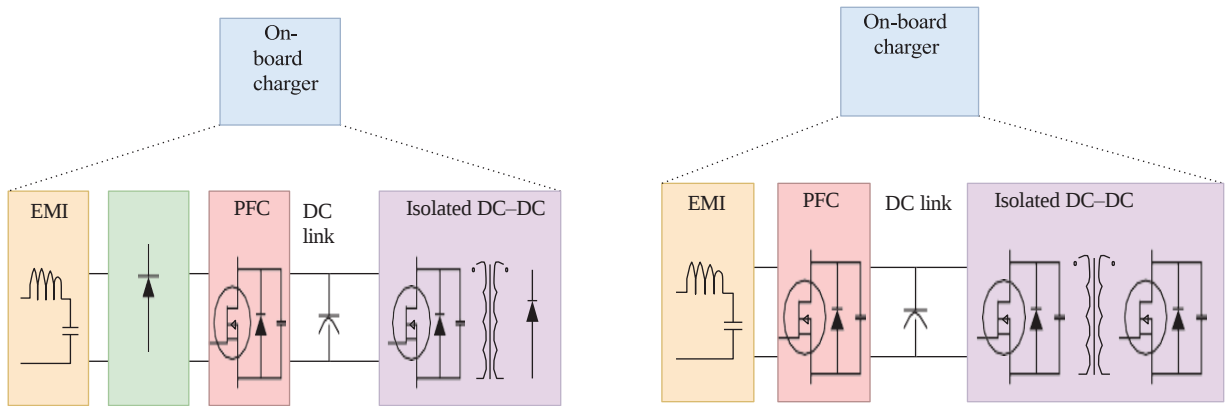


Figure 3.2 Unidirectional on-board charger (OBC) and (b) bidirectional OBC.

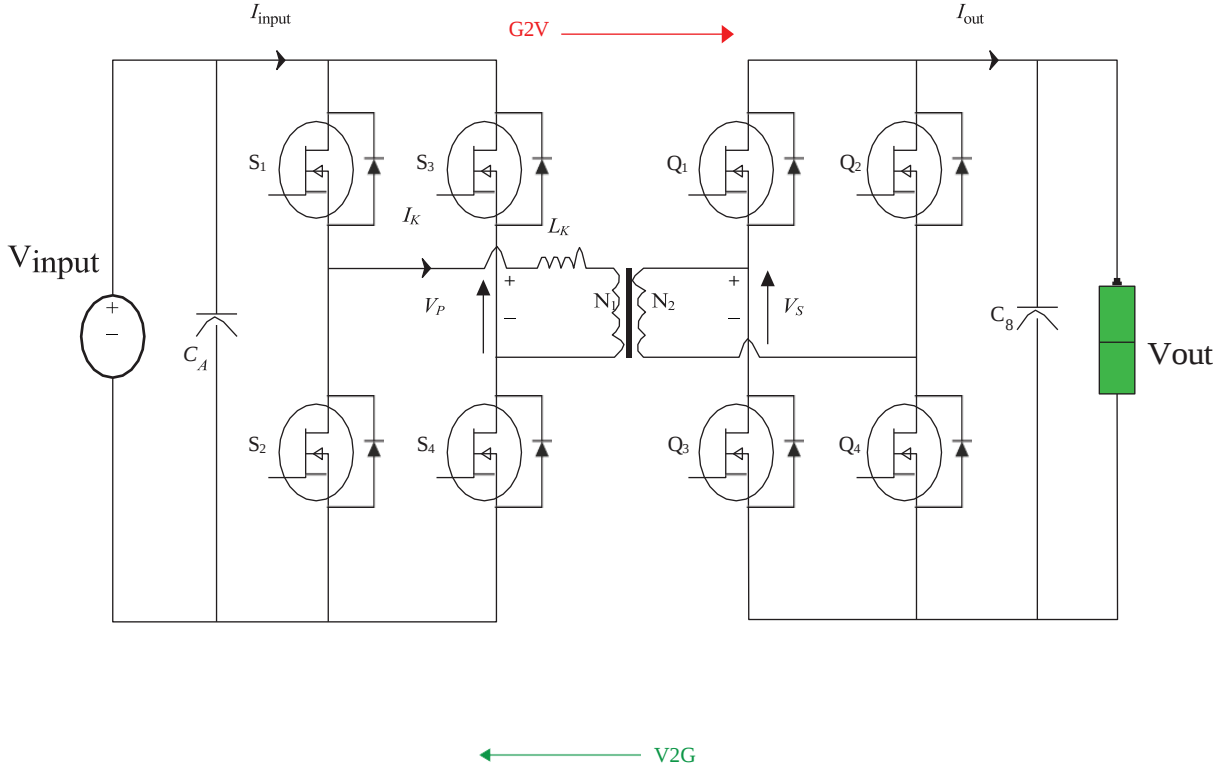


Figure 3.3 : Single phase Dual Active bridge converter circuit description

3.2 DAB Modelling

The primary and secondary voltages across the HFT are indicated by the variables V_{DC1} and V_{DC2} , respectively. The way the current behaves as it passes through the leak. The HFT replicates the inductor in a way that is similar to the latter portion of the cycle. The inherent symmetry in a single switching cycle is what causes this replication. The DAB's primary, secondary, and inductor currents are shown in Figure 3.4. Our research will therefore be limited to the first half of the waveform within the parameters of mathematical modeling.

- **Mode 1: $\theta_0 < \theta < \theta_1$**

The voltage difference between the two is seen across the leaky inductor in this operating state. Because of the positive value of V_{DC1} and the negative value of V_{DC2} , the resulting voltage becomes positive, which causes the current to increase. The following is the mathematical expression for the rise in electricity rent.

$$i(\theta) = i(\theta) + \frac{V_{DC1} + nV_{DC2}}{2\pi f L_K} (\theta_1 - \theta_0) \quad (1)$$

- **Mode 2: $\theta_1 < \theta < \theta_2$**

Both the primary and secondary voltages exhibit positive polarity in the current operating condition, and the combined voltage is visible across the leaking inductor. HFT current is seen to be increasing in this particular situation. This is explained by the fact that there is a positive net potential since the secondary voltage is comparatively lower than the primary voltage:

$$i(\theta) = i(\theta_1) + \frac{V_{DC1} + nV_{DC2}}{2\pi f L_K} (\theta_2 - \theta_1) \quad (2)$$

We change the boundary values in the appropriate modes to answer the aforementioned equations:

$$i(\theta_1) = i(\theta_0) + \frac{V_{DC1} + nV_{DC2}}{2\pi f L_K} (\theta_1 - \theta_0) \quad (3)$$

$$i(\theta_2) = i(\theta_1) + \frac{V_{DC1} + nV_{DC2}}{2\pi f L_K} (\theta_2 - \theta_1) \quad (4)$$

Equations (2) through (4) give us the following:

$$i(\theta_2) = i(\theta_0) + \frac{V_{DC1} + nV_{DC2}}{2\pi f L_K} (\theta_1 - \theta_0) + \frac{V_{DC1} + nV_{DC2}}{2\pi f L_K} (\theta_2 - \theta_1) \quad (5)$$

According to the inductor current balancing principle, the average current flowing through the HFT will be zero in steady-state conditions. Assume that $i(\theta_0) = -i(\theta_2)$, which yields the maximum instantaneous current that causes current stress for the traditional DAB:

$$2i(\theta_2) = \frac{V_{DC1} + nV_{DC2}}{2\pi f L_K} (\theta_1 - \theta_0) + \frac{V_{DC1} + nV_{DC2}}{2\pi f L_K} (\theta_2 - \theta_1) \quad (6)$$

$$i(\theta_2) = \frac{V_{DC1} + nV_{DC2}}{4\pi f L_K} (\theta_1 - \theta_0) + \frac{V_{DC1} + nV_{DC2}}{4\pi f L_K} (\theta_2 - \theta_1) \quad (7)$$

From figure – 3.4 :

$$i(\theta_2) = \frac{V_{DC1} + nV_{DC2}}{4\pi f L_K} \delta + \frac{V_{DC1} + nV_{DC2}}{4\pi f L_K} (\pi - \delta) \quad (8)$$

$$|i_{Lmax}| = i(\theta_2) = \frac{nV_{DC2}}{4\pi f L_K} (\pi(k-1) + 2\delta) \quad (9)$$

The average power transmission P_{avg} is determined using Fourier series analysis as follows:

$$P_{avg} = \frac{4nV_{DC1}V_{DC2}}{\pi^3 f L_K} \sin \delta, \quad 0 < \delta < \pi \quad (10)$$

The maximum power transfer is achieved at $\delta = \pi/2$:-

$$P_{max} = \frac{4nV_{DC1}V_{DC2}}{\pi^3 f L_K} \quad (11)$$

For comparative analysis , the unified power P_T is defined as follows:

$$P_T = \frac{P_{avg}}{P_{max}} = \sin \delta \quad (12)$$

$$V_{DC2} = \frac{4nV_{DC1}R}{\pi^3 f L_K} \sin \delta \quad (13)$$

The following is the generalized expression for the output power:

$$P = \frac{nV_{DC1}V_{DC2}\delta(\pi-|\delta|)}{2f_{sw}L_K\pi^2}, \frac{-\pi}{2} \leq \delta \leq \frac{\pi}{2} \quad (14)$$

The following provides the current value at locations i_1 and i_2 in the inductor current waveform shown in Figure 7:

$$i_1 = 0.5(2\delta - (1 - d)\pi)I_{nom} \quad (15)$$

$$i_2 = 0.5(2d\delta + (1 - d)\pi)I_{nom} \quad (16)$$

Where

$$d = \frac{V_{DC2}}{n \times V_{DC1}} \quad (17)$$

According to the specifications, I_{nom} is the converter's base current.

3.2.1 Waveforms and Analysis Of Dual Active Bridge Converter .

A Dual Active Bridge (DAB) converter consists of two full-bridge circuits: the primary bridge, which functions as an inverter, and the secondary bridge, which operates as a rectifier. These bridges are connected through a high-frequency transformer that ensures electrical isolation between the input and output sides. Both bridges are controlled simultaneously, typically using a 50% duty cycle for all switches. The switching pattern involves diagonal pairs of switches turning on and off together, generating square wave outputs on both sides. The primary side uses switches labeled S1 to S4, while the secondary side uses Q1 to Q4. The switching sequence is divided into four intervals: the first activates S1, S2, Q2, and Q3; the second triggers S1, S4, Q1, and Q4; the third involves S2, S3, Q1, and Q4; and the fourth activates S2, S3, Q2, and Q3. A key feature of the DAB converter is the phase shift between the control signals of the primary and secondary bridges, typically ranging from 0° to 30° , which enables efficient power transfer and control.

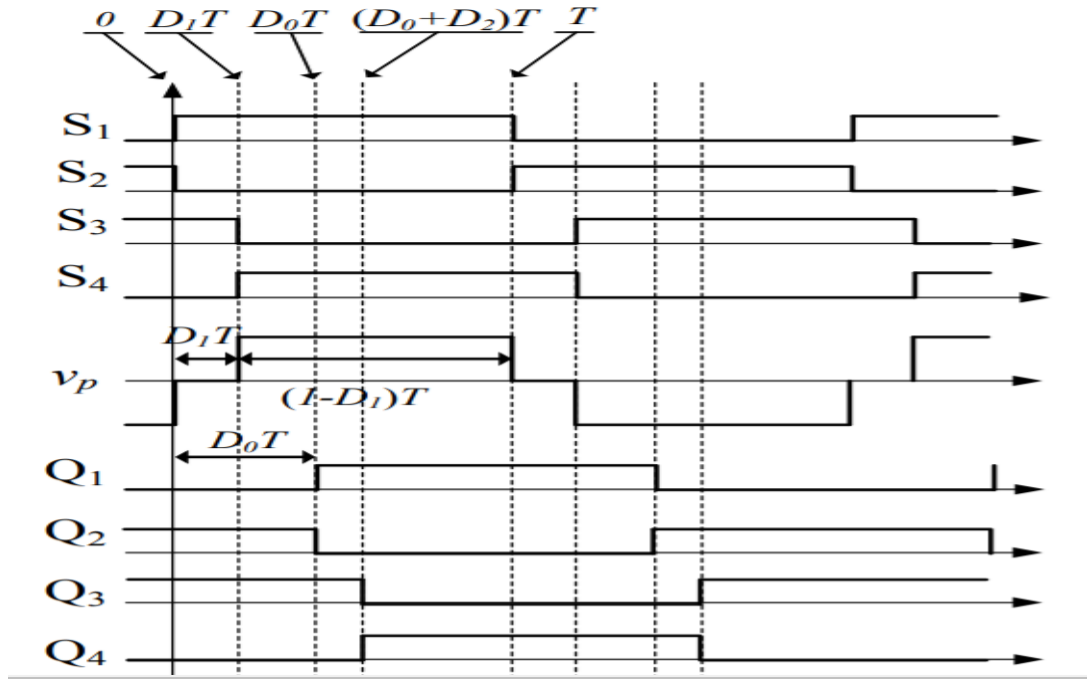
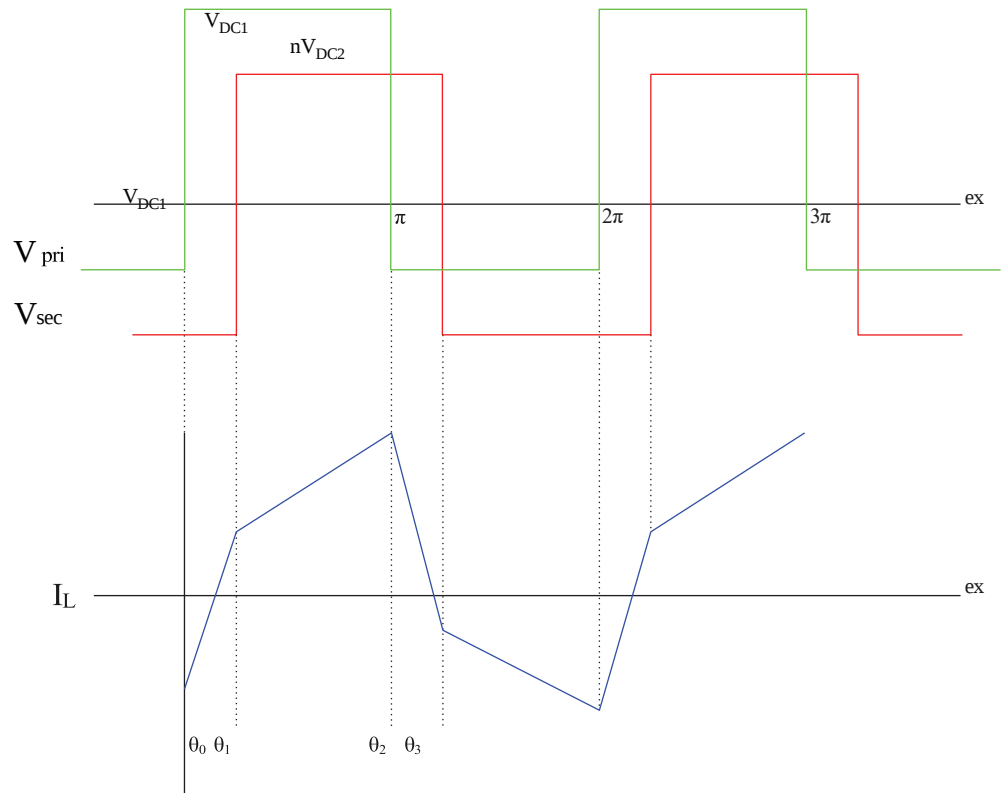


Figure 3.4: Dual active bridge converter switching waveforms



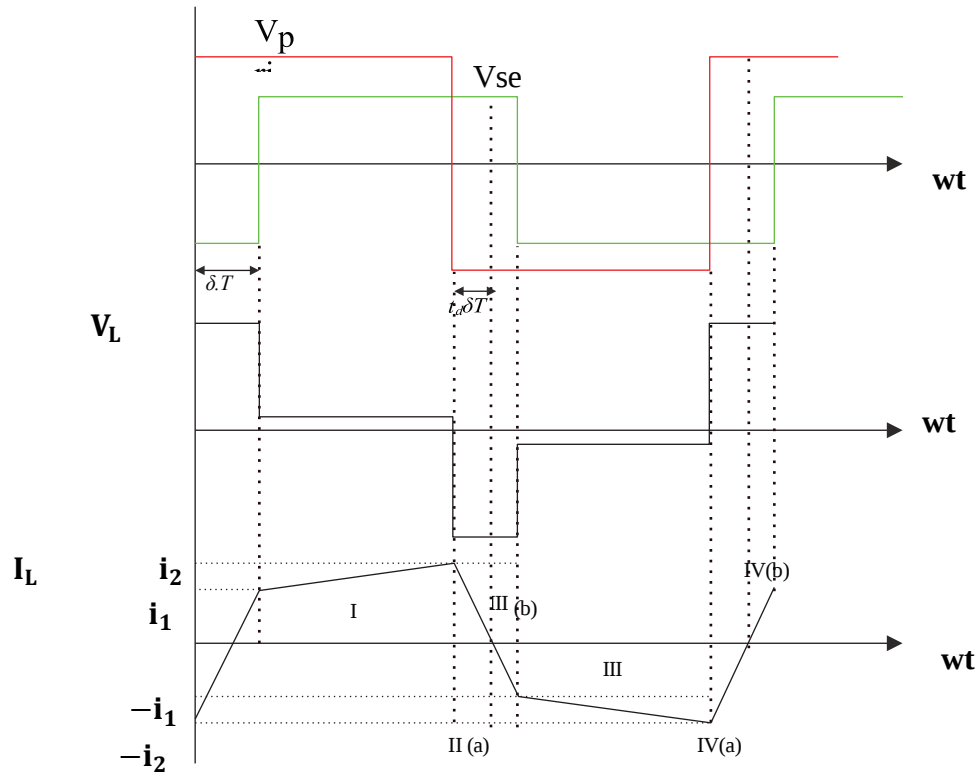


FIGURE 3.5 : Voltage and current waveforms of dual active bridge (DAB).

3.2.2 CONVERTER DESIGN

□ Converter Specification

- Input voltage : 400 V
range
- Switching : 50 kHz
Frequency
- Output Voltage : 24V
- Output Current : 10A
- Current Ripple : 20%
- Voltage Ripple : 1%

Abbreviations:

V_i : Input voltage	f_s : Switching frequency
V_o : Output Voltage	V_L : Voltage across the inductor
D : Duty Cycle	I_{ripple} : Window factor
V_{ri} : Voltage Ripple ppl e	T_s : Switching Time
C : Capacitance A_c : Area of cross section	B_{max} : Maximum permeability

3.2.3 Calculation and Parameters :

Turns ratio(n) :- $\frac{N_s}{N_p} = 0.1$
$V_L = V_i \frac{N_s}{N_p} - V_o = 6 \text{ V}$
$D = \frac{1}{2} * \frac{24}{30} = 0.4$
$I_{ripple} = 0.2 \text{ A}$
$L = \frac{V_L D T_s}{I_{ripple}} = 24 \mu\text{H}$
$V_{ripple} = 1\% \text{ of } 24 = 0.24 \text{ V}$
$C = \frac{I_{ripple} * D * T_s}{V_{ripple}} = 66.67 \mu\text{H}$

3.2.4 Transformer design :

Core material with a permeability of 2000–2500 is chosen for operations below 500 KHz. Ferrite cores are preferred in high frequency transformers because of their high permeability, minimal eddy current losses, and good resistance to high current.

The chosen core form is an EE core, and the cross sectional area is 1.54 cm².

$N_p = \frac{V_i * 10^8}{4 * f * B_{\max} * A_c} = 29$
$\frac{N_p}{N_s} = \frac{V_p}{V_s}$
$N_s = 7$

The transformer is being wound using 19SWG copper wire, which has a 3.2A current carrying capacity and a 1.016mm cross section area . The twin active bridge converter's closed loop control is constructed using the phase shift modulation technique. In phase shift modulation, the primary side of a Dual Active bridge converter's duty cycle is phase-shifted with respect to the secondary side. By adjusting the phase shift angle, the output voltage and current can be controlled as necessary. For closed loop control in this work, a digital controller is employed. The dual active bridge converter's output voltage and current are controlled by a program written in a Matlab function block that is implemented in Matlab Simulink. The software is created by switching from a PI controller to a discrete PI controller.

3.3 Operation of DAB :

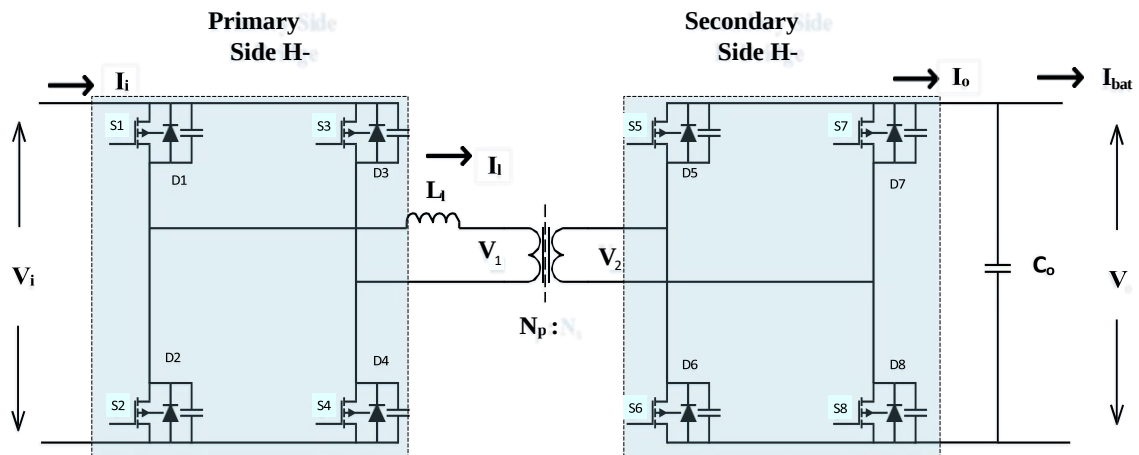


Figure 3.6 Description of a single phase dual active bridge converter circuit

3.3.1 BUCK operation Forward mode

Current moves from high-voltage port V_1 to low-voltage port V_2 when the buck is operating. In this mode, power moves from the main to the secondary by directing the gate pulses generated by the HV side toward the LV side.

Switching States of Converter in BUCK mode

Time Interval	Conducting devices in Primary Bridge	Conducting devices in Secondary Bridge
t_0-t_1	D1 & D4	D6 & D7
t_1-t_2	D1 & D4	S5 & S8
t_2-t_3	S1 & S4	D5 & D8
t_3-t_4	D2 & D3	D5 & D8
t_4-t_5	D2 & D3	S6 & S7
t_5-t_6	S2 & S3	D6 & D7

Table 3.1 Switching states of DAB in BUCK mode

3.3.2 BOOST operation Forward mode (reverse power transfer)

When gate pulses are created at the HV side VSC and trail the LV side by an angle, power transfers from the secondary to the primary side in this case. Table II lists the statuses of the devices that switch .

Table 3.2:- Switching States of Converter in boost mode

Time Interval	Conducting devices in Primary Bridge	Conducting devices in Secondary Bridge
t_0-t_1	S2 & S3	S5 & S8
t_1-t_2	D1 & D4	S5 & S8
t_2-t_3	S1 & S4	D5 & D8
t_3-t_4	S1 & S4	S6 & S7
t_4-t_5	D2 & D3	S6 & S7
t_5-t_6	S2 & S3	D6 & D7

Furthermore, the waveforms of several electrical parameters, including currents, voltages, and inductor current, are displayed in Figure 3.7. The behavior of the system in both the charging and discharging phases is depicted by these waveforms. A positive output current during the charging mode indicates that the secondary side source is receiving current [22]. On the other hand, current obtained from the principal side source is indicated by a negative input current. The major side source is receiving current during the discharge mode when a positive input current is recognized. Conversely, a negative output current signifies that the secondary side source is losing current.

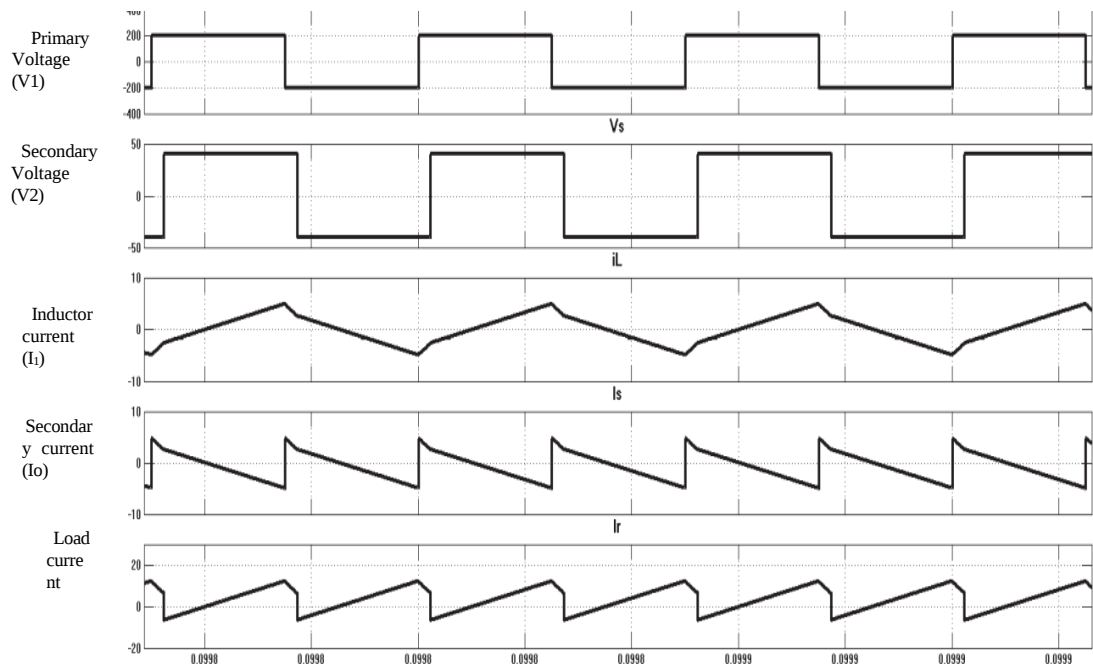


Figure 3.7 Primary, Secondary and Inductor voltages and currents along with Sending and receiving current for forward mode

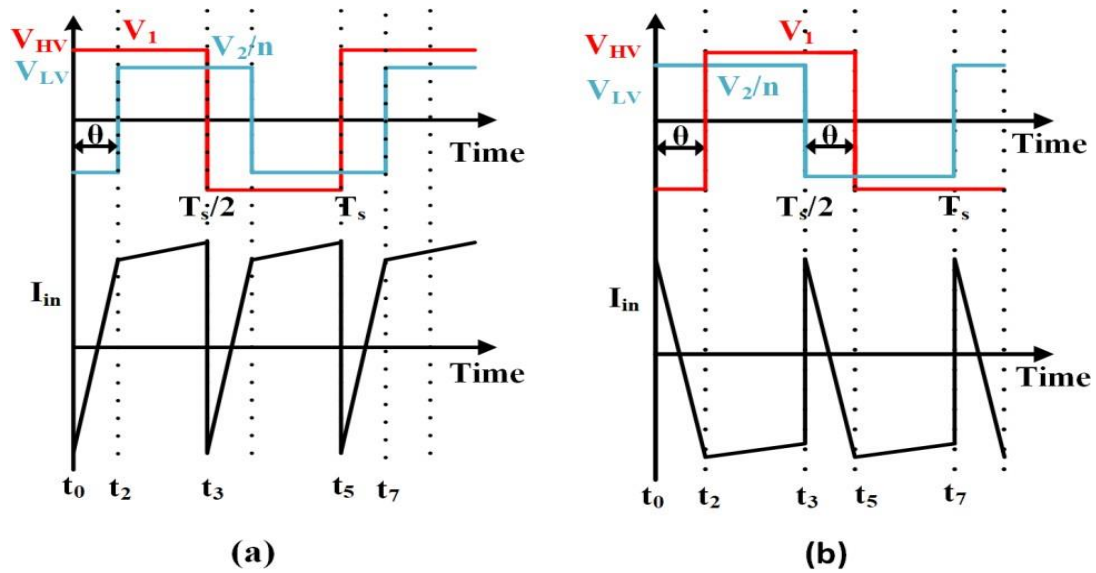


Figure 3.8 (a) Input voltage and current waveforms in buck operation; b) Input voltage and current waveforms in boost operation .

3.4 Simulation and Results :

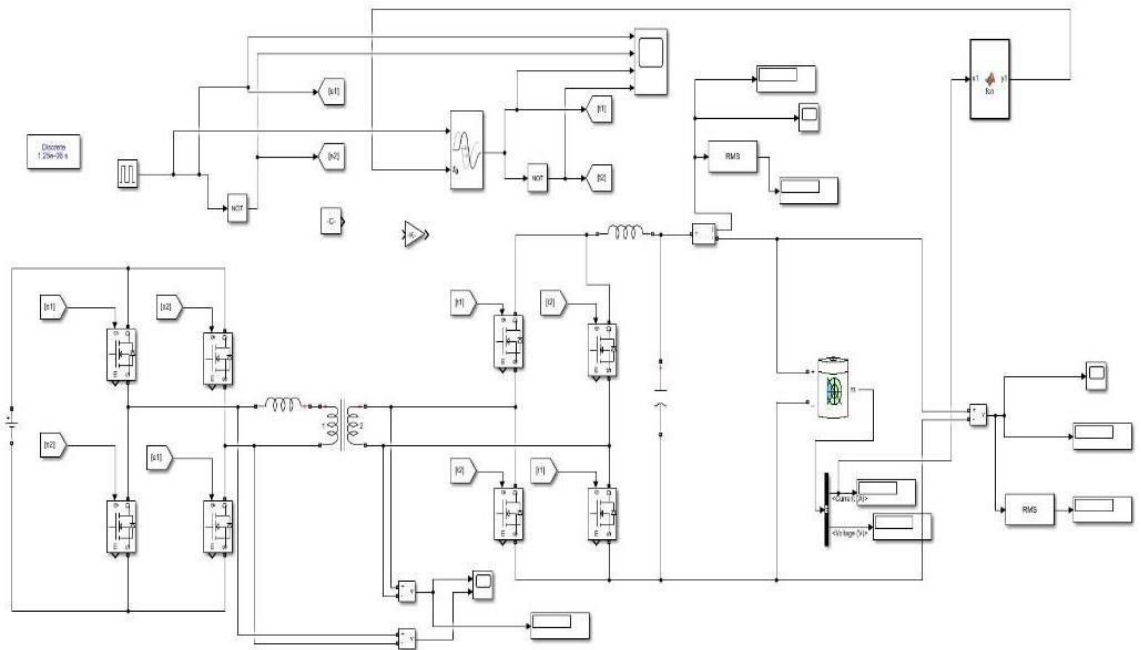


Figure 3.9 Simulation model for the closed loop control

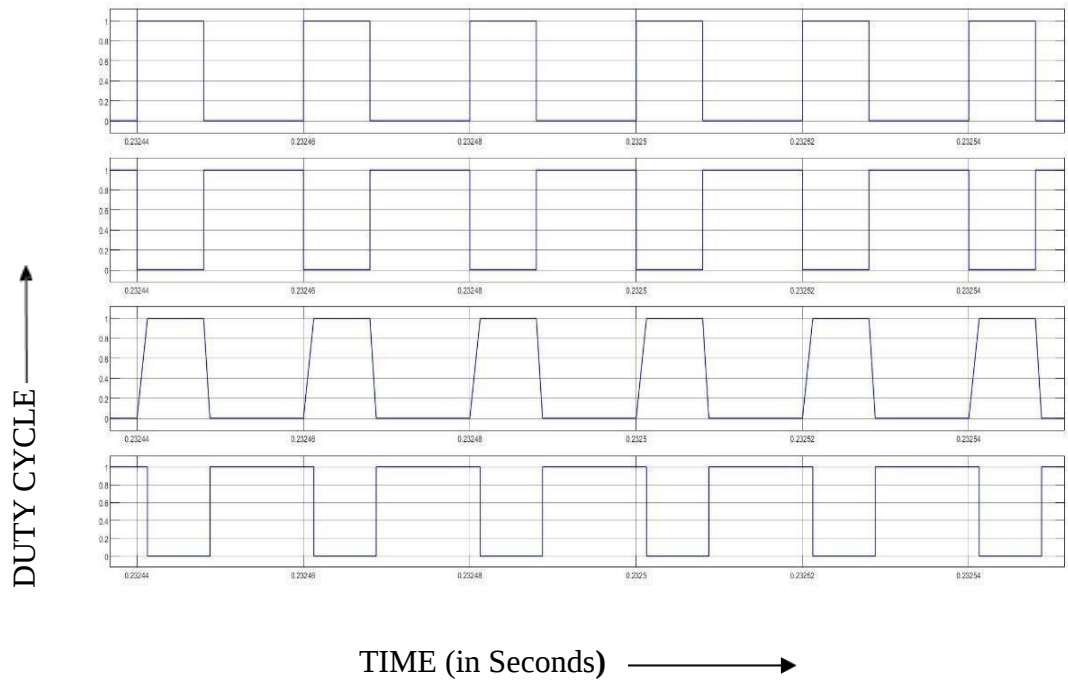


Figure 3.10 Switching waveforms for the dual active bridge converter

The graph for input voltage change in relation to output current for battery charging is shown in Fig. 3.8. In order to maintain a constant output current of 10A, the input voltage is adjusted between 260V and 360V.

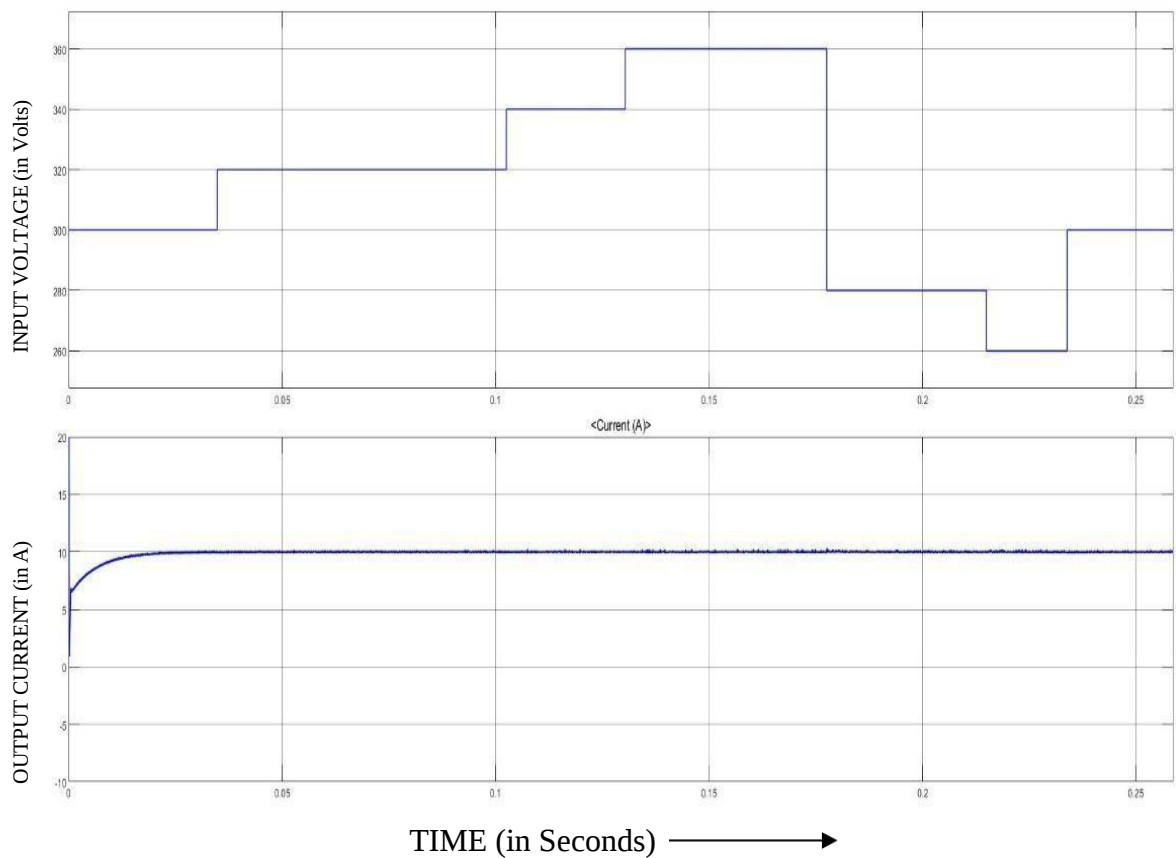


Figure 3.11 Input voltage & Output current variation against time for battery charging

3.5 Conclusion

The Dual Active Bridge (DAB) converter has been thoroughly examined in this chapter, with particular attention paid to its topology, control schemes, and performance in a range of power conversion applications. The DAB is a viable option for contemporary power systems, especially in solid-state transformers, electric vehicle charging, and renewable energy integration, thanks to its high efficiency, galvanic isolation, and bidirectional power flow capacity. The DAB converter stands out as a **versatile and powerful solution** for future power electronics. With ongoing innovation and research, it holds great promise for powering the next generation of technologies across electric vehicles, smart grids, and renewable energy systems.

CHAPTER 4

Constant Current- Constant Voltage Battery Charging

4.1 Introduction

The process of delivering an external electric current to a battery in order to refill its stored energy is known as battery charging. Rechargeable batteries depend on this procedure to remain functional and long-lasting. Optimizing battery performance requires an understanding of the several charging techniques, especially Constant Current (CC) and Constant Voltage (CV).

- **Here's a tabular comparison between Constant Current (CC) and Constant Voltage (CV) charging methods:**

Feature	Constant Current (CC) Charging	Constant Voltage (CV) Charging
Definition	Current remains constant while voltage varies	Voltage remains constant while current varies
Charging Phase	Typically used in the initial phase of charging	Typically used in the final phase of charging
Control Parameter	Current is regulated and kept constant	Voltage is regulated and kept constant
Voltage Behavior	Increases gradually as the battery charges	Remains fixed throughout the charging process

Feature	Constant Current (CC) Charging	Constant Voltage (CV) Charging
Current Behavior	Remains constant throughout the phase	Decreases as the battery approaches full charge
Application	Common in fast charging and bulk charging	Common in topping off and maintaining full charge
Battery Stress	Can cause more heat and stress if not managed properly	Gentler on the battery, especially near full charge
Charging Time	Faster in the early stage	Slower as it nears full charge
Used In	Lithium-ion, NiMH, and lead-acid batteries	Mostly in lithium-ion and lead-acid batteries

Table 4.1 Brief comparison b/w CC-CV charging in tabular format

4.2 Advantages of CC-CV Charging

- Battery Safety: Minimizes risks of overcharging and overheating.
- Extended Battery Life: Reduces stress on the battery during the final stages of charging.
- Efficiency: Quickly restores the battery to a usable state in the CC phase, while the CV phase ensures optimal capacity

4.3 State of Charge (SOC) varies during both charging and discharging of battery

Charging Curve (Blue)

- SOC increases linearly from 0% to 100%.
- Represents energy being stored in the battery.
- Ends at Full Charge (100%).

Discharging Curve (Red)

- SOC decreases linearly from 100% to 0%.
- Represents energy being drawn from the battery.
- Ends at Full Discharge (0%).

Dashed Lines

- Green Line: Indicates fully charged state.
- Black Line: Indicates fully discharged state..

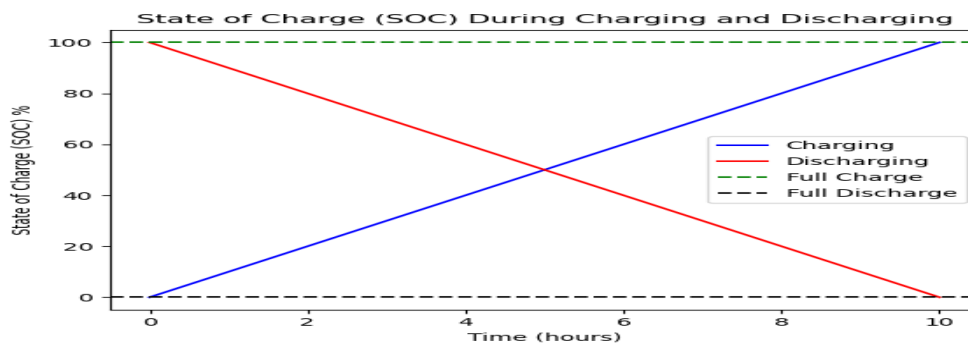


Figure 4. 1 SOC(%) vs Time (Hr)

4.4 Battery Parameters

Parameter	Value
Number of cells in series	16
Voltage Per Cell	3.2 V
Rated Capacity	80AH
Charging SOC	0.5C
Discharging SOC	1C
Initial State of Charge (SOC) / State of Charge	39.99
Threshold Value(T_H)	40

Table 4.2 Battery Parameter Designations

4.5 Simulation and Results

First Simulation

4.5.1 Charging Batteries Without CC-CV Control

There are a number of negative consequences of charging a battery without using the Constant Current- Constant Voltage (CC-CV) control method, especially for lithium-ion batteries, which are frequently used in contemporary gadgets. The following are the main repercussions of avoiding this control strategy:

Possible Repercussions of Charging Without CC-CV Management .

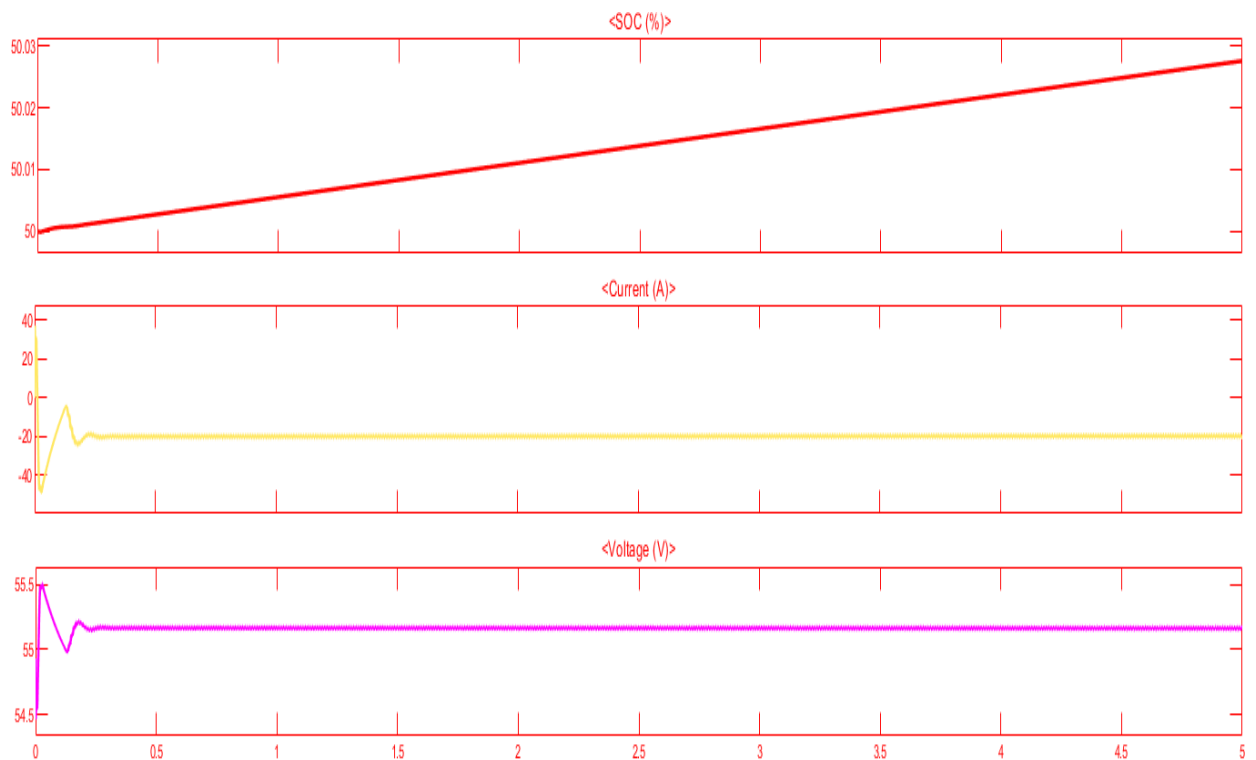


Fig 4.2 Charging of a battery without CC-CV control

4.5.2 Charging Batteries With CC-CV Control

Simulation: CC-CV Control for Battery Charging

Phases of Charging . There are two separate stages to the CC-CV method:

(i) Phase of Constant Current (CC)

The battery is charged with a steady current throughout this first stage until it hits a preset voltage threshold, usually the highest voltage the battery can withstand safely (4.2 V for lithium-ion batteries, for example). Because the current is constant, quick charging is

possible without going over the battery's thermal limits. This stage is essential for rapidly charging the battery to almost full capacity.

(ii) Constant Voltage (CV) Phase

The charger transitions to constant voltage mode when the battery voltage hits the predetermined threshold. As the battery gets closer to full charge, the charging current progressively drops while the voltage remains constant during this phase.

(iii) CC-CV Charging Advantages

Efficiency: Fast charging is made possible by the CC phase, which is especially useful in situations where time is of the essence, like in electric cars and portable electronics.
Safety: The technique successfully avoids overvoltage situations that could cause battery damage or safety risks including thermal runaway by switching to CV mode.

This block implements the CC-CV algorithm in constant-current and constant-voltage modes. This figure shows the operation of these modes:

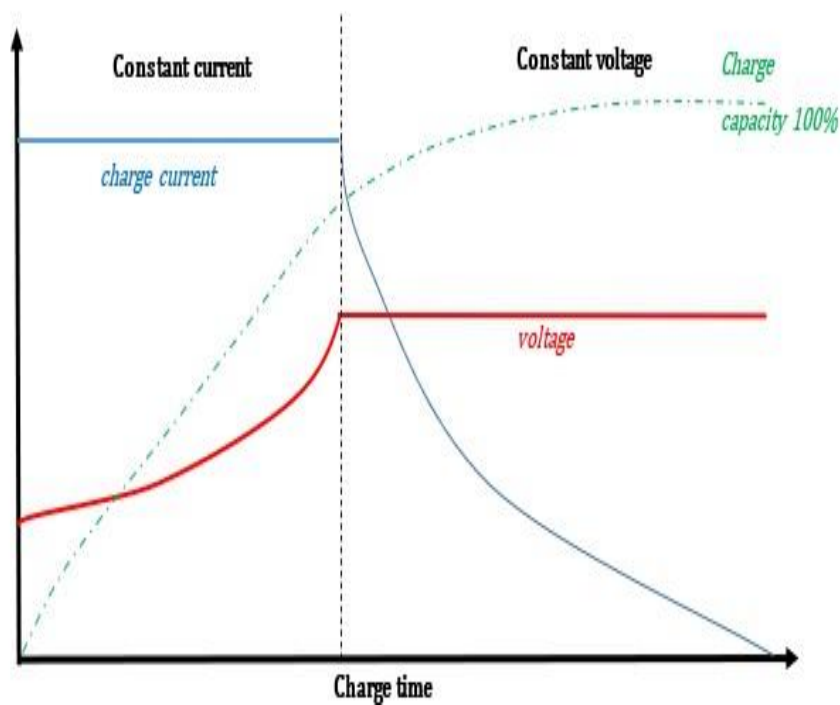


Figure 4.3 : CC-CV CURVE

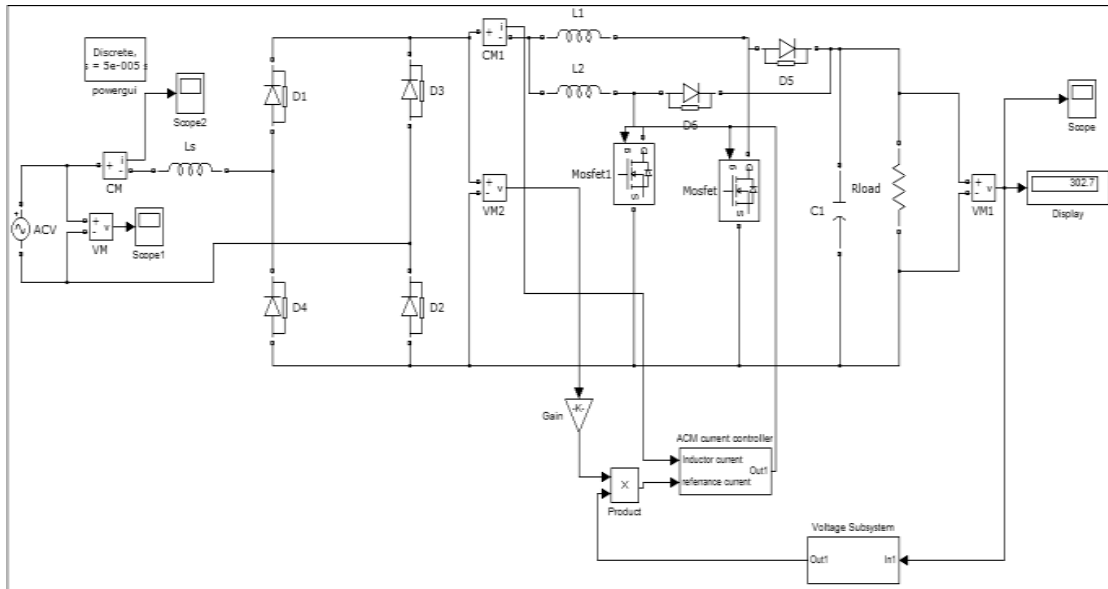


Fig 4.4 Simulink Model of 2 phase IBC

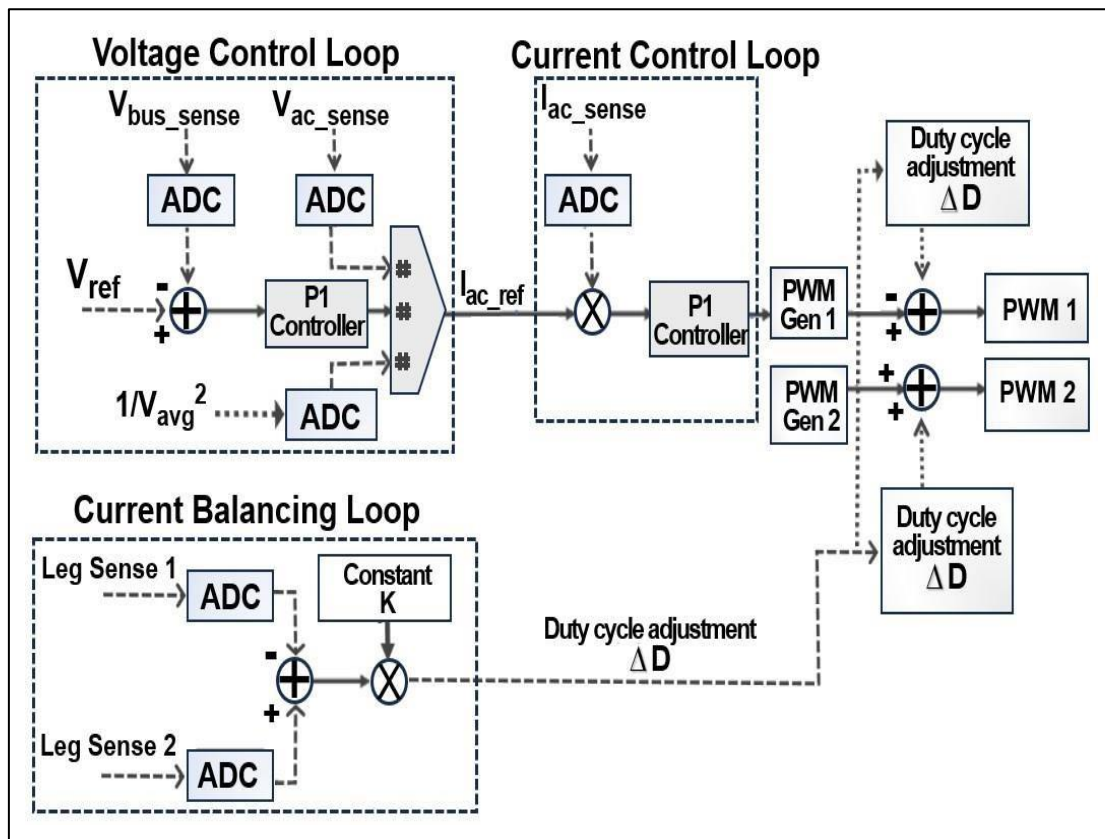


Fig 4.5 Control loop model

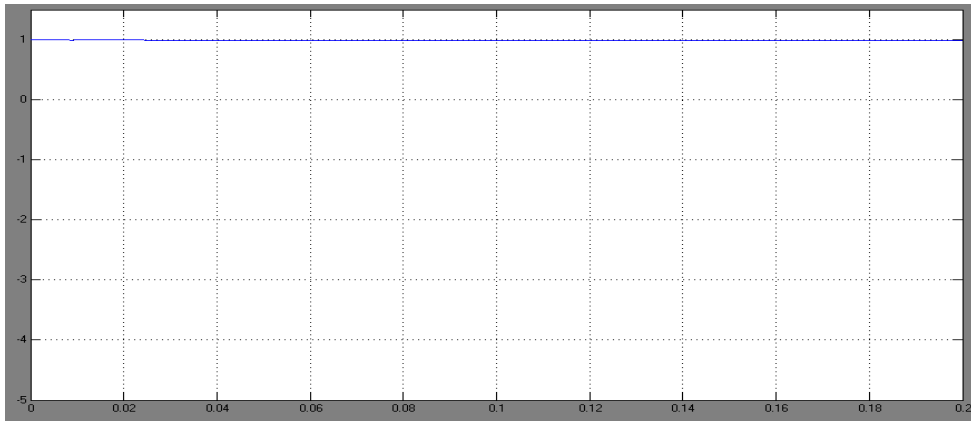


Fig 4.6 Input Power factor

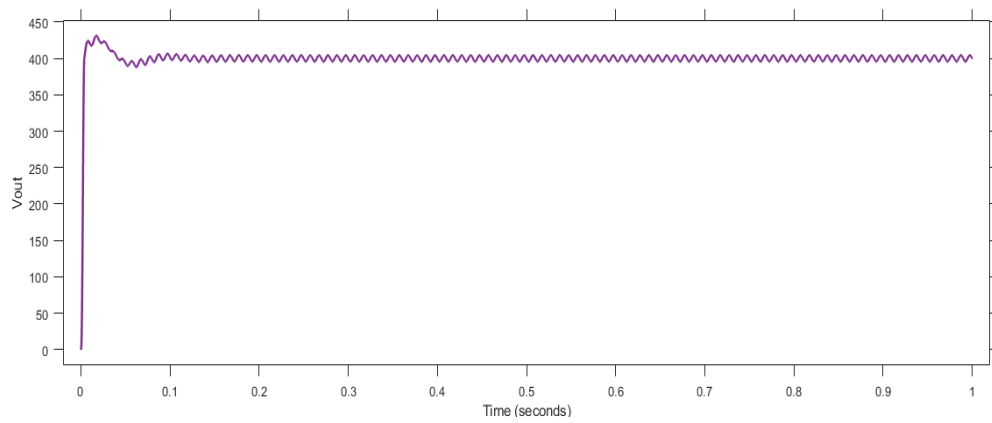


Fig 4.7 Output Voltage Waveform(IBC)

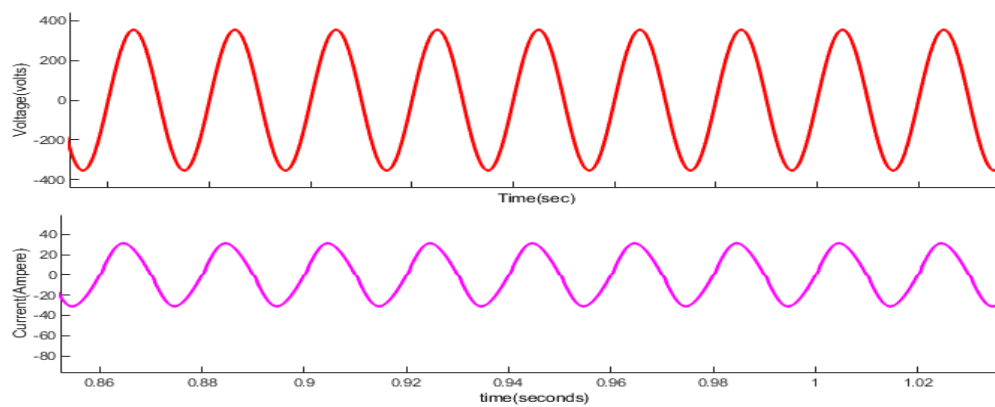


Fig 4.8 Input current and voltage waveforms (IBC)

Figure 4.9 is the matlab circuit of DAB converter, showing two H-bridges with 8 controlled switches 2 for each leg, with having both input and output side Capacitance filter to ensure smooth input and output voltage.

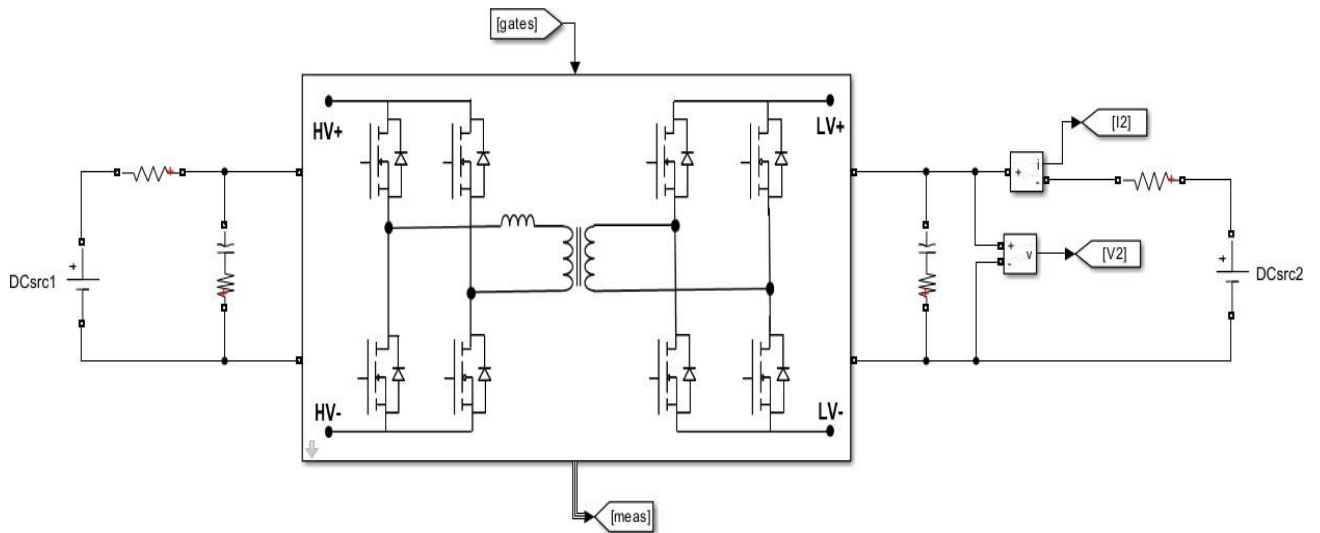


Figure 4.9 Simulink model of Dual Active Bridge

Figure 4.10 shows the control strategy used in the DAB converter , a PI loop is used to find the current error this error is now used to control phase difference between the input side voltage and output side voltage and then pulse generator is used which contains the function to calculates relation between pahse and the gate pulse which then are fed to the switches.

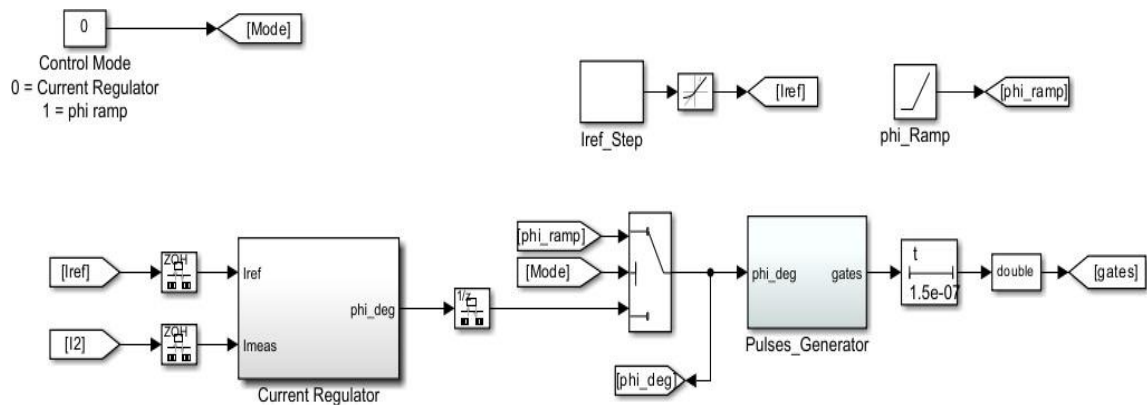


Figure 4.10 Control strategy of Dual Active Bridge

Figure 4.11 shows the respective waveforms of the simulation results, (a) shows the variation of phase and how the variation of phase shows the change in power flow (b) from primary to secondary side of the DAB along with the current flow (c) in both the cases.

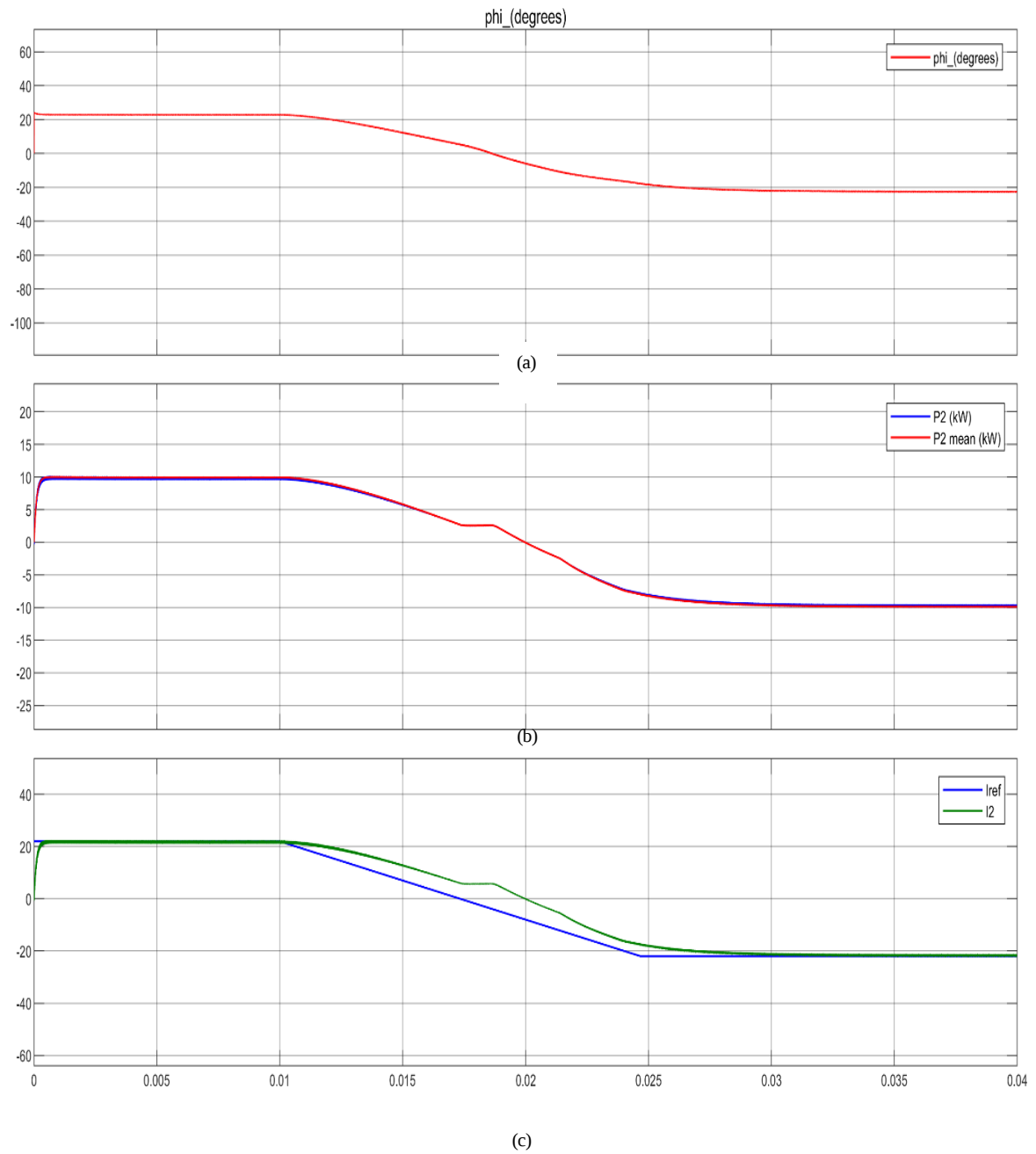


Figure 4.11 Phase variation (b) Power transferred (c) output Current

Figure 4.12 shows the primary and secondary voltages and the inductor current in DAB converter and how the difference in voltages and the phase difference causes the inductor current to follow this pattern

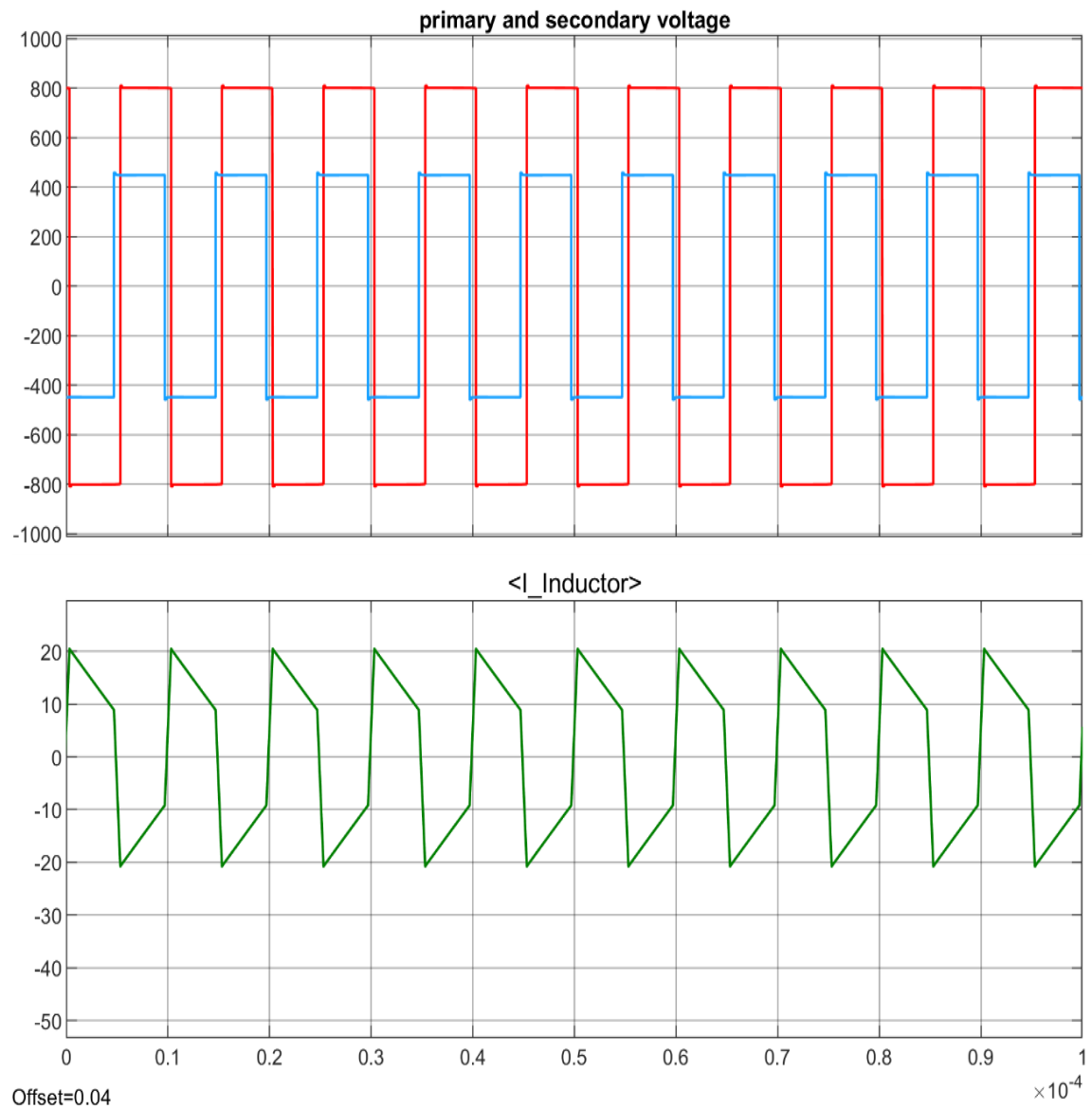


Figure 4.12 Primary voltage secondary voltage and inductor current

Figure 4.13 and 4.14 represents constant current and constant voltage charging, during constant current charging , current remains constant where as voltage increases just like a ramp signal , on the other hand during constant voltage charging , voltage remains constant where as current decreases .

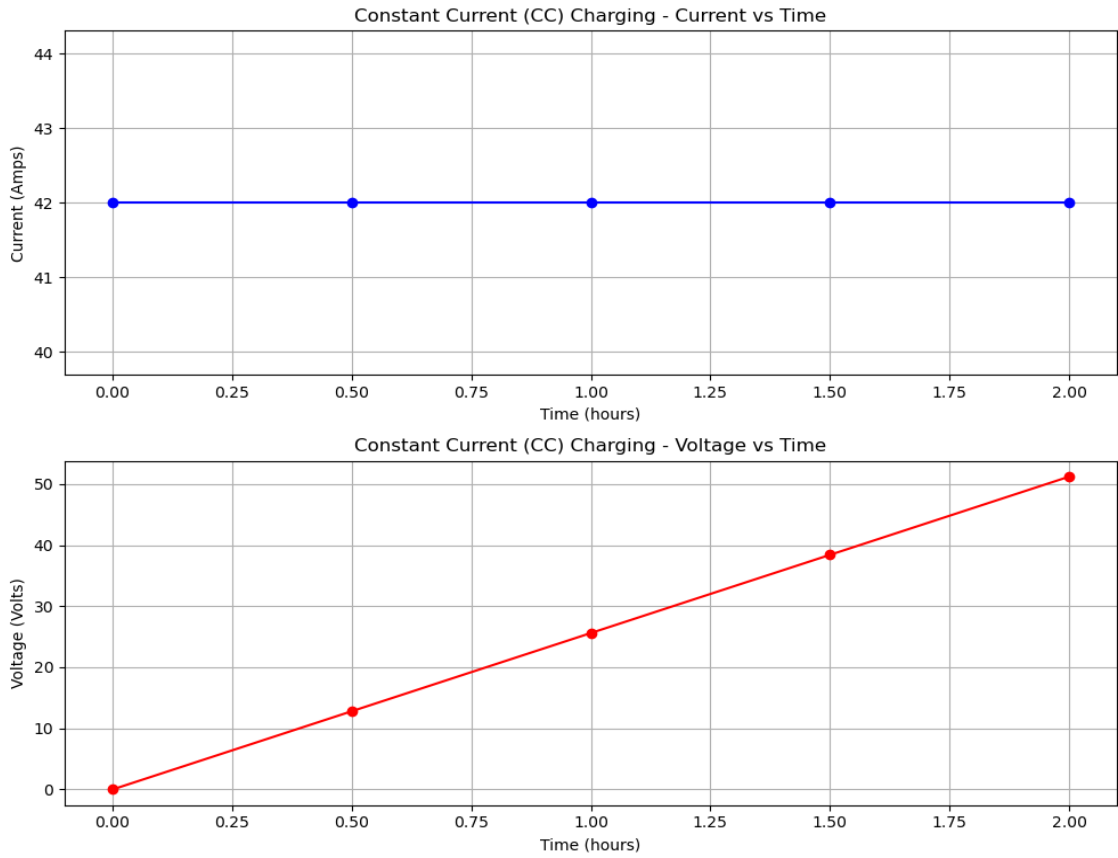


Fig 4.13 Constant Current Charging

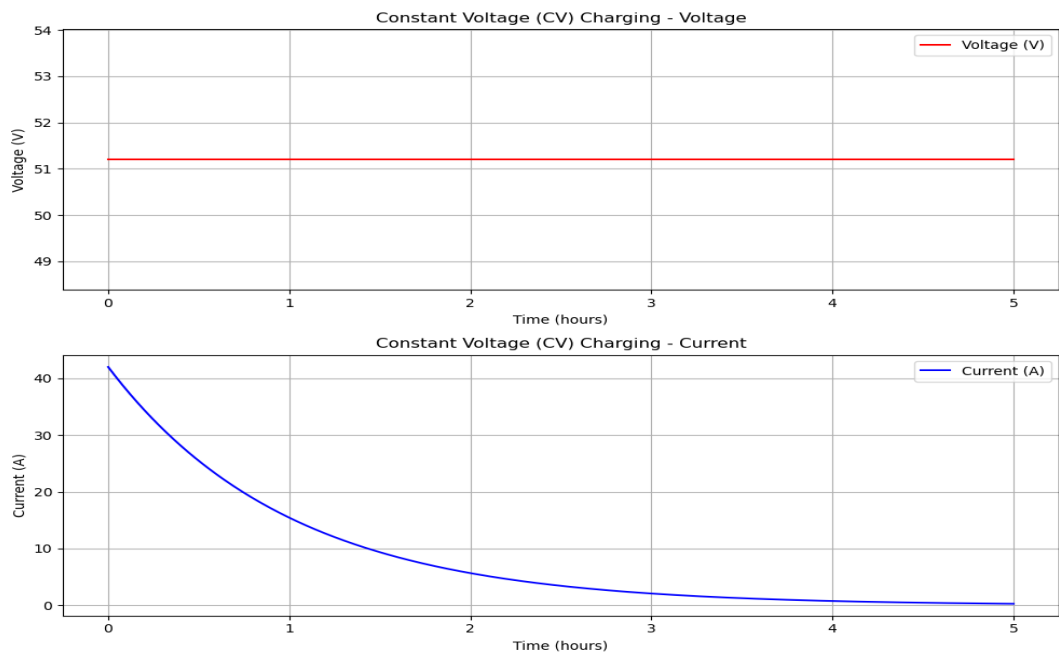


Fig 4.14 Constant Voltage Charging

Figure 4.15 represents both Constant Current and Constant Voltage charging , during initial phase battery charges with constant current after that, battery charges with constant voltage.

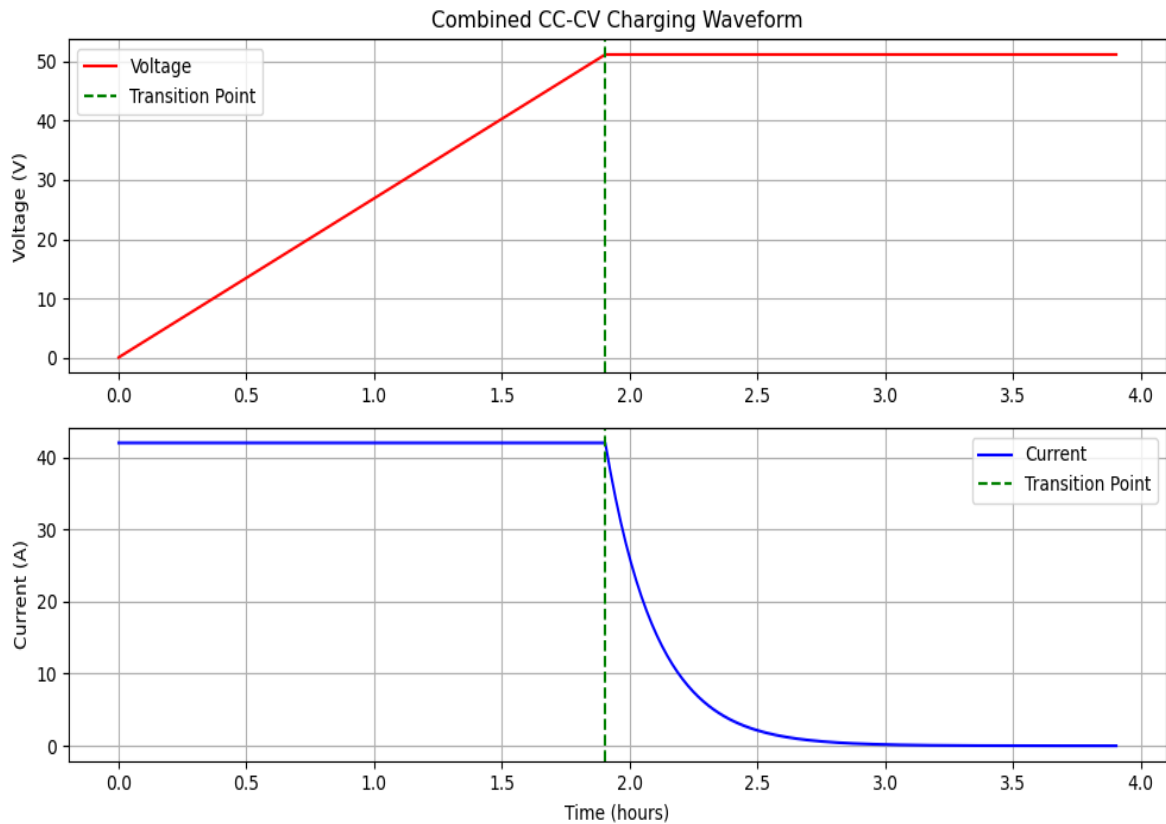


Fig 4.15 Constant Current – Constant Voltage Charging

4.6 Conclusion

This Chapter includes all the Circuit diagrams , waveforms and simulations which are required for CC-CV charging .Although , we are using three wheeler Electric Vehicle Battery Charger . Prior to this charging methodology , we come to know that lifespan of battery degraded heavily if we don't use CC-CV charging , but if use this charging type , life-span of battery increases and battery gets charged in more efficient way .

First our battery charges with Constant Current mode , then it charges to Constant voltage mode . During Constant Current mode , Current remains constant and during Constant Voltage charging , Voltage remains constant .

CHAPTER 5

MAIN CONCLUSION AND FUTURE SCOPE OF WORK

5.1 Main Conclusions

The Interleaved Boost Power Factor Correction Circuit (2 phase IBC) discussed in this Thesis . This 2 phase IBC used widely in Electric Vehicle Battery charging . However , There are other topologies too, which are also discussed in this Thesis . But , Interleaved Boost PFC stand out to be the best than the other PFC's available . Although there are 2 boost converters are connected in parallel, due to which ripple in inductor current further reduces as compared to Boost PFC Electric Vehicle battery charging .Also , not only input ripple current reduces but output voltage ripple also reduces and output settles to desired 400 Volts in lesser time as compared to Conventional Boost PFC .It is little bit complex due to some complex circuitry , but it comes out be the best than other PFC's in terms of efficiency , Input and Output voltage ripple , Input and Output Current ripple. My next chapter was all about DAB , It's bidirectional way of charging makes it a suitable DC-DC converter for EV battery charging . DAB's isolated nature , and Single phase shift technique for power flow in DAB converter while phase shifting between the primary and secondary sides of transformer . This Thesis also contain various switching states , waveforms , Circuit analysis of DAB . Next chapter was all about how we charge our battery under CC-CV charging ,it's waveform and analysis have been discussed in this thesis .

5.2 Future scope of work

In this Thesis , we have used Interleaved boost PFC with 2 phases. We can also use more than that like 3,4 . If we use more than 2 phases , current and voltage ripple further reduces . We can also use Totem-Pole PFC in place of Interleaved Boost PFC ,as Totem-Pole PFC is also a power factor correction circuit for EV battery charging . Next thing is that we have used DAB converter as a dc-dc converter ,It's performance can also be improved by using ZVS scheme for all switches used in this converter .If we do so with the help of wide-band gap technologies to further increase the efficiency and overall size of converter. We can also use Phase Shift full Bridge converter (PSFB) in place of DAB . As PSFB contains only 4 switches and 4 diodes , it's controlling will be little bit less complex as compared to Dual active Converter which contains 8 switches . There is also a further scope of Multi-Port connection topology due to presence of transformer present in the DAB Converter .

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