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CHAPTER 1

Electric vehicles (EVs) are becoming increasingly practical, as demand for fossil fuels is sharply rising.. To instil confidence in drivers for long-distance travel, various battery technologies are being proposed, and chargers are being developed in diverse forms and sizes. The charging infrastructure is evolving daily to keep pace with the rapid growth of EVs, ranging from off-board chargers and battery swapping to DC fast charging. The technology in electric vehicle charger has advanced abruptly, leading to higher energy efficiency and faster charging times.

Modern charger are equipped with BMS that allow for remote access to charging. Some feature cutting-edge Vehicle To Grid (V2G) technology that can re-turn power to the Large grid when the vehicle is in idol, thus helping to balance the load demand on the grid.

1.1 Comparison of IC Engine and Electric Vehicle

Both ICE vehicles and EVs offer unique way to approach at leisure transprtation, each with own set of good and bad. Ice vehicles, which has dominated market until recently, operate on the principle of converting chemical energy into mechanical energy through combustion engine. They benefit from a well-established fuel station infrastructure, a wide variety of models, and easily accessible fuel stations. Additionally, ICE vehicles typically offer a higher driving range and require less time to refuel. However, a significant drawback is their substantial contribution in polluting the air and change in climate due to the emission of toxic pollutants and increase in global warming. Further, continuous depletion of petroleum products and their rising prices are major concerns towards use of EVs.

Conversely, EVs are becoming more popularity as a clean, sustainable and reliable alternative, powered by rechargeable batteries and electric motors, resulting in zero tailpipe emissions. This shift leads to better quality in air and reduced reliance on conventional fuels. EVs also provides smooth and quiet drivng experience with instnt torque with quick acceleration. Although the purchase price of EVs is relatively high, they tend to be more economical over time compared to ICE vehicles.

1.2 Hybrid Electric Vehicle vs. Electric Vehicle

Although they use different technology in working but the idea is same for the both hybrid EVs and EVs is to lower the emission of harmful gases and making a greener environment. A schem. diagram of EVs & HEVs is shown in Fig. 1.1.

Mostly All-electric vehicles take exclusively electricity as fuel are known as electric vehicles, or EVs. They are powered by batteries with recharging capabilities and move by electric motors. Electric cars have nil exhaust emissions, which reduces air pollution and greenhouse gas emissions. This has a major positive ecological impact. However, EVs can be challenging to recharge on lengthy excursions and in areas with a lack of charging stations because they typically have a small driving range and require frequent access to a charging infrastructure. HEVs are made up of an electric motor, battery system, and IC engines. Minimizing emissions and maximizing fuel efficiency are the two main objectives of HEV design.

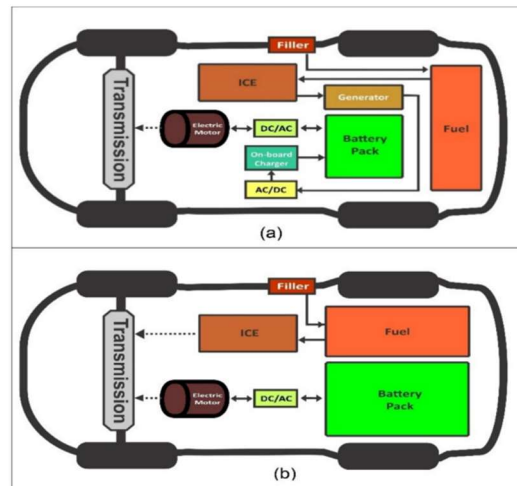


Fig 1.1: Schematic Diagram of BEV and HEVs

When more power is needed or at higher speeds, the ICE powers the vehicle, while motor helps with low-speed driving and initial acceleration. Compared to conventional cars, hybrid electric vehicles (HEVs) produce less pollution and use less gasoline because they may operate entirely on electricity in certain situations. They also remove the limit on the range pertaining to fully EVs as the internal combustion engine picks up when the battery is depleted. However, as hybrid electric cars (HEVs) still run mostly on fossil fuels, their ability to cut emissions may be limited compared to fully electric cars.

1.3Chargers 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,

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.

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.

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 displays about the overall architectural block diagram of a charger.

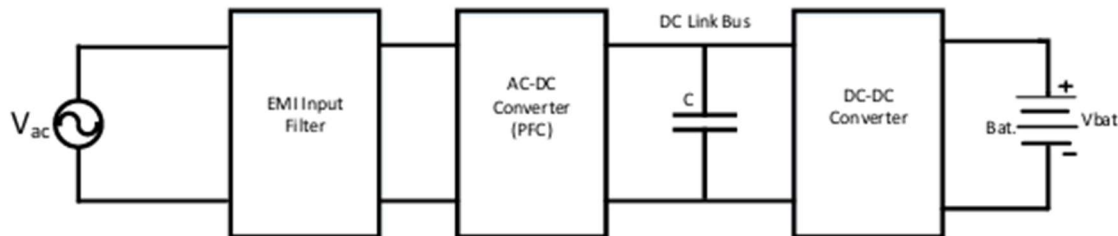


Figure 1.2: Topology of Charger Circuit

1.4 Battery Technology

Selecting a particular type of battery for our Electric vehicles is a very crucial task as generally battery costs the half of the whole vehicle itself hence to make the vehicles more effectively priced in the market and for what purpose the vehicle will be used, the battery selection should be taken into consideration with utmost importance.

In selecting a battery there are some requirements that must be fulfilled for example energy and power, energy density, operating temperature, self-discharging rate, number of the life cycle, cost, efficiency and environmental adaption. Keeping these parameters into mind battery can be divided into 4 categories:

- I. Lithium-ion Battery
- II. Lead-acid Battery
- III. Nickel-Metal Hydride Battery
- IV. Ultra capacitors

1.4.1 Lithium-Ion battery

Lithium-Ion battery have become industry standard in rechargeable batteries technology Because of their lengthy life cycle, high energy density, and lightweight design. Those batteries have their cathode made of lithium cobalt oxide or lithium iron phosphate[2] or other lithium compounds the anode is usually made of graphite electrolyte[2] is generally a lithium salt dissolved in organic solvent, a separator which is micro-porous membrane is used which prevents the direct contact between anode and cathode.

Lithium-ion has several advantages such as greater energy density providing high energy per unit weight and volume. Low self-discharge rate longer charge cycle .But there are some disadvantage of using lithium ion battery such as thermal runaway, limited amount of lithium and cobalt deposits in the world causing the lithium battery to be more costly than others.

1.4.2 Lead Acid battery

These are the oldest technologies present in rechargeable batteries and are mainly used in automotive and industries due to their reliability and less buying cost. In their design the cathode is made up of lead dioxide and anode is made up of sponge lead and electrolyte is made of dilute sulphuric acid [3]. Reasonably priced to manufacture and acquire, reliable technology has a long history of use. Because they can provide large surge currents, they are appropriate for applications involving engine starting. Some disadvantages are, heavier and more voluminous than contemporary Li-ion batteries. Shorter lifespan in terms of cycles of charging and discharging. Some kinds need to have their electrolyte levels checked on a regular basis. Recycling lead can be dangerous because it is poisonous. These batteries are generally used in car batteries, renewable systems, off grid backup power systems.

1.4.3 Nickel-Metal Hydride (NiMH) battery

NiMH battery is a famous kind of rechargeable battery found in hybrid cars and consumer devices. They stand on a middle ground between lead-acid battery durability and Li-ion battery high density of energy. The battery construction is as follows: the cathode is made up of Nickel oxyhydroxide, anode is made of Hydrogen-absorbing alloy and electrolyte present is potassium hydroxide. Advantage of NiMH battery is that higher energy capacity in comparison to batteries made of nickel-cadmium (NiCd) less harmful metals are present than in lead-acid and nickel-cadmium batteries. Rechargeable several times. However they suffer from faster rate of self-discharge than Li-ion batteries. May have decreased capacity (albeit less severe than in NiCd batteries) if not completely depleted before recharging and more costly than batteries made of lead acid. These batteries can be used in AA and AAA batteries, cordless power drills and other portable devices.

1.5 Ultracapacitors or Supercapacitors

Supercapacitors, another name for ultracapacitors, are energy-storage devices that rely less on chemical reactions and more on electrostatic forces. In comparison to normal batteries they have quick charge/discharge times and have very high power density. The electrodes are made up of activated carbon or high surface area material and electrolyte is taken such that it has adequate ion conductivity and the separator is material that allows ions to pass through it without allowing electrical conductivity between the electrodes. They are very efficient with minimal energy loss during charging or discharging cycle. Quickly delivers and absorbs high currents; operates well throughout a wide temperature range; may be charged and discharged in a matter of seconds; and can be cycled for hundreds of thousands to millions of times without experiencing significant deterioration. The main disadvantage is that compared to batteries, it holds less energy per unit weight or volume. More expensive per watt-hour than batteries. These ultracapacitors can be used in short term backup power, providing burst of power in electrical and mechanical system, can help with the levelling of voltage fluctuations.

1.6 Modelling of Battery

Figure 1.3 shows the analogous circuit model, Is a typical electrical representation of a li-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 model:

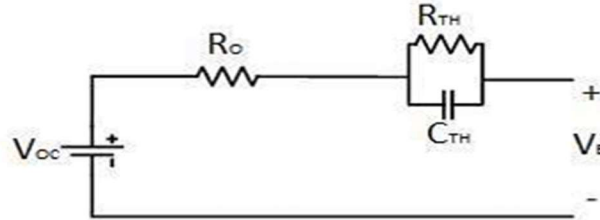


Figure 1.3: Equi. circuit of li-ion Battery

1.6.1 Voltage of open circuit (VOC):

This is the battery's voltage in the absence of any current. State of soc of the battery play a major role & is often ascertained by measurement or calibration.

1.6.2 Internal Resistance (Rth):

The internal resistance present in the battery is what prevents current from flowing through it. It encompasses a range of resistance sources, including contact resistance, electrode resistance, and electrolyte resistance. Within the battery, internal resistance results in power losses and voltage drops. The internal resistance in this model is explained by both the polarization resistance (R_{TH}) and the ohmic resistance (R_O).

1.6.3 Internal Capacitance (Cth):

The battery capcity to hold and release charge is represented by capacitance. It explains the intercalation capacitance and the double-layer cap. at the electrode-electrolyte interfrence

1.6.4 Operating voltage of the Battery (VB):

It indicates operating voltage of battery that is battery is connected to a source or acting as a source.

1.7 Charging and Discharging Characteristics of Battery

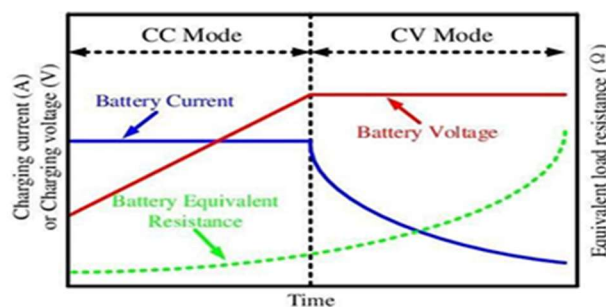


Figure 1.4: Characteristics

When charging li-ion batteries, the const crnt and const volt (CC and CV) mode is often used. The performance of a one lithium-ion cell in charging at a specified voltage (VDC) of a cell is shown in Figure 1.4. The charging process can be divided into four noteworthy stages [5]. The main point denotes the switch from the Const crnt to Const Volt charging mode and the rated value indicates when the battery acquires a stable state. When the cell is exhausted, the voltage falls below its nominal rating. The battery is first charged using a const current operation until it reaches the kink point, at which point its voltage must be increased to its nominal value and is at a 100% state of charge (SoC). Hence the charging of battery is done in const voltage until the charging current falls to an appropriate level.

The efficiency and durability of electric vehicle (EVs) and other Vattery-powered devices are highly dependent on battery health. You can tell if a battery is healthy by looking at these important metrics:

1.7.1 State of Charge (SoC):

It is defined as its present charge level as a percentage of its maximum capacity. It helps customers plan charging and usage by indicating the quantity of energy left in the battery. To prevent battery damage, accurate system-of-charge monitoring is necessary to avoid overcharging or deep discharging.

1.7.2 State of Health (SoH):

SoH is a measure of the overall condition of battery relative to its initial condition upon purchase. The standard unit of measurement is the percentage, with 100% indicating the initial capacity and performance of the battery. Charge cycles, temperature fluctuations, and aging are some of the processes that cause SoH to decrease with time. Capacity and efficiency are both diminished with a decreased SoH.

1.7.3 State of Power (SoP):

SoP is a measure of a battery's maximum power output that can be displayed at any given moment. The internal resistance of the battery, temperature, and current state of charge are some of the variables that affect it. The SoP can be negatively impacted by low temperatures or high internal resistance, which in turn affects the device's performance.

1.7.4 Energy Storage Capacity:

Measured in Ampere-hours (Ah) or Watt-hours (Wh), quantity of energy stored in battery . The quantity of energy that a battery can store and release decreases as its capacity deteriorates over time as a result of being charged and discharged multiple times.

1.7.5 Resistance from Within:

The barrier to current flow within the battery is known as internal resistance. Greater heat generation and energy loss might result from higher internal resistance, which in turn reduces efficiency and performance. It worsens the battery's capacity to swiftly supply power as it ages and is used more frequently.

1.7.6 Cycle Life:

The battery life cycle is the amount of times it can be fully charged and discharged before losing some proportion of its initial capacity, usually about 80%. While significant discharges can reduce a battery's cycle life, a longer cycle life implies a more robust battery.

1.7.7 Battery Temperature:

Battery performance and lifespan are greatly impacted by temperature. Batteries are susceptible to degradation, decreased efficiency, and accelerated aging when exposed to extremely hot or cold temperatures. Optimal battery health is achieved by proper temperature management.

1.7.8 Battery Voltage:

Both the system on a chip (SoC) and the load on the battery affect its voltage. It is possible to estimate SoC and make sure the battery is operating within safe limits by monitoring the voltage. Both low voltage and high voltage can shorten the life of a battery.

1.7.9 Rates of Charging and Discharging:

Charge and discharge rates, abbreviated as C-rates, have an effect on the life of a battery. An increase in stress, which in turn increases heat and speeds up degradation, can be caused by high C-rates. To keep batteries in good condition, it's best to charge and discharge them at moderate rates.

1.7.10 The rate of self-discharge:

When a battery is not being used, its charge slowly drains away, a process known as self-discharge. The condition or quality of the battery may be compromised if its self discharge rate is excessively high. It changes as the battery ages and the temperature changes. The health, safety, and longevity of batteries in a variety of applications—and EVs in particular—can be better managed with an understanding of and adherence to these principles. The performance and lifespan of your battery can be greatly improved with regular maintenance and following recommended usage guidelines

1.8 Objectives of the Present Work

Objective of this thesis is to design and analyze EV chargers, one isolated and other non isolated topology in order to implement them in low powered electric vehicles. This thesis also explains the design of both of the chargers and the control mechanism related to it. A brief summary of the work is as follows.

- I.** For non-isolated charger the topology used is a Modified version of the traditional SEPIC converter is taken into consideration. The SEPIC converter is modified by using switched capacitance circuit and using 3 switches to incorporate bidirectional functionality, the use of switched capacitance ensures that the converter's component size is decreased and hence decreasing the cost.
- II.** For isolated charger, the topology that is studied is Dual Active Bridge (DAB) converter. The DAB converter uses a transformer and a primary side bridge and a secondary side bridge which then uses phase shift techniques to transfer power from

primary side to secondary side, the phase shift technique being used here is single phase shift (SPS) technique.

- III. All the design calculations of both Modified SEPIC and DAB are done in a single chapter along with the matlab simulations, the simulation shows waveforms of respective voltages, currents, ripples in them voltage stress present in the switches and components.

1.10 Outline of Thesis:

Chapter 1:- In this chapter, a comprehensive overview to Electric Vehicles and their technology giving information on the importance of a feedback structure. It also tells about the charging levels and battery charging characteristics

Chapter 2:- A Bidirectional Charger topology has been explained in the chapter. The Modified-SEPIC DC-DC converter being used for low powered EVs with switched capacitance inclusion to decrease the size of component use and better control strategy for both G2V and V2G power flow.

Chapter 3:- This chapter considers the design of Dual Active Bridge converter working in single phase shift (SPS) mode

Chapter 4:- This chapter presents the design and mathematical calculations and matlab Simulink simulation results.

Chapter 5:- This chapter, the main contribution in the thesis are summarised. Also this thesis highlights the possibility for further study opportunities and summarizes the contributions made by this thesis.

1.11 Conclusion

This thesis begins with an overview of the key differences between internal combustion engines (ICEs) and electric vehicles (EVs) in Chapter 1. Moreover, a succinct description of electric vehicles (EVs) and hybrid electric vehicles (HEVs). The progress in electric vehicles (EVs) and hybrid electric vehicles (HEVs) has resulted in the acceptance of high voltage Lithium-Ion battery packs for fuel. The potential benefits of using Li-ion batteries also understanding charging profile referred to as constant current and constant voltage mode, as advocated by battery makers. Moreover, an exhaustive elucidation of the battery's comparable electrical model is described. The literature review also categorises EV chargers according to their power levels and further subdivides into power requirements and availability. The section additionally examines previous research on EV chargers and their corresponding converters. The EV charger layout includes a Basic Block diagram is made of a PFC unit as a front end converter with a suitable rating DC-DC converter as a backend converter.

CHAPTER 2

MODIFIED SEPIC CONVERTER FOR LIGHT-WEIGHT EV BATTERY

2.1 Introduction

7 A SEPIC (Single-Ended Primary-Inductor Converter) is a DC-DC converter that steps voltage up, down, or keeps it the same, unlike buck-boost converters, it doesn't invert output polarity and uses two inductors, two capacitors, a switch, and a diode for energy transfer, offering advantages like low input ripple and stable output for varying inputs, making it great for solar panels or battery applications.

2.2 Features & Operation

- **Non-Inverting Buck-Boost Capability:** The SEPIC output voltage is non-inverted relative to the input, allowing values greater than, less than, or equal to the input voltage. Apply SEPIC when non-inverting voltage output and true shutdown mode are mandatory in battery-based applications.
- **Fourth-Order Dynamics:** It is a fourth-order system because of having two inductors and two capacitors. Closed-loop stability becomes much harder in fourth-order systems compared to second-order systems such as buck and boost topologies. Employ current-mode control with Type II and III compensations for right-half-plane zero and resonant coupling capacitor pole respectively.
- **Protection Against Fault Conditions:** With the use of a series coupling capacitor in the input and output lines, there is inherently a short-circuit protection in SEPIC. Utilize this unique characteristic in automotive and industrial applications where fault-tolerant loads exist.
- **Voltage Conversion Ratio of $D/(1-D)$:** As an equation, the ratio of output to input voltage in continuous conduction mode is $D/(1-D)$ which is exactly the same as the buck-boost converter. Thus, with the same duty ratio range, step-up and step-down modes will operate. Design according to D_{max} under $V_{IN(min)}$.
- **Use of Mutual Inductance to Decrease Size of Inductors:** Inductors L_1 and L_2 can share a common core, resulting in lower PCB real estate and cost. Due to mutual inductance, the amount of inductance per turn is half. In order to determine the value of each, apply $L_1' = V_{IN(min)} \times D_{max} / (2 \times \Delta L \times f_{sw})$. However, you need to add snubber circuits to protect against the large spikes of leakage inductance.
- **Output Current Pulsation:** Unlike Cuk converter, the output current of the SEPIC converter is pulsed rather than continuous which requires larger output capacitance or addition of extra filters. Add a pi or LC filter after the SEPIC circuit if your output load is a radio frequency transceiver.
- **Role in Power Factor Correction Circuits:** SEPIC based bridgeless power factor correction converters have been reported to achieve better performance in terms of

power factor and reduced conduction loss. They find their place in EV chargers and LED drivers among other applications. Use SEPIC PFC circuits in single-phase AC to DC converters with inputs of 120V and 240V with IEC 61000-3-2 compliance.

- **Advantages with Wide Bandgap Semiconductors:** With SiC and GaN semiconductors, SEPIC converters can take advantage of low losses at high frequencies to decrease the size of passive components. Use GaN-based devices for high-frequency (>500kHz) SEPIC converters to reduce inductor size by up to 40% to 60%.
- **Energy Management in Three-port Converters:** SEPIC-based three port converters are suitable in handling the simultaneous PV solar input and battery bank. Utilize SEPIC based circuits in DC microgrids where the source voltage is around the bus voltage.
- **Interleaved and Soft-Switching Extensions:** By employing an interleaved structure, the SEPIC converter can mitigate input/output ripple and evenly distribute thermal stress. Using ZVS and ZCS approaches, multi-phase SEPIC converters will operate with efficiencies over 95%. Choose SEPIC interleave structure when currents exceed 5A in order to decrease per phase RMS values.

2.3 Historic Development and Topologies origins

- The birth of the SEPIC topology took place during the development era of DC-DC switching converters which took place in the 1970s and 1980s. The term Single-Ended Primary-Inductor Converter was chosen due to the structural relation between this type of converters to the flyback circuit which in return is an isolated version of buck-boost converter. SEPIC topology is similar to a cascade structure of a boost converter and an inverted buck-boost topology using the coupling capacitor. It was formally defined by Ray Ridley among others in his paper explaining the theory of operation by applying State Space Averaging developed by Slobodan Cuk at Caltech in the late 1970s.
- The Cuk converter which was invented by Dr. Slobodan Cuk in his PhD dissertation published in 1977, had the same fourth-order characteristics of the SEPIC converter. However, the path of energy flow takes another route through the coupling capacitor yielding a negative voltage output. SEPIC, on the other hand, is complementary to this circuitry with only a few adjustments on the positions of diodes and inductors, resulting in a positive output voltage. Therefore, the use of SEPIC was evident for applications requiring positive outputs.
- As far as the SEPIC converter references, the one by Texas Instruments (AN-1484) is considered to be canonical for SEPIC designs. Published in May 2006 and then revised in April 2013, this technical report offers a detailed explanation of the component sizing equations as well as a fully designed example for designing a 3.0-5.7V input to 3.3V/2.5A output SEPIC converter. The theoretical analysis of the transfer function of the SEPIC converter was offered by Dr. Ray Ridley in the article titled "Understanding the Small-Signal Behavior of the SEPIC Converter" published in Power Systems Design Europe in November 2006. Since then, the SEPIC topology has received much attention in applications such as battery management systems, LED driving, automotive electronics, and power factor correction. The comprehensive study done by Ahmed et al. published in Results in Engineering in 2025 gives a complete overview of the SEPIC topology in the last two decades.

2.4 Circuit Topology and Operating Principles.

Basic Topology and Component Functions

- The basic circuit topology of the SEPIC converter comprises of seven components; two inductors (L_1 and L_2), a coupling capacitor (C_s), a MOSFET switch (Q_1), a diode (D_1), output capacitor (C_{out}), and input capacitor (C_{in}). The distinguishing feature of the coupling capacitor is the capability of transferring the energy between input and output while blocking DC current to ensure fault-tolerant short-circuited loads. At steady-state condition of continuous conduction mode, the average voltage across C_s will equal V_{IN} since it connects the input side with the switch-drain line and thus DC voltage across it balances.

- **Switch-On Interval (MOSFET Conducting)**

When the MOSFET Q_1 turns on, current flows through L_1 from the input source, storing energy in L_1 's magnetic field. Simultaneously, the coupling capacitor C_s discharges through Q_1 and L_2 , increasing the current magnitude in L_2 and storing energy in L_2 's magnetic field. During this interval, the output diode D_1 is reverse-biased, and the load is supplied entirely by the output capacitor C_{out} . The drain-to-source voltage of Q_1 is approximately zero during the on-time. The inductor currents I_{L1} and I_{L2} both increase linearly with slopes determined by V_{IN}/L_1 and V_{IN}/L_2 respectively (assuming $V_{L1} = V_{L2} = V_{IN}$ during the on-time).

- **Switch-Off Interval (MOSFET Non-Conducting)**

When Q_1 turns off, the energy stored in L_1 and L_2 is transferred to the output through diode D_1 . Current from L_1 flows through C_s (charging it) and D_1 to the output, while current from L_2 flows through D_1 to the output, recharging C_{out} and supplying the load. The drain-to-source voltage of Q_1 equals $V_{IN} + V_{OUT}$ during the off-time, which determines the voltage rating requirement for the MOSFET. Both inductor currents decrease linearly during this interval with slopes determined by $-V_{OUT}/L_1$ and $-V_{OUT}/L_2$ respectively.

- **Continuous and Discontinuous Conduction Modes**

In continuous conduction mode (CCM), the currents through both inductors never reach zero during a switching cycle. The voltage conversion ratio in CCM is $V_{OUT}/V_{IN} = D/(1-D)$, where D is the duty cycle, assuming ideal components with no diode forward voltage drop. When the diode drop V_D is included, the duty cycle becomes $D = (V_{OUT} + V_D)/(V_{IN} + V_{OUT} + V_D)$. In discontinuous conduction mode (DCM), the current in at least one inductor falls to zero before the end of the switching cycle, and the conversion ratio becomes load-dependent, complicating the control design. The boundary between CCM and DCM depends on the inductance values, switching frequency, load current, and duty cycle. Designers typically select inductance to maintain CCM at minimum load to avoid the mode transition, which can cause output voltage instability.

2.5 Mathematical Modeling and Transfer Functions

- **Steady-State Voltage and Current Relationships**

For CCM operation, the fundamental voltage conversion ratio is:

$$V_{OUT}/V_{IN} = D/(1-D)$$

Including the diode forward voltage V_D :

$$D = (V_{OUT} + V_D)/(V_{IN} + V_{OUT} + V_D)$$

The maximum duty cycle occurs at minimum input voltage:

$$D_{max} = (V_{OUT} + V_D)/(V_{IN(min)} + V_{OUT} + V_D)$$

The minimum duty cycle occurs at maximum input voltage:

$$D_{min} = (V_{OUT} + V_D)/(V_{IN(max)} + V_{OUT} + V_D)$$

These expressions are critical because they define the operating range and the worst-case stresses on all components [ti.com](https://www.ti.com). The input current equals $I_{IN} = I_{OUT} \times (V_{OUT} + V_D)/V_{IN(min)}$ at the worst case, and this value drives the selection of L1's current rating [ti.com](https://www.ti.com).

- **State-Space Averaging Model**

The SEPIC converter is a fourth-order system with four state variables: the two inductor currents (i_{L1} , i_{L2}) and the two capacitor voltages (v_{Cs} , v_{Cout}). The state-space averaging technique, formalized by Middlebrook and Cuk, derives separate state equations for the switch-on and switch off intervals, then weights them by D and $(1-D)$ respectively to produce an averaged model or the on-interval (switch closed, diode open), the state equations are:

$$di_{L1}/dt = V_{IN}/L1 \quad di_{L2}/dt = v_{Cs}/L2 \quad dv_{Cs}/dt = -i_{L2}/Cs \quad dv_{Cout}/dt = -v_{Cout}/(R \times C_{out})$$

For the off-interval (switch open, diode conducting):

$$di_{L1}/dt = -(v_{Cs} + v_{Cout})/L1 \quad di_{L2}/dt = -v_{Cout}/L2 \quad dv_{Cs}/dt = i_{L1}/Cs \quad dv_{Cout}/dt = (i_{L1} + i_{L2})/C_{out} - v_{Cout}/(R \times C_{out})$$

The averaged model is obtained as $dx/dt = D \times A1 \times x + (1-D) \times A2 \times x + \text{perturbation terms}$. This averaged model captures the low-frequency dynamics and serves as the foundation for small-signal analysis ieeexplore.ieee.org digitalxplore.org.

- **Small-Signal Transfer Functions**

Perturbing the averaged model around the steady-state operating point yields the control-to-output transfer function $G_{vd}(s) = v_{out}(s)/d(s)$, which for the SEPIC contains a right-half-plane (RHP) zero, a complex conjugate pole pair from the coupling capacitor resonance, and

the output filter pole. The RHP zero, which also appears in boost and buck-boost converters, imposes a fundamental bandwidth limitation: increasing the crossover frequency beyond approximately one fifth of the RHP zero frequency causes phase margin erosion and potential instability [e2e.ti.com](#). The coupling capacitor creates a resonant dip in the magnitude response at approximately $f_{Res} = 1/(2 \times \pi \times \sqrt{C_s \times (L_1 + L_2)})$, which can introduce additional phase lag near crossover if not properly managed in the compensation design.

Dr. Ridley's analysis showed that current-mode control effectively removes the complex pole pair from the control-to-output transfer function, simplifying the compensation to a single-pole system with the RHP zero as the primary bandwidth limiter. This is a key reason why current mode control is strongly preferred for SEPIC converters. The duty-cycle-to-inductor-current transfer function and the line-to-output transfer function are also derived from the same small-signal model, enabling input feedforward and output impedance analysis.

2.6 Component Design and Selection

• Inductor Design

A widely accepted design rule sets the peak-to-peak ripple current at approximately 40% of the maximum input current at minimum input voltage [ti.com](#). The ripple current in each inductor is:

$$\Delta I_L = I_{IN} \times 0.40 = I_{OUT} \times (V_{OUT}/V_{IN}(\min)) \times 0.40$$

The inductance value for uncoupled inductors is:

$$L_1 = L_2 = L = (V_{IN}(\min) \times D_{max})/(\Delta I_L \times f_{sw})$$

For coupled inductors wound on the same core, the mutual inductance doubles the effective inductance, so each winding needs only half the value:

$$L_1' = L_2' = (V_{IN}(\min) \times D_{max})/(2 \times \Delta I_L \times f_{sw})$$

The peak current in L1 is:

$$I_{L1}(\text{peak}) = I_{OUT} \times (V_{OUT} + V_D)/V_{IN}(\min) \times (1 + 0.20)$$

The peak current in L2 is:

$$I_{L2}(\text{peak}) = I_{OUT} \times (1 + 0.20)$$

The peak switch current equals the sum:

$$I_{Q1}(\text{peak}) = I_{L1}(\text{peak}) + I_{L2}(\text{peak})$$

The inductor must be selected to handle the peak current without magnetic saturation, and the core material must be chosen to minimize AC losses at the switching frequency [ti.com](#). In the TI design example with $V_{IN}(\min) = 3.0V$, $V_{OUT} = 3.3V$, $I_{OUT} = 2.5A$, and $f_{sw} = 330 \text{ kHz}$, the calculated inductance is $4.6 \mu H$, rounded to the standard value $4.7 \mu H$ [ti.com](#).

• Coupling Capacitor Selection

The coupling capacitor C_s carries the AC current between the two inductors and must handle a significant RMS current. The RMS current in C_s is:

$$I_{C_s}(\text{rms}) = I_{\text{OUT}} \times \sqrt{((V_{\text{OUT}} + V_D)/V_{\text{IN}}(\text{min}))}$$

The voltage ripple across C_s must be kept small relative to V_{IN} to maintain proper converter operation, and the capacitance is determined by:

$$C_s \geq (I_{\text{OUT}}(\text{max}) \times D_{\text{max}})/(f_{\text{sw}} \times \Delta V_{C_s})$$

A non-polarized capacitor is generally recommended for C_s because its voltage can reverse direction during each switching cycle, though polarized types may be used in specific cases where the switch on-time is too short for resonance with L_2 to reverse the capacitor voltage [ti.com](https://www.ti.com) [wikipedia.org](https://en.wikipedia.org). Ceramic capacitors with low ESR are preferred for their ripple current capability and stability [ti.com](https://www.ti.com).

• Output and Input Capacitor Selection

The output capacitor C_{out} filters the pulsating output current and determines the output voltage ripple. Its value is calculated as:

$$C_{\text{out}} \geq (I_{\text{OUT}}(\text{max}) \times D_{\text{max}})/(f_{\text{sw}} \times \Delta V_{\text{OUT}})$$

The ESR of C_{out} contributes an additional ripple component $\Delta V_{\text{OUT}}(\text{ESR}) = I_{\text{OUT}}(\text{max}) \times \text{ESR}$, and in many practical designs the ESR contribution dominates the total output ripple. The input capacitor C_{in} is essential in real circuits to filter the pulsating input current and mitigate the effects of parasitic inductance in the power supply leads.

• MOSFET Selection

The MOSFET must satisfy voltage and current requirements. The peak switch voltage is $V_{\text{IN}} + V_{\text{OUT}}$, so the rated drain voltage must exceed $V_{\text{IN}}(\text{max}) + V_{\text{OUT}}$ [ti.com](https://www.ti.com). The RMS switch current is:

$$I_{Q1}(\text{rms}) = I_{\text{OUT}} \times \sqrt{((V_{\text{OUT}} + V_{\text{IN}}(\text{min}) + V_D) \times (V_{\text{OUT}} + V_D)/V_{\text{IN}}(\text{min}))^2}$$

The MOSFET power dissipation combines conduction and switching losses:

$$P_{Q1} = I_{Q1}(\text{rms})^2 \times R_{\text{DS}}(\text{ON}) \times D_{\text{max}} + (V_{\text{IN}}(\text{min}) + V_{\text{OUT}}) \times I_{Q1}(\text{peak}) \times (Q_{\text{GD}} \times f_{\text{sw}}/(2 \times I_{\text{G}}))$$

Logic-level or sub-logic-level threshold MOSFETs should be selected based on the available gate drive voltage, and the $R_{\text{DS}}(\text{ON})$ value should be derated for maximum operating junction temperature [ti.com](https://www.ti.com). In the TI design example, the Si4442DY MOSFET with $R_{\text{DS}}(\text{ON}) = 8 \text{ m}\Omega$ and $Q_{\text{GD}} = 10 \text{ nC}$ yields an estimated power loss of 0.55W with gate drive current $I_{\text{G}} = 0.3\text{A}$.

• Diode Selection

The output diode must withstand a reverse voltage of $V_{\text{IN}}(\text{max}) + V_{\text{OUT}}$ and carry a peak current equal to the switch peak current $I_{Q1}(\text{peak})$ [ti.com](https://www.ti.com). The average

diode current equals the output current, and the diode power dissipation is $I_{OUT} \times V_F$. Schottky diodes are strongly recommended for their low forward voltage drop (typically 0.3-0.5V) and fast switching characteristics, which minimize both conduction and reverse-recovery loss.

- **Snubber Design**

The parasitic inductance in the loop formed by Q1, D1, and Cs can cause voltage spikes at the MOSFET drain during turn-off. A resistor-capacitor-diode (RCD) snubber across D1 or Q1 absorbs this energy. The snubber capacitor is chosen to limit the voltage spike to an acceptable level, and the resistor is selected to discharge the capacitor before the next switching cycle while not dissipating excessive power. Snubber design is particularly important when using coupled inductors, where leakage inductance between windings generates additional voltage spikes.

2.7 Matlab Model

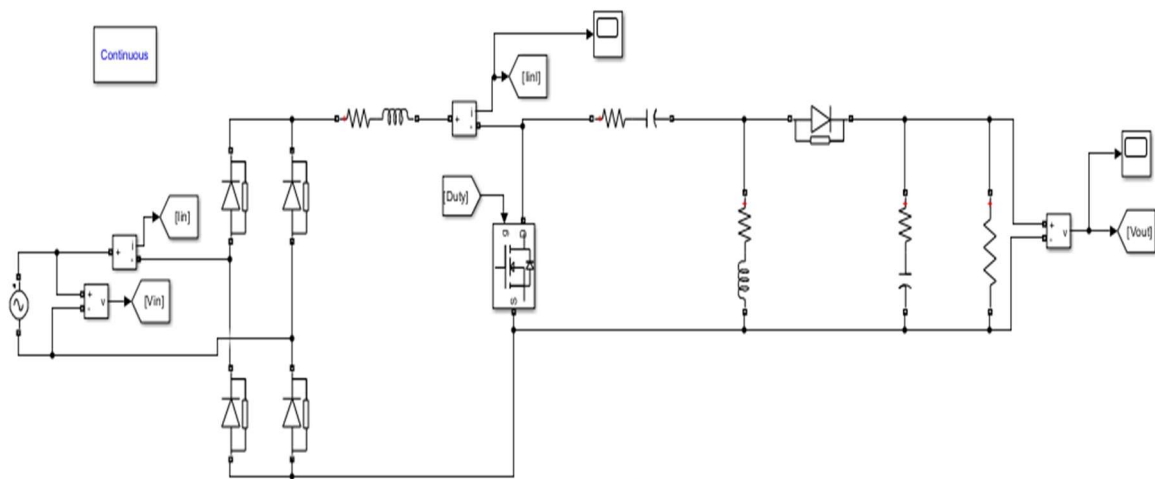


Fig. 2.1 SEPIC Converter Matlab Model

4.8 Matlab Control Model

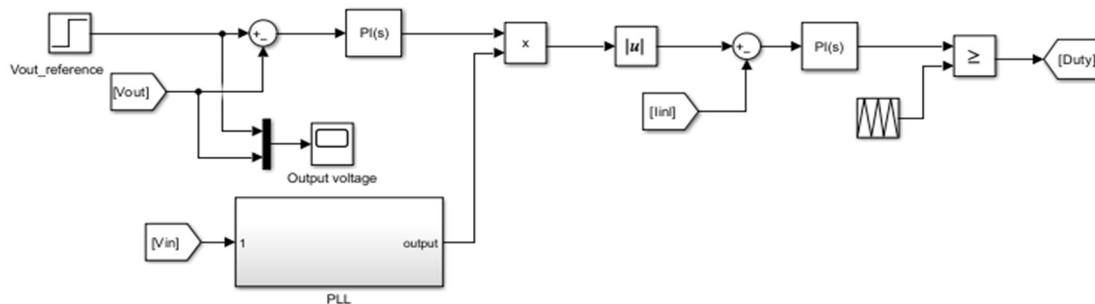
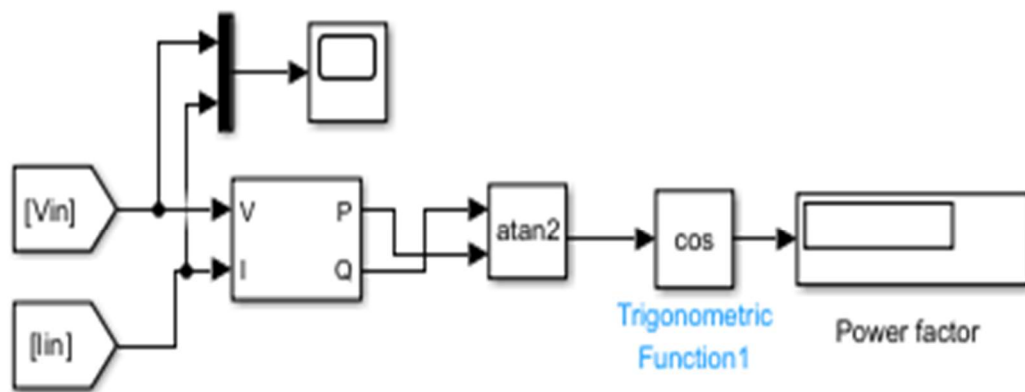


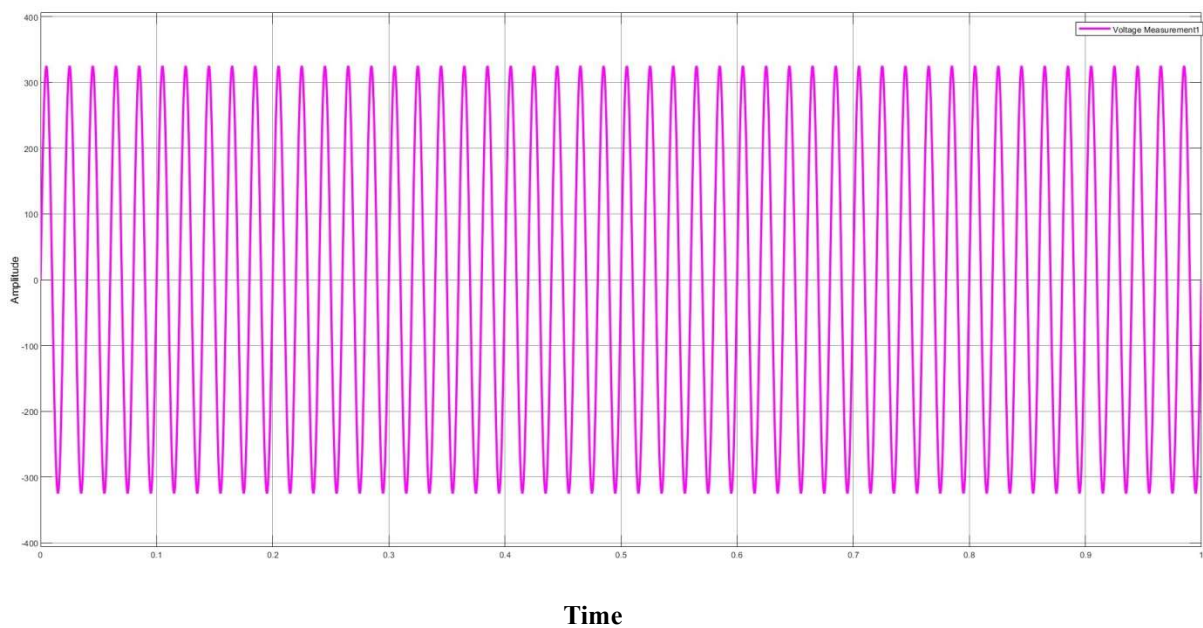
Fig 2.2 SEPIC Matlab Control Model

4.9 Matlab Power Factor Analyser

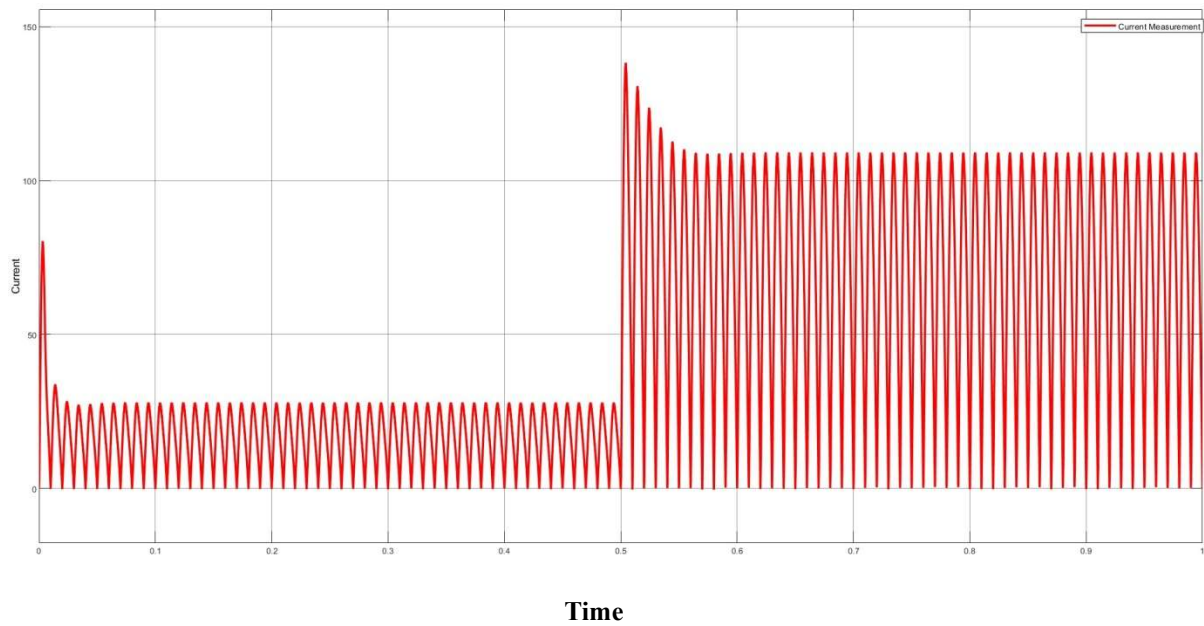


4.10 Matlab Results

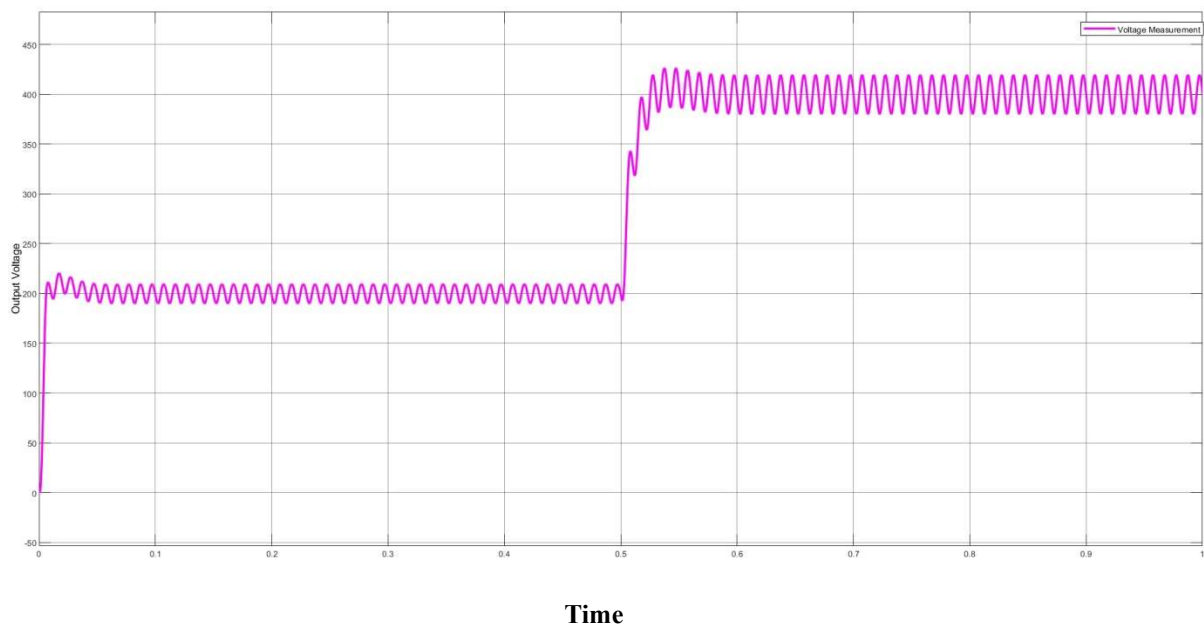
4.10.1 Supply Voltage.



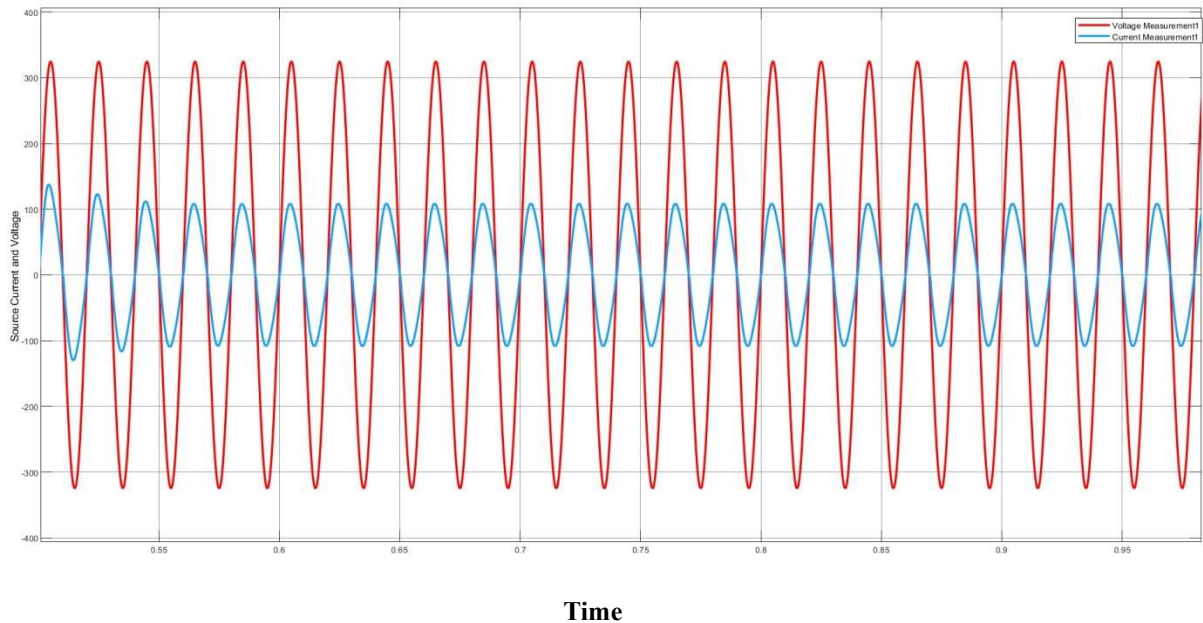
4.10.2 Current



4.10.3 Load Voltage



4.10.4 Supply Power Factor



2.11 Conclusion

The SEPIC converter occupies a unique position in DC-DC converter design: it is the simplest non isolated topology that simultaneously provides non-inverted output, continuous input current, true shutdown, and inherent short-circuit protection. No other single topology among the buck-boost, Cuk, Zeta, or flyback offers this exact combination. However, this versatility comes at the cost of fourth-order dynamics, higher component count, pulsating output current, and lower peak efficiency compared to simpler topologies.

The choice between SEPIC and its alternatives reveals a fundamental tension in power electronics design: the trade-off between functional versatility and control simplicity. The Cuk converter matches the SEPIC's continuous input current and fourth-order dynamics but adds continuous output current at the expense of inverted polarity. The conventional buck-boost offers second-order simplicity and minimal component count but sacrifices polarity, input current continuity, and short circuit protection. The Zeta converter provides non-inverted output like the SEPIC but has pulsating input current, making it unsuitable for battery applications where input ripple must be minimized.

CHAPTER 3

Dual Active Bridge Converter For Bidirectional Charging

3.1 Introduction

Ever since the Dual Active Bridge (DAB) converter's outstanding performance in the previous ten years has led to its meteoric rise in popularity. Voltage boost and buck functions are made possible by power transfers between the energy storage element and the dc voltage bus, which keep the voltage at the dc buses steady. The use of DABs has skyrocketed due to their extensive use in power electronics and industrial applications. These include micro grids, electric vehicles, aerospace energy storage systems, uninterruptible power supplies (UPS), and many more power applications that employ intermediate energy storage systems. Connecting two active bridge converters in a UPS system is shown in Figure 3.1.

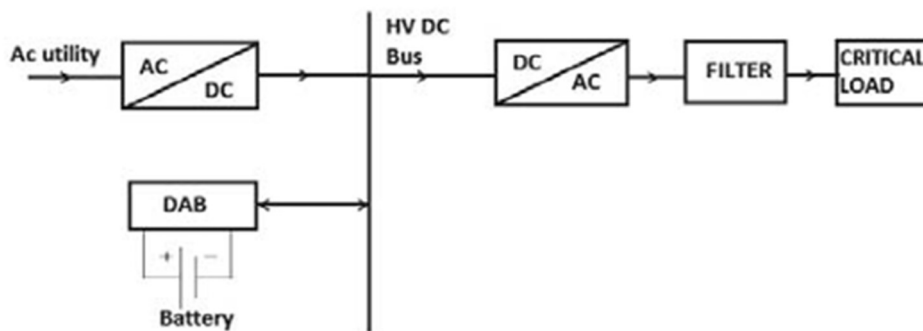


Fig 3.1 DAB converter block diagram

In order to modify the direction of power flow, the SPS control method [5] keeps the high frequency transformer's primary and secondary voltages in phase. Researchers have examined many facets of performance and operation for standard control schemes like SPS, as well as for steady state operation, closed loop control, inductor selection, and zero voltage switching (ZVS). According to [8], the DPS control method provides two tiers of control: first, an external phase shift between the high frequency transformer's main and secondary voltages; and second, an equal internal phase shift between the bridges' cross connected switches. The use of high-frequency link power conversion systems in DAB control algorithms has been the subject of much research [10]. The effects of step load change, inductor peak current, switch stress, and closed loop operation on circuit design and comparison are investigated in this thesis. Waveforms from the two control strategies—single phase shift and dual phase shift—are compared. The aforementioned control mechanisms can be tested and results obtained through simulation studies conducted in MATLAB and SIMULINK. A single phase Dual Active Bridge topology is shown in Figure 3.2.

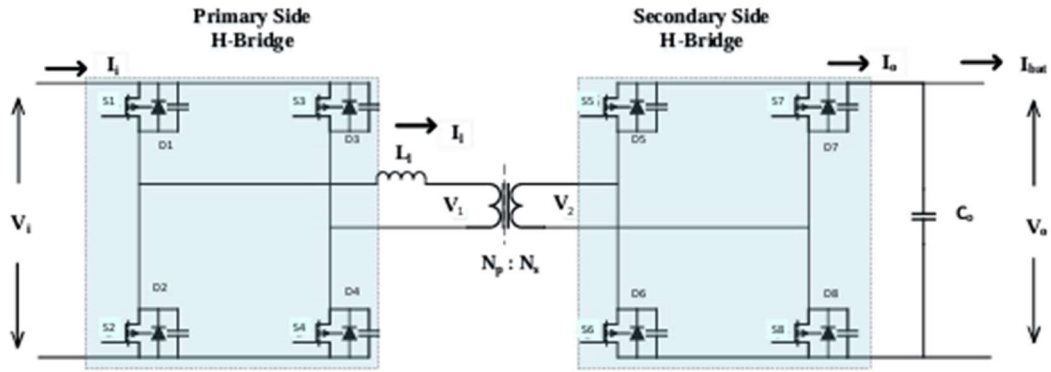


Fig 3.2 Single Phase Dual Active Bridge Converter circuit

The Figure 3.2 shows the converter circuit configuration for the single-phase dual-active bridge model. S1 and S2 on one leg represent the switches in the primary side H Bridge, and D1 and D2 on the other leg represent the anti-parallel diodes. S3 and S4 are the switches in the second leg [5]. The matching anti-parallel diodes are D3 and D4. On the other side, S5 and S6 are the secondary side H bridge switches, and D5 and D6 are the anti-parallel diodes that correspond to them. The switches in the second leg are S7 and S8, and the associated anti-parallel diodes are D7 and D8. Two bridge converters linked by a high frequency transformer make up the system, as depicted in the image. The primary side leakage inductance is represented by the inductor (L), whereas the secondary side inductor is the same thing. Control pulses with a duty ratio of 50% are used to operate the switches. The terminals across the HF transformer produce voltages that are square waves with high frequencies. Power flows in the opposite direction of the phase shift in a transformer, from the higher-phase voltage side to the lower-phase voltage side.

3.2 Description and feature

- Two Active Full Bridges Isolated via High-Frequency Transformer with Leakage Inductance -> select DAB converter when simultaneous presence of galvanic isolation and bidirectional power flow is required, as for EV onboard charger with V2G functionality and battery energy storage.
- Power Control via Phase-Shifting Approach: Power transmission depends on $P = (nV_pV_s)/(f_{sw} L_{tot}) * \phi(1-2|\phi|)$, where ϕ refers to the phase shift -> use advanced control algorithms with multiple degrees of freedom (EPS, DPS, TPS) in order to overcome the drawbacks caused by reactive current and reduced ZVS range.
- Limited Range of Soft-Switching in SPS Mode: In the mode of operation with phase shifting, a loss of zero-voltage switching takes place starting from the 20-30% of rated load -> implement EPS/TPS control algorithm with analytical calculation of ZVS boundary to maximize soft-switching region.
- DAB has Lower Maximum Efficiency Than CLLC: According to Texas Instruments, CLLC topology reaches peak efficiency of 97% compared to DAB, which is limited by 96% when working with GaN-FET switches at 250 kHz frequency -> prefer CLLC topology if full efficiency at full load is required.
- Leakage Inductance – Critical Parameter in DAB Design: The maximum allowable leakage inductance can be calculated using formula $L_{max} = (V_{in} * V_o)/(8 * f_s$

P_{rated}); if this parameter exceeds, it will impossible to ensure zero reactive current flow; low values of leakage inductance limit ZVS range -> calculate optimal inductance analytically.

- **GaN/SiC Enables Increased Switching Frequencies and Power Density:** WBG-based DAB allows working at 250kHz+ switching frequencies, thus ensuring high power density with efficiency over 96%; prefer GaN-FETs for sub-10kW design, and SiC MOSFETs for high-power DAB solutions -> achieve greater power density at expense of increased thermal dissipation.
- **Multi-Criterion Optimization of DAB Modulation is the Future:** The recent research (2025) on DAB optimization targets simultaneous minimization of current stresses and reverse power flow, which leads to increased efficiency -> thesis should target multi-criterion optimization problem of TPS DAB modulation with analytical or AI-assistance.
- **Variable Frequency Control Improves Light-Load Efficiency:** Hybrid approach, based on combining SPS operation with the variable switching frequency improves efficiency at light load due to impedance matching adjustment, however, causes frequency fluctuations, thus increasing complexity of EMI filter design -> optimal approach combines constant EPS at heavy load and SPS with variable frequency at light load.
- **3-Phase DAB for High-Power Solutions:** This modification of conventional DAB improves power handling capacity through current ripple reduction at expense of increased component count -> prefer DAB with 3-phases for power conversion exceeding 10kW with strict current ripple requirements.
- **Application for Solid-State Transformers:** Bidirectional nature and possibility of galvanic isolation make DAB converter ideal solution for DC-DC stage of solid-state transformers used for smart grid and railway traction applications -> conduct research related to DAB applied in SST technology.

- **Battery Energy Storage Systems**

DAB converters interface battery banks to DC microgrids, where bidirectional power flow is essential for both charging and discharging modes. The converter must accommodate wide battery voltage ranges while maintaining high efficiency in both power flow directions. The DAB's symmetrical topology makes it inherently suited for this application, unlike the CLLC which may require asymmetric tank design for optimal reverse operation

- **Solid-State Transformers**

Solid-state transformers (SSTs) for smart grid and railway traction applications use DAB converters as the isolated DC-DC conversion stage between the AC-DC front end and the DC-AC output stage. The DAB's high-frequency isolation dramatically reduces size and weight compared to line-frequency transformers, while bidirectional capability enables power flow management in both directions. The CLLC resonant DAB variant (combining DAB structure with resonant tank elements) has been identified as particularly suitable for SST applications, offering both bidirectional capability and full-range soft switching CLLC Resonant Dual Active Bridge - Texas Instruments.

3.8 Matlab Model

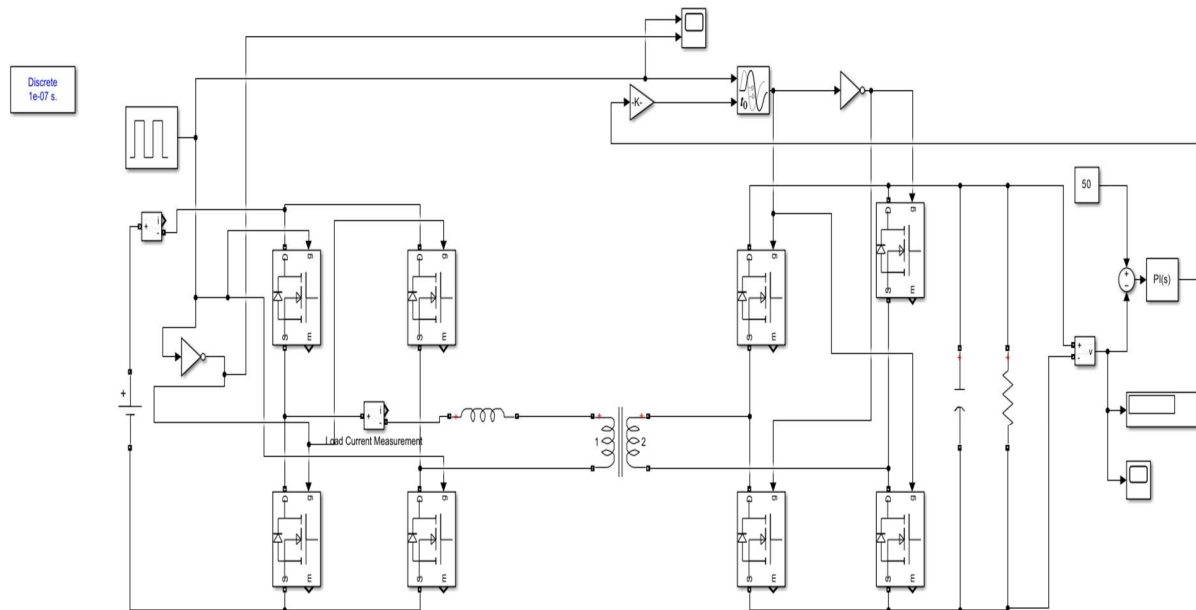


Figure 3.3 DAB Matlab Simulation

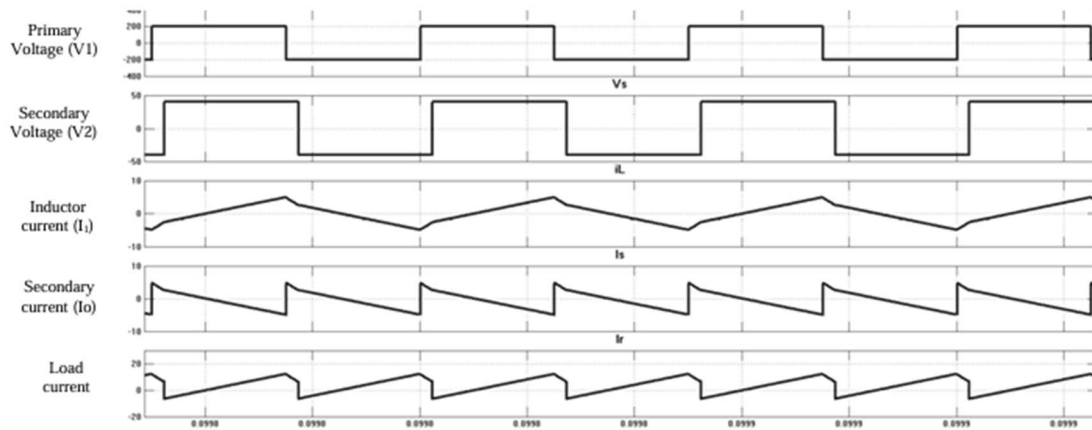


Fig. 3.4 Primary, secondary and inductor voltages and current along with sending and receiving current for forward mode

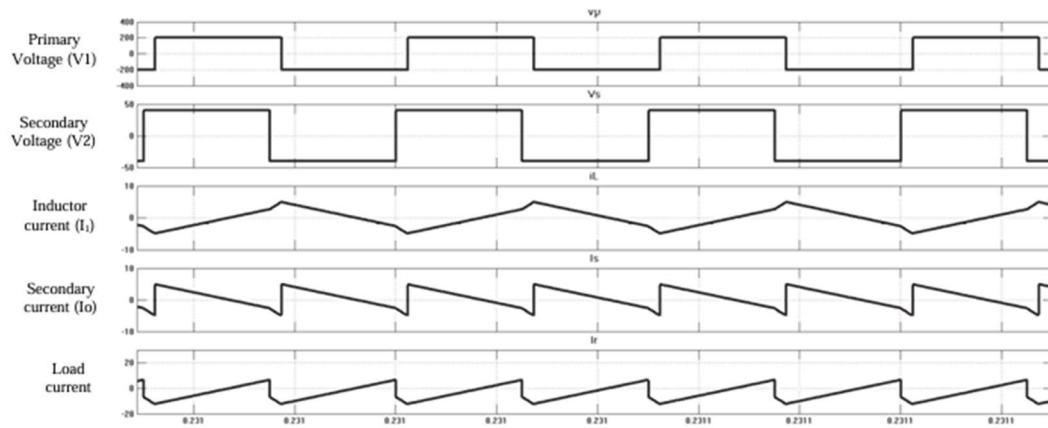


Fig 3.5 Primary, secondary and inductor voltages and current along with sending and receiving current for forward mode

3.2 Regulated DV voltage at 48V

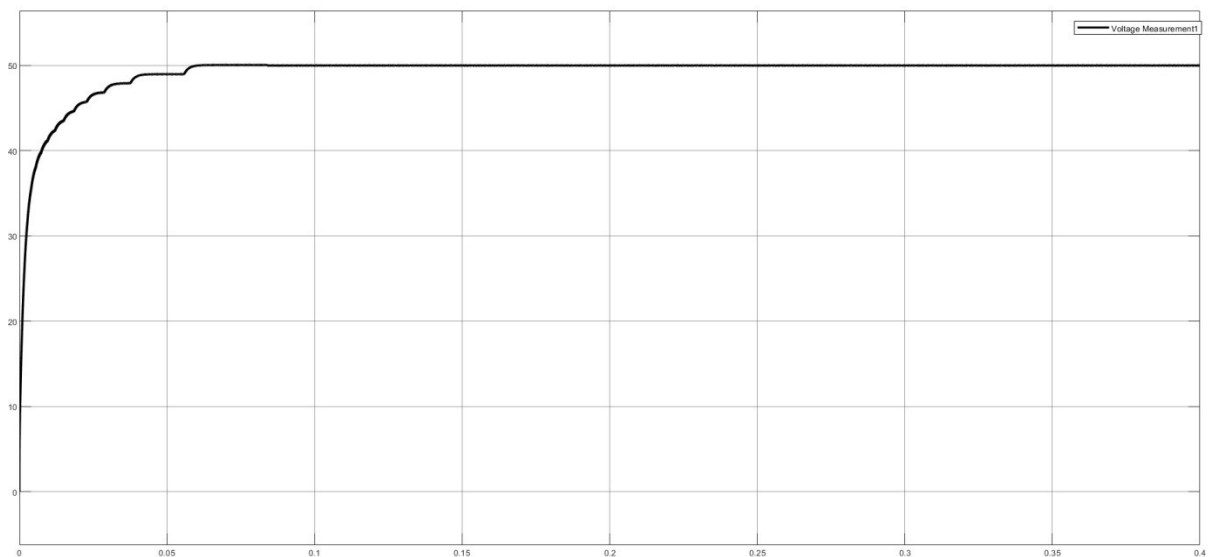


Fig 3.6 output of DAB Matlab Simulation

CHAPTER 4

BOOST CONVERTER FOR BATTERY CHARGING

4.1 Introduction

This type of converter is developed using the basic boost converter topology. By spreading the power factor correction improve overall efficiency, Minimize current ripple, which reduces stress on components Lower electromagnetic interference (EMI), making the system more compliant with power quality standards. 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.

4.2 Efficient power factor for battery charging

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.

4.2.1 Traditional PFC Boost

2.2.2 Traditional PFC Boost Ideal for: Power levels that are low to medium (less than 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.

4.2.2 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.

4.2.3 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.

4.2.4 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.

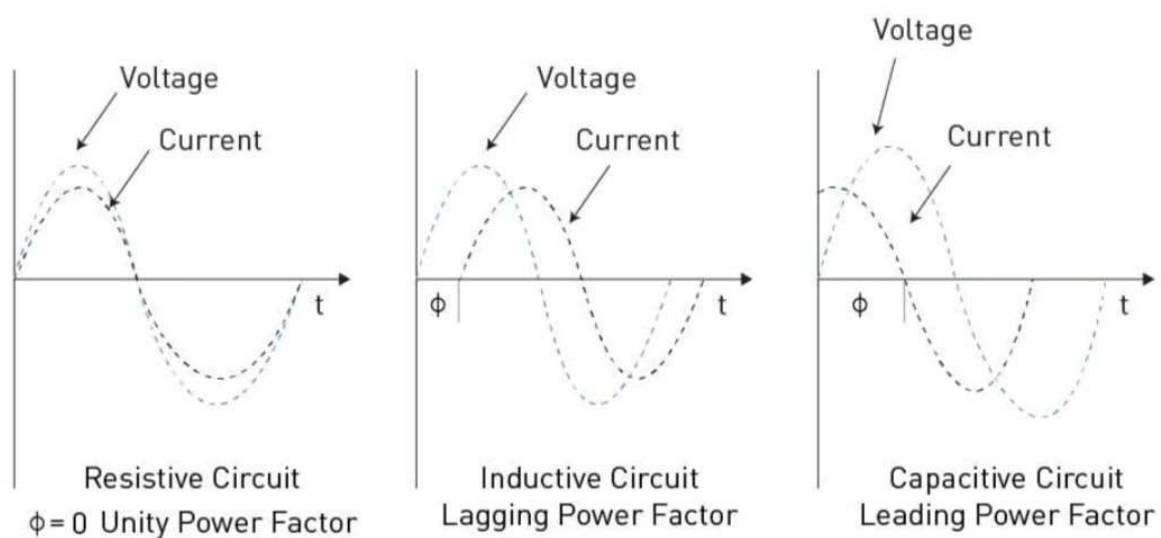


Figure 4.1 Unity, Inductive and Capacitive Power Factor

4.3 Operation of Boost Power Factor

Operation (Mode1)

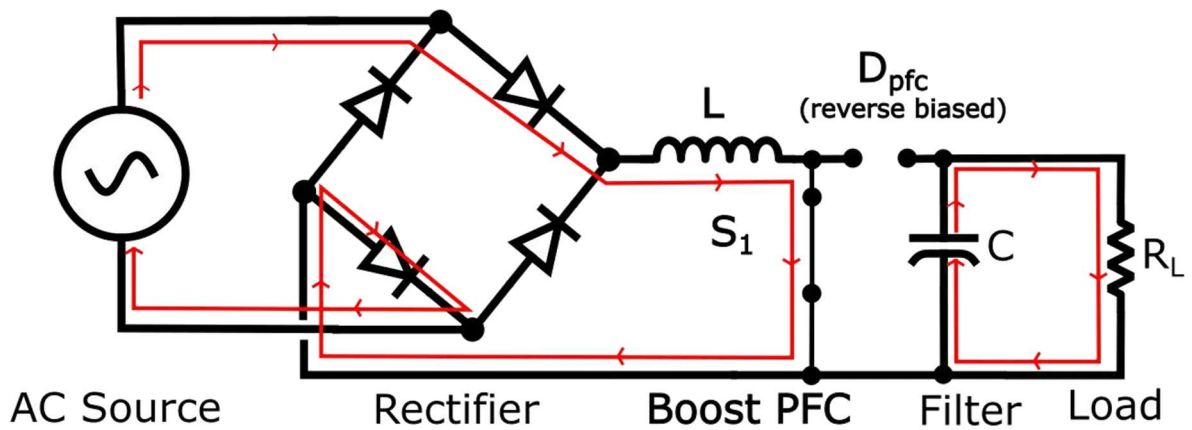


Figure 4.2 Boost PF Correction Operation Mode 1

Operation (Mode2)

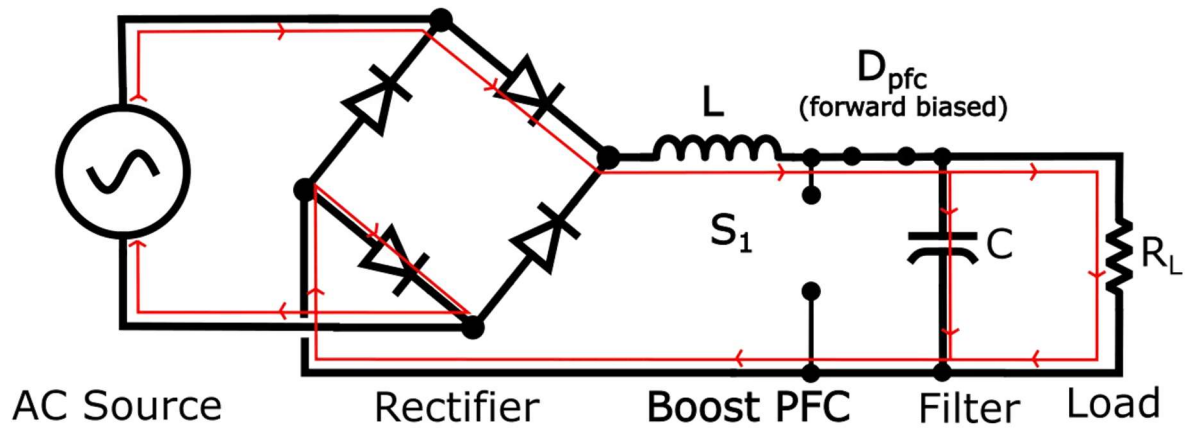


Figure 4.3 Boost PF Correction Operation Mode 2

4.4 Design Procedure

- Specification:**

Power: 2KW

Output Voltage: 400V/5A

Efficiency : 90%

Input Voltage regulation 15% of Input

Op Voltage ripple 20%

Design Calculations		
Power	2000	Watts
Efficiency	90.00%	
Switching Freq	10000	Hz
Vo	400	Volts
Io	5	Amps
Vin Rated	230.00	
Disturbance Range	25.00%	
Vin_min	172.5	Volts
Vin_max	287.5	Volts
Fline	50	Hz
Is_max	11.5942029	Amps
Is_min	6.956521739	Amps
L	0.002322252	
	2.322252141	mH
Delta Vo	Vo	5% of
		20
C		
	=	0.000796178
	=	796.2 uF
R Load	80	ohm

- **Calculation of Inductor:**

$$L = \frac{1}{\%Ripple} \cdot \frac{V_{ac.min}^2}{P_o} \left(1 - \frac{\sqrt{2} \cdot V_{ac.min}}{V_o} \right) \cdot T$$

- **Calculation of Capacitor:**

$$C_o \geq \frac{P_o}{2 \cdot \pi \cdot f_{line} \cdot \Delta V_o \cdot V_o}$$

4.4 Matlab Simulation Block Diagram:

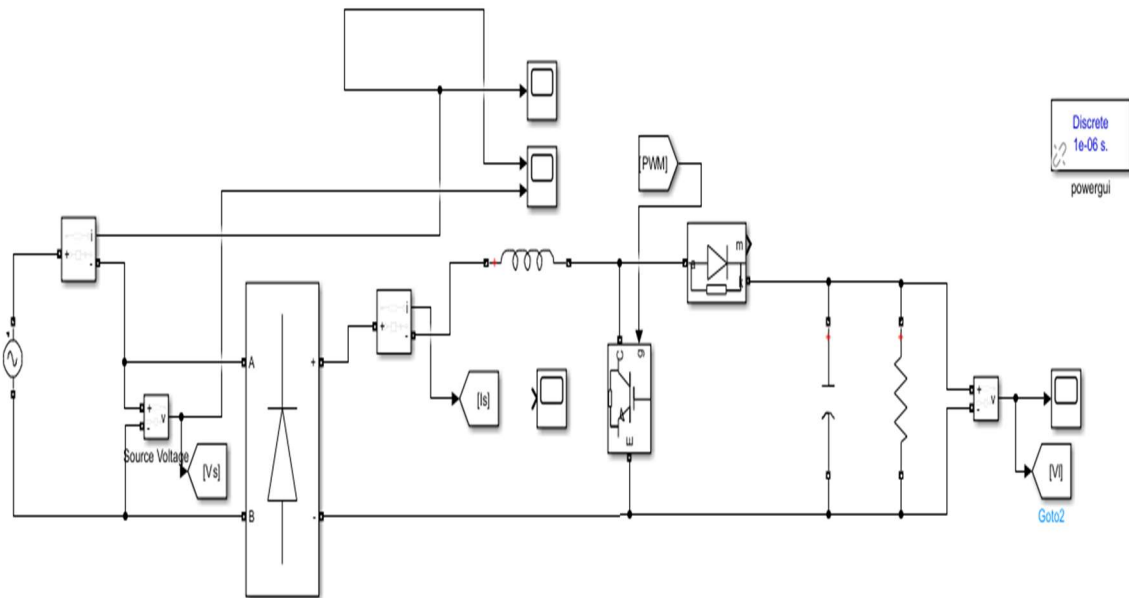


Figure 4.4 Matlab Simulation Block Diagram

4.5 Matlab Simulation Control Diagram:

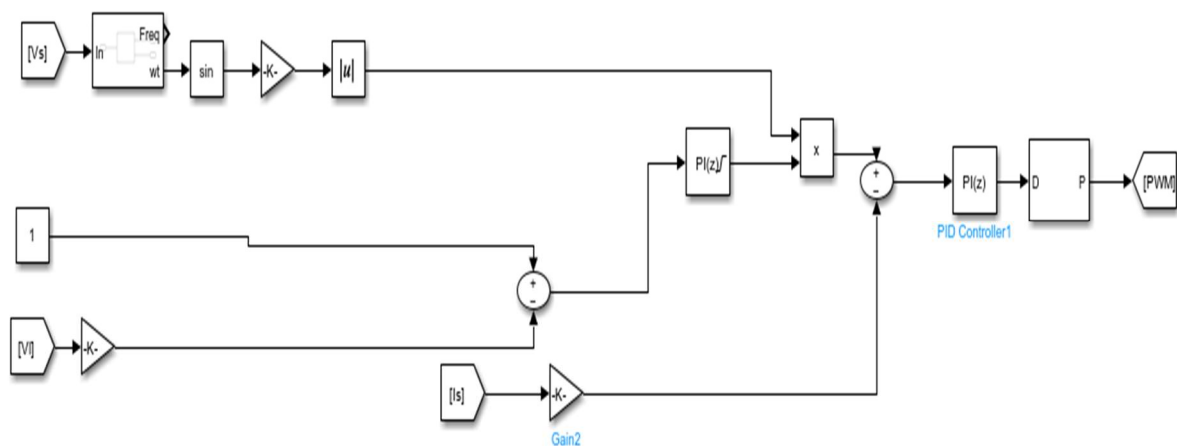


Figure 4.5 Matlab Simulation Control Diagram

4.6 Required Output Voltage Input Voltage and Input current:

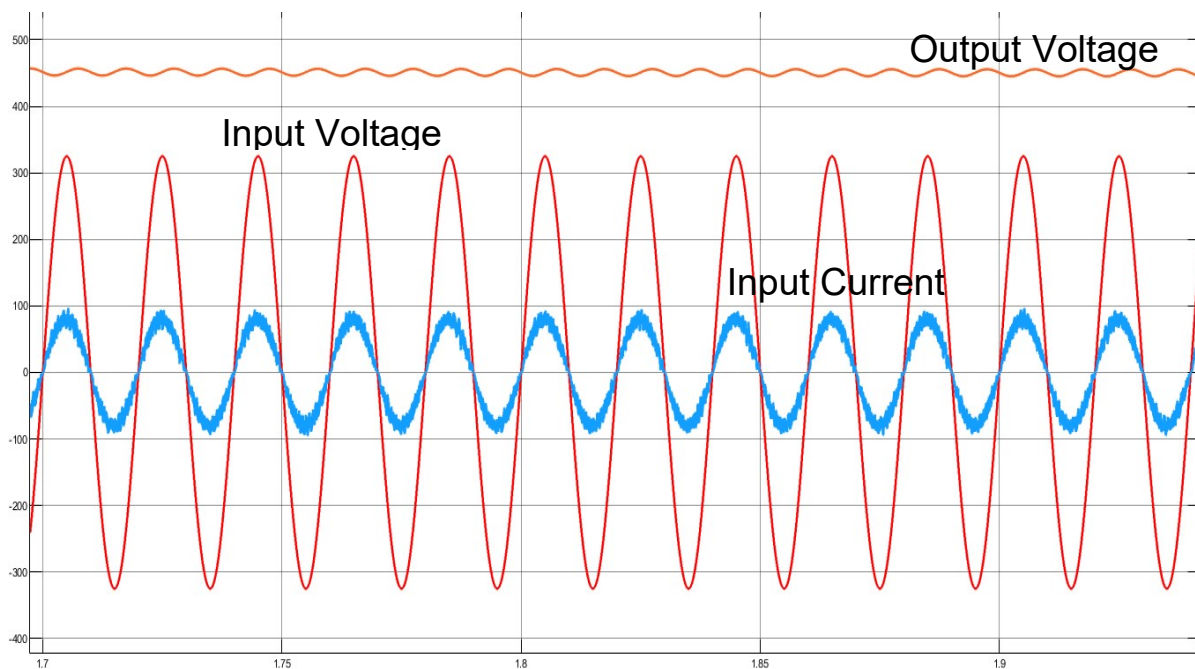


Figure 4.6 Required Output

4.7 Matlab Simulation Result:

SOURCE VOLTAGE AND CURRENT ARE IN PHASE.

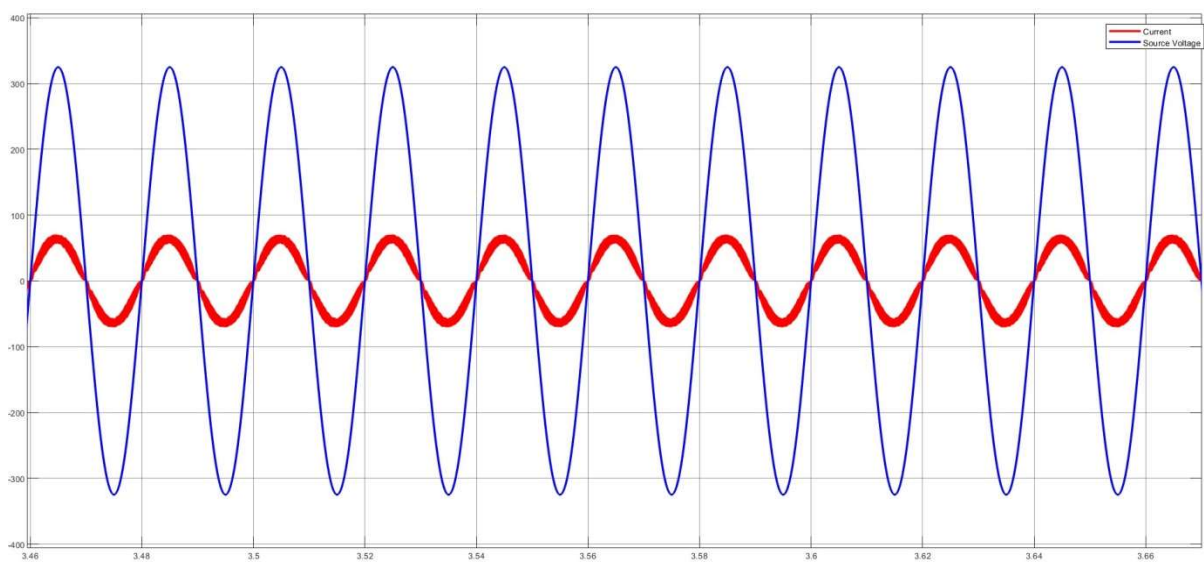
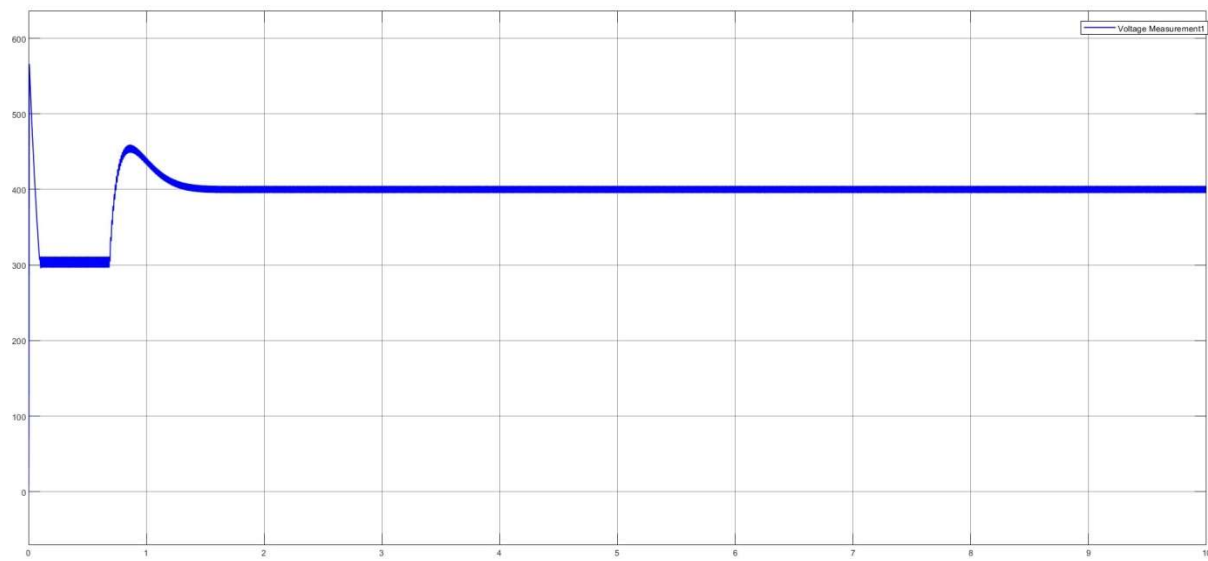


Figure 4.7 Source Voltage and Current

LOAD VOLTAGE AS REQUIRED 400V.**Figure 4.8 Load Voltage**

CHAPTER 5

MAIN CONCLUSION AND FUTURE SCOPE OF WORK

4.1 Main Conclusion

The bidirectional modified-SEPIC charger discussed in this thesis designed for low powered EVs working at 48V and 120V is designed at 1.1kW and can be used for light utility vehicles in the market. How it is different from traditional SEPIC, by introduction of switched capacitors the rating and component sizing has been reduced and hence it can be working at comparatively high voltage without breaking the threshold limit of the capacitor. The closed loop controller design for the Modified SEPIC converter can be worked in both Constant current or Constant voltage, here the flow of power either in forward or reverse is controlled using a constant choosing a positive value will ensure the converter is working in forward direction and choosing negative value will make the converter work in negative direction. Another converter discussed in this thesis is Dual Active Bridge converter this isolated converter is in this topic design and analysis of single phase shift technique (SPS) for power flow in DAB converter is used the power transfer due to shifting of phases in between the primary and secondary coils of a transformer. The DAB converter is working in closed loop control system by appropriately implementing PI compensation technique and finding phase relation between Current and phase.

4.2 Future scope of work

In this thesis the use of bidirectional charger can be backed up by using a front end PFC converter which can make sure that the whole setup can withstand grid fluctuations, this is done with the help of a Voltage Source converter with LCL filter and the grid synchronization can be done using SOGI-PLL, we can also implement more robust control strategy instead of PI controller used in the following converter. Another converter discussed in this thesis is Dual Active Bridge converter this isolated converter is suitable for high voltage DC fast charging and can be further improved by using ZVS scheme for all the switches the DAB converter can be further explored with wide band Gap technologies to further increase the efficiency and decrease the overall sizing of component. Exploring more advanced control techniques to control the feedback mechanism by inclusion of techniques like Model predictive control (MPC) can be very insightful, there is also scope of multi port connection topology due to presence of transformer in DAB converter.

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