

Bridgeless Modified Boost Converter to Improve Power Factor in EV Battery Charging Applications

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IN

POWER ELECTRONICS AND SYSTEMS

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CANDIDATE’S DECLARATION

I, Aakash Kumar, Roll No. 24/PES/17 student of MTech (Power Electronics & Systems), hereby declare that the project Dissertation titled “ Bridgeless Modified Boost Converter to Improve Power Factor in EV Battery Charging Applications ” which is submitted by me to the Department of Electrical Engineering, Delhi Technological university, Delhi in partial fulfilment of the requirement for the award of the degree of Master 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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Date: 31st May 2026

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CERTIFICATE

I hereby certify that the project Dissertation titled “ **Bridgeless Modified Boost Converter to Improve Power Factor in EV Battery Charging Applications** ” which is Submitted by **Aakash Kumar**, Roll No. **24/PES/17**, Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the 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

This work offers another approach to conventional boost converter without bridge for improving the input power factor and the charger performance of electric vehicle battery charger. In most power electronic- based battery chargers, diode bridge rectifier circuit is employed. Hence, many harmonics exist on the input side, which reduces efficiency. The innovative scheme based on two original boost-converter during positive and negative line half cycle does not contain diode bridge rectifier.

To make this happen, the introduced system uses two boost converters in different switching cycle to reduce the conduction losses and lower the input current harmonic, and It also simplifies the circuit by having only on control circuit with voltage-sensing feedback control. The converter will run most of the time in the discontinuous conduction mode. So that the circuit can be designed with smaller components with less ripple. The simulation as well as the experiment results show that this circuit retains unity power factor and low total harmonic distortion while providing a steady DC voltage, which is suitable for the charging technique of constant current and constant voltage.

TABLE OF CONTENTS

Titlepage.....	i
Candidate'sDeclaration.....	ii
Certificate.....	iii
Acknowledgement.....	iv
Abstract.....	v
CHAPTER 1: INTRODUCTION.....	9
1.1 Overview of Electric Vehicle Charging Systems.....	10
1.2 Need for Power Factor Correction in EV Battery Charging.....	11
1.3 Problems with Conventional DBR.....	11
1.4 Problem Statement.....	12
1.5 Need for an improved PFC solution.....	13
1.6 Need for bridgeless Modified Boost converter.....	14
CHAPTER 2: LITERATURE SURVEY.....	15
2.1 Bridgeless PFC Converter.....	16
2.2 Limitation of Diode bridge rectifier based boost pfc.....	16
2.3 Research Gap Identified.....	18
CHAPTER 3: Mathematical Modelling.....	19
3.1.1 Mode Positive I.....	19
3.1.2 Mode Positive II.....	20
3.1.3 Mode Positive III.....	23
3.1.4 Mode Negative I.....	24
3.1.5 Mode Negative II.....	26
3.1.6 Mode Negative III.....	28
3.2 Operation of Bridgeless Boost Converter.....	31
CHAPTER 4: Design and Component Sizing	37
4.1 Design Parameters.....	37
4.2 Control Strategy of PFC Converter	38
4.3 Control Principle.....	38
CHAPTER 5: Simulation Analysis.....	42
5.1 Simulation Setup.....	42
5.2 Simulation Parameter.....	42
5.3 Simulation Results.....	43
CHAPTER 6: Conclusion and Future Scope.....	46
6.1 Conclusion.....	46
6.2 Future Scope.....	46

LIST OF FIGURE

Figure 1.1 DBR.....	11
Figure 1.2 Block Diagram of system.....	13
Figure 2.1 Conventional boost based PFC Converter.....	16
Figure 3.1 Mode Positive I.....	18
Figure 3.2 Mode Positive II.....	20
Figure 3.3 Mode Positive III.....	22
Figure 3.4 Mode Negative I.....	23
Figure 3.5 Mode Negative II.....	25
Figure 3.6 Mode Negative III.....	27
Figure 3.7 DCM.....	31
Figure 3.8 CCM.....	32
Figure 5.1 Simulation Setup.....	41
Figure 5.2 Waveform of input voltage and current.....	42
Figure 5.3 Waveform of achieving unity power factor.....	42
Figure 5.4 Waveform of state of charge	43
Figure 5.5 Waveform of output voltage & current of BL Boost Converter.....	43
Figure 5.6 Waveform of output voltage & current of Flyback Converter.....	44

List of Abbreviations

Lop	Boost inductor for the upper/positive path
Lon	Boost inductor for the lower/negative path.
Lac	AC Input Inductor Filter
Cac	Input AC filter capacitor
Dn	Diode for the negative path
Dp	Diode for the positive path
Sp	Main switch for the positive path (upper switching device)
Sn	Main switch for the negative path (lower switching device)
PLL	Phase locked loop
PWM	Pulse Width Modulation
SOC	State of Charge
THD	Total harmonic distortion

Chapter 1

INTRODUCTION

With the ever growing need of cars with electric powered engines and boom of environmentally conscious people, the electric car mobility issue has risen to be a popular one. As a step toward reducing the burden on the environment, the electric car charging has proved to be pretty handy and handy. With the increasing popularity of the electrical vehicles, some issues might come up one of which would be the efficient and high-quality charging of the batteries in the electric vehicles. Efficient charging with minimum distortions of the electricity and maximum energy transition from the mains to the battery is one of the prime distinguishing attribute of any EV charger. In this regard, one of the major flaws of majority of the current EV chargers can be listed as the high distorting and inefficient use of a diode bridge rectifier.

This problem lead to the investigations on power factor correction techniques and the ultimate goal of these investigations is to ensure a quality of the power delivered by the source . To realize these techniques, numerous sorts of topologies can be used. However, most of them, although difficult to control, demand a significant switching or a significant volume of the circuit. Among these topologies, a specific one does not include a diode bridge at its topology and use less power elements. Consequently, a switching losses will be lower, avoiding the heat losses generation. Therefore, the new bridgeless boost PFC converter topology has been derived.

The basic theory concerning the converter, is based on the concept that the two sections of the circuit are permitted to run in parallel, with both positive and negative half cycles of input supply. This effectively will prevent duplication of conductive components, so increasing the efficiency of this equipment. As there is no requirement for any other controller or phase lock loop to be designed for the purpose as like in other converters available, the circuitry is kept comparatively simple. As there is a discontinuous conduction of some of the inductors, therefore it becomes necessary to minimize their amount, and ripple current; similar to in other circuitry.

Among many features of the presented circuit configuration it can achieve near unit power factor with sinusoidal input current. It is a small size, simple and constructed so that the proposed converter can achieve better power quality thus providing a best option when compared to the conventional circuit configuration. The innovative design of the EV battery charger, presented in the thesis is capable of performing its task effectively.

1.1 Overview of Electric Vehicle Charging Systems

Electric Vehicles are gradually finding their way into current transportation modes due to the efforts of states to limit Pollution and consumption of fossil fuels. Each electric vehicle uses a Battery charger, which needs to provide power efficiently from grid, which supplies the car with clean and controlled power.

All the standard charger circuitry has a circuit rectifier circuit; which has a diode bridge circuit, so the circuitry is quite simple, and there is only one drawback that is distorted input current wave form and low power factor of this type circuitry.

Since the world standards in terms of the power quality about the IEC 61000-3-2, it is more difficult for the DBR charging system to fulfill all the criteria when other circuitries are not involved.

To find the solution of the problem, it is decided to use the bridgeless PFC converter circuit. It is used since it does not have any diode bridge, maximum conducting devices with less conduction loss, hence high efficiency.

By removing the formation of the bridge, the bridge-less boost converter generates comparatively less current ripples and requires lesser number of components with smooth functioning in discontinuous conduction mode. Further, it produces stable DC output and hence applicable for CC/CV battery charger in EVs. Therefore there is a clear demand for improvement in efficiency, miniaturization and standardization to support for electric vehicle (EV) applications of this better topology of bridgeless modified boost converter.

1.2 Need for Power Factor Correction in EV Battery Charging

Electric vehicle charger absorbs electrical energy from the network. The electric current passing through the electric vehicle charger without the application of PFC (Power factor Correction) would be discontinues resulting in loss of energy. Power factor would be high; this would be in direct proportion with the reactive power required hence the current is increased and energy consumed as losses increases in the wire as it passes through the windings of the transformers. Power factor thereby is high discarding the distortion. There will be no distortions for the electric vehicle charger.

1.3 Problems with Conventional DBR

Nevertheless, the simple circuit configuration and the relatively low cost of DBR still make it quite attractive. However, with the the demands of power generation mounting for the purpose of charging electric vehicle, these two features have been pushed down and diminishing gradually. During the work of DBR, it only tans currents at the peak-point of AC voltage, which causes waveforms distortion with the poor power factor and higher losses, and the system needs the more reactive power that consume from the grid, due to provides the power completely with the regulator respectively; This also causes the high conduction losses because the current to flow through many diodes when switch from positive to negative voltages. Therefore, the DBR cannot achieve with the newest requirement by IEEE and IEC, such as THD.

Without a doubt, this kind of distortion (for they are multiple) will create problems not only for the grid, but also for appliances. Yet to avoid these problems, filters will be need. These filters will have a physical bulky size, thus creating a bulky charger. The importance of a small charger is now more and more required.

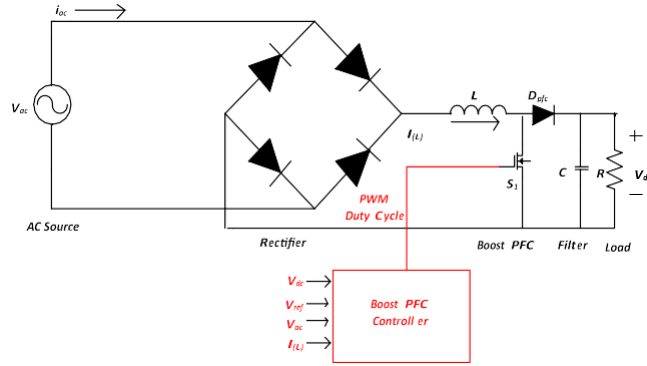


Figure 1.1 DBR

1.4 Problem Statement

In nowadays, they have been trying to put EVs in our life, the same as they need the energy efficient charger to be applied into our modern electric power system. However, with the electric vehicle charger design nowadays, the following conclusion can be achieved very simply at the initial step. The majority of the electric vehicles built today employ the use of the "diode bridge rectifier" at the first step.

Thus, there are numerous facts that we should also take into account about the aforementioned problem. So, the first issue concerning the employment of the aforesaid element in the charger under description is that it does not take any balanced electric energy from the electricity network, but relies entirely upon the energy that exists in peaks of the waves of voltage alternations. As a result, the distortion of the current reaches 55%, which is absolutely inadmissible according to IEC 61000-3-2. Moreover, other problems induced by the afore mentioned circumstance are, among other things, extra electric energy losses since due to the specific structure of the particular charger (the current flows through several diodes in each cycle), further increases in power flow through additional conduction losses.

In the end, the solutions outlined in found that suggested 's without bridges tested was found to be doing much better than the conventional circuits. It can be observed while examining these circuits that the majority of them tested do not work due to some

restriction. Some had to use phase locked loop or some extra sensing circuit while some only had single mode that will not help in making an EV charger.

This is precisely the criteria such that the thesis seeks to cater. The "improved converter, easy to implement and yet work efficiently" is the criterion. The more detailed criteria are: rectifier with no diode bridge, only one sensed voltage feedback loop, operated in both modes well, have steady DC output for battery charger operation, efficiency/ unity power factor.

1.5 Need for an Improved Power Factor Correction (PFC) Solution

Now as we see that there are lot of EVs (electric vehicles) around us, the demands for good and efficient and more effective chargers for such batteries will surely increased. The problem that rises because of charging these Batteries of vehicles is how to get the electricity from the source, without any wastages of the harmful power while providing the required energy. It can be observed from the charging techniques that the power factor draw using such systems ranges from 0.7 and 0.8 that indicates the maximum harmonic distortions and the power wastage. So a more advanced type of power factor correction has to be employed to reach to a unity power factor.

The existing EV-charging station employs low-cost and straightforward power control system with low input voltage; therefore, the complicated topology which applies diode bridge rectifier and control system is unnecessary. The ideal PFC circuit can operate over wide range of voltages; require less sensing and dc-bus regulation for top charging operation under CC/CV mode. In view of the future development of efficient PFC circuits, it can be prognosticated that the efficiency requirement of the PFC circuit with power quality will be planned on IEC 61000-3-2.

1.6 Need for Bridgeless Modified Boost Converter

As this and other number of Electric Vehicles are increasing. The solution to the issue with the conventional EV charging system is an EV charging system that are efficient, reliable and grid friendly to supply the high quality energy needed for charging without introducing any extra harmonics and distortion. There are many difficulties with conventional EV chargers today, including problems with, harmonics, power factors and conduction losses. By proper employment of the right PFC method, it is possible to

guarantee that the current is in phase with source voltage without forcing source to supply the reactive power needed by the system. Besides, the EV charger designed should be reduced in size, cheap and simple to operate. This can be achieved without the use of costly diode bridges and sophisticated controls if the following characteristics can be found in the optimal PFC converters: high efficiency across a wide spectrum of input voltages; less sensors; stabilization of DC voltage in the CC/CV chargers. The future of PFC converter seems to be efficiency gain, power quality improvement, reduced electrical/thermal stress and achievement of international standards such as IEC 61000-3-2, etc. After evaluating all the techniques discussed in this report, modified boost converters without bridge can apply for these standards as they can generate the required charging capacities as they have the right input current.

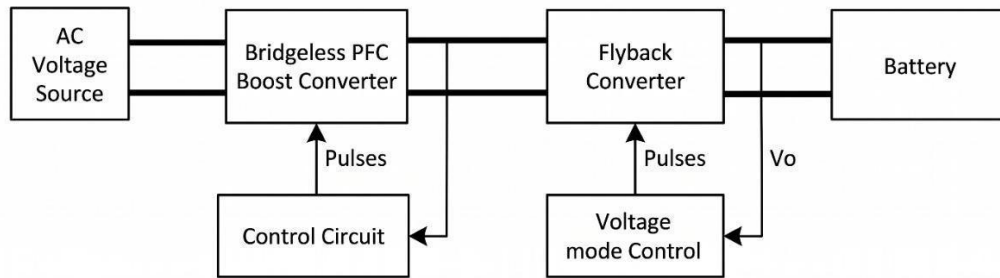


Figure 1.2 Block Diagram of system

Chapter 2

LITERATURE SURVEY

However, optimization of the AC-DC converter topologies for high power quality and high efficiency of EV chargers is being pursued over a long time. Among them the common AC-DC converter topology has been using the line frequency rectifier (DBR) coupled with DC-DC converter. Design of DBR and DC-DC converter possesses advantages in terms of ease of design and cost. However, some disadvantages like low power factor and significant current harmonics along with the high thermal stress of the converter has a bad influence on them. These consequently drive a necessity for improvement in PFC.

Optimization of the PFC circuit design is inclined toward improving the BL converter topologies in the expectation of enhancing the efficiency and minimizing the loss by virtue of reducing the conduction elements in current flow path. Different kinds of designs on the BL converter topologies such as BL boost converter, BL SEPIC, BL Cuk, BL current source converter and others are found in earlier work. They have differences in switching frequency, operating characterization and efficiency. However most of the proposed solutions were at the cost of some drawbacks, as for instance complexity of control circuit, significant electromagnetic disturbance, or not sufficient gain. Investigations on LLC resonant converters and interleaved PFC would enable achieving extremely high efficiency and extremely low ripple but the associated problems were the complex design itself and additional switching losses at certain situations. Whereas some hybrid converters would give better voltage-range but they needed numerous sensors and complex control loops which are not suitable for low-cost EVs charging.

Furthermore, the efficiency remains excellent and the complexity is decreased on the PFC stage. To be more specific, a bridgeless boost power converter without DBR is used. Consequently, harmonic elimination and improved power factor is achieved by a very simple scheme, i.e. No sophisticated inner loop controller and PLL are required and only one sensor is used.

Compared to previous topologies, the solution offers Reduced conduction losses and stress to the elements, better compliance with the power quality requirements and simplified configuration. Therefore, it can be deduced from the literature that there was a evident progress to achieve the higher performance, less distortion and more controllable topologies by the development of DBR converters starting from the basic topologies. The thesis also makes a step forward in this context.

2.1 Bridgeless PFC Converter

In the context of the bridgeless PFC converter it can be seen as a solution to overcome some disadvantages of an ordinary EV battery charging system that employs a diode bridge at the front stage. In this case, no bridge structure exists since the two legs are actually two boost converters. Each of these legs are supposed to deal with one half of the input AC voltage, either positive or negative. This arrangement leads to lower conduction losses as there is only one conduction path during each half-cycle. A common goal of such configurations is to achieve unity power factor as well as a proper DC-link voltage regulation with a relatively simple control strategy. Unlike normal PFC converters, which usually employ an advanced control circuit involving a phase or current locked loop in order to properly shape input current, this configuration utilizes a single-loop voltage controller as the simplest possible control approach. In such an implementation, the major aim is simplicity of overall circuit and reasonable cost along with minimal lagging of input current with respect to input voltage control being much simpler to implement in DCM rather than all other modes, will lead to ease in overall procedure. Input inductors will work in CCM mode, to ensure that the input current is smooth. With operation in DCM and CCM modes the output voltage will be well regulated to provide good power quality and small size, both desirable in today's EV chargers due to low harmonic distortion.

2.2 Limitation of Diode bridge rectifier based boost pfc

The standard arrangement of the charger circuit to charge the battery in electric car uses the input AC supply after being passing through the bridge rectifier then it would be connected to boost converter stage. This topology is a cheap and simple one but however, has some

drawbacks as follow: Firstly, the diode bridge rectifier only absorbs current only a short interval in AC cycle. This will result in serious distortion of the input current which contains high harmonics. As analyzed in the referred thesis, the degree of the harmonics distortion could reach about 55% THD which is considered too high in compared with the standard like IEC 61000-3-2. Finally, power factor drops. This time the problem is non sinusoidal input current and distortion and phase discrepancy that significantly limits the power factor of the system. The inefficiency in the power factor means that current is drawn from the grid in the form of unnecessary reactive power, lowering the overall system efficiency. Furthermore, power supplies driven by DBR have large conduction losses as four diodes are used and the conduction of the four diodes happens when two diodes in every half cycle conducting. This causes large voltage drops and thus, heat dissipation and hence lowers system efficiency particularly at lower voltage level and charging currents. The third main drawback of nearly all DBR power supply requires sophisticated multi loop control or extra filter stage in order to satisfy stringent power factor conditions. Such components add size and increase the cost of the power supply. Thus, we can state that a power supply with DBR requires higher conduction losses, power factor distortion and it will also require extra component in the circuit as multi-loop control and filter.

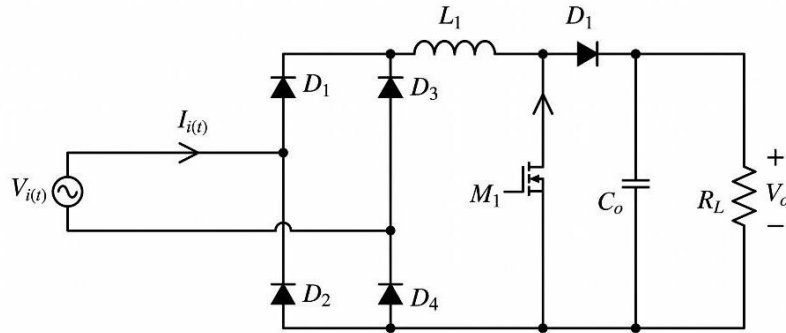


Fig2.1:Conventional boost based PFC converter

2.3 Research Gap Identified

Nevertheless, reviewing quite some existing PFC topologies and BL converters suggested by engineers in the past decades it has been clearly proved that a lot of them cannot meet the real needs for the modern electric vehicle charger. It has been seen that, conventional DBR-based charger is unacceptable with present international standard like IEC 61000-3-2 since it causes input harmonics and poor PF. Several kinds of BL converters were proposed to solve problems of traditional converter; however, it has been found that majority of them possess a poor characteristics-high switching stress and excessive EMI, and complex control

Most of the conventional converters and quite a number of BL boosts and SEPIC converters have displayed a good performance of PFC, but, such good performance are at the expense of an additional sensor or a complicated circuit (like multi-loop or PLLs), therefore making the circuit complicated and expensive.

Other converters only function in CCM, and naturally this also increases the size and cost of components. Yet other converters operate in DCM, but suffer from high voltage stresses or uncontrolled input current. The BL converters have few common problems remaining even the modern topologies, presented all along literature,:

Challenging to obtain solutions with unity power factor, using simple control strategy with no need of PLL and more sensors.

- It is hard to regulate and maintain a stable output voltage while varying input voltage.
- In the EV charger operation, at high powers, switching losses and emission levels are increased.
- The increase in size of components inhibits size reduction of the charger.
- The input harmonics distortions is not greatly reduced as THD goes above 5% limit value.

A suitable bridgeless topology that is able to minimize harmonics, control is more effective, switching stress is lower, the DC output is more stable, fewer components are required and international standard of power factor correction would be very important. The modified BL-boost converter exhibits unity power factor and one control loop, no front end bridge of diode and $THD < 3\%$, hence it is more applicable than other topologies to EV battery charging systems.

Chapter 3

Mathematical Modelling

3.1.1 MODE (a) Positive Half Cycle: S_p ON

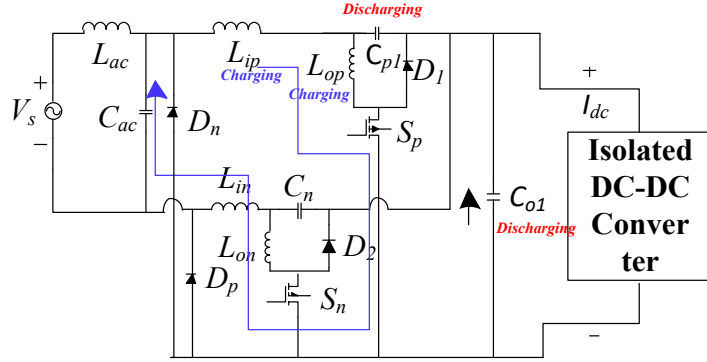


Figure 3.1 Mode Positive I

L_{ip} Charging, L_{op} Charging, C_{p1} Discharging, C_{o1} Discharging

Active devices: S_p ON, D_n conducting Inactive: S_n , D_p , D_1 , D_2 all OFF

KVL Loop 1 AC Input:

$$V_s - L_{ac} \frac{di_{Lac}}{dt} - v_{Cac} = 0 \quad (3.1)$$

$$\boxed{\frac{di_{Lac}}{dt} = \frac{1}{L_{ac}} (V_s - v_{Cac})} \quad (3.2)$$

KVL Loop 2 C_{ac} node (KCL):

$$\boxed{\frac{dv_{Cac}}{dt} = \frac{1}{C_{ac}} (i_{Lac} - i_{Lip})} \quad (3.3)$$

KVL Loop 3 L_{ip} Charging through D_n , S_p :

$$v_{Cac} - L_{ip} \frac{di_{Lip}}{dt} - v_{S_p} = 0 \quad (v_{S_p} = 0 \text{ since } S_p \text{ ON}) \quad (3.4)$$

$$\boxed{\frac{di_{Lip}}{dt} = \frac{1}{L_{ip}} (v_{Cac})} \quad (3.5)$$

KVL Loop 4 L_{op} Charging, C_{p1} Discharging:

$$v_{Cac} - L_{op} \frac{di_{Lop}}{dt} + v_{Cp1} = 0 \quad (3.6)$$

$$\boxed{\frac{di_{Lop}}{dt} = \frac{1}{L_{op}}(v_{Cac} + v_{Cp1})} \quad (3.7)$$

KCL at C_{p1} node Discharging:

$$\boxed{\frac{dv_{Cp1}}{dt} = -\frac{i_{Lop}}{C_{p1}}} \quad (3.8)$$

KCL at output node C_{o1} Discharging:

$$\boxed{\frac{dv_{Co1}}{dt} = -\frac{I_{dc}}{C_{o1}}} \quad (3.9)$$

Mode (a) State-Space Matrix:

$$\frac{d}{dt} \begin{bmatrix} i_{Lac} \\ i_{Lip} \\ i_{Lop} \\ v_{Cac} \\ v_{Cp1} \\ v_{Co1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -\frac{1}{L_{ac}} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_{ip}} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_{op}} & \frac{1}{L_{op}} & 0 \\ \frac{1}{C_{ac}} & -\frac{1}{C_{ac}} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{C_{p1}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{Lac} \\ i_{Lip} \\ i_{Lop} \\ v_{Cac} \\ v_{Cp1} \\ v_{Co1} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{ac}} \\ 0 \\ 0 \\ 0 \\ 0 \\ -\frac{1}{C_{o1}} \end{bmatrix} \begin{bmatrix} V_s \\ I_{dc} \end{bmatrix}$$

3.1.2 MODE (b) Positive Half Cycle: S_p OFF (Transition)

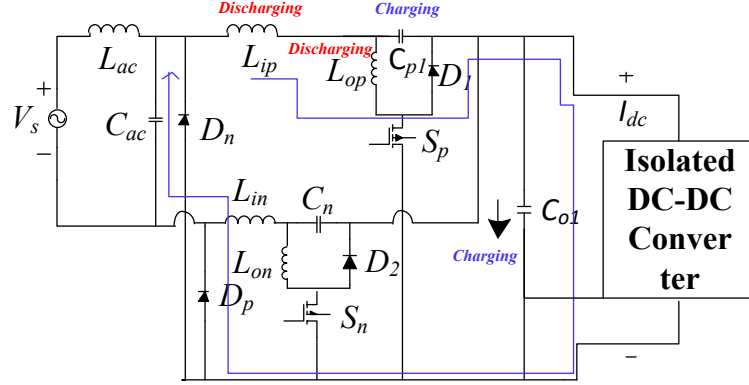


Figure 3.2 Mode Positive II

L_{ip} Discharging , L_{op} Discharging, C_{p1} Charging, C_{o1} Charging

Active devices: D_1 conducting, D_n conducting Switches: Both S_p , S_n OFF

KVL Loop 1 AC Input (unchanged):

$$\frac{di_{Lac}}{dt} = \frac{1}{L_{ac}} (V_s - v_{Cac}) \quad (3.10)$$

KVL Loop 2 C_{ac} :

$$\frac{dv_{Cac}}{dt} = \frac{1}{C_{ac}} (i_{Lac} - i_{Lip}) \quad (3.11)$$

KVL Loop 3 L_{ip} Discharging to output via D_1 :

$$v_{Cac} - L_{ip} \frac{di_{Lip}}{dt} - v_{Co} = 0 \quad (3.12)$$

$$\frac{di_{Lip}}{dt} = \frac{1}{L_{ip}} (v_{Cac} - v_{Co}) \quad (3.13)$$

KVL Loop 4 L_{op} Discharging, C_{p1} Charging:

$$-L_{op} \frac{di_{Lop}}{dt} - v_{Cp1} + v_{Co1} = 0 \quad (3.14)$$

$$\frac{di_{Lop}}{dt} = \frac{1}{L_{op}} (v_{Co1} - v_{Cp1}) \quad (3.15)$$

KCL at C_{p1} Charging:

$$\boxed{\frac{dv_{Cp1}}{dt} = \frac{i_{Lop}}{C_{p1}}} \quad (3.16)$$

KCL at C_{o1} Charging:

$$C_{o1} \frac{dv_{Co1}}{dt} = i_{Lip} + i_{Lop} - I_{dc} \quad (3.17)$$

$$\boxed{\frac{dv_{Co1}}{dt} = \frac{1}{C_{o1}} (i_{Lip} + i_{Lop} - I_{dc})} \quad (3.18)$$

Mode (b) State-Space Matrix:

$$\frac{d}{dt} \begin{bmatrix} i_{Lac} \\ i_{Lip} \\ i_{Lop} \\ v_{Cac} \\ v_{Cp1} \\ v_{Co1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -\frac{1}{L_{ac}} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_{ip}} & 0 & -\frac{1}{L_{ip}} \\ 0 & 0 & 0 & 0 & -\frac{1}{L_{op}} & \frac{1}{L_{op}} \\ \frac{1}{C_{ac}} & -\frac{1}{C_{ac}} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{C_{p1}} & 0 & 0 & 0 \\ 0 & \frac{1}{C_{o1}} & \frac{1}{C_{o1}} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{Lac} \\ i_{Lip} \\ i_{Lop} \\ v_{Cac} \\ v_{Cp1} \\ v_{Co1} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{ac}} \\ 0 \\ 0 \\ 0 \\ 0 \\ -\frac{1}{C_{o1}} \end{bmatrix} \begin{bmatrix} V_s \\ I_{dc} \end{bmatrix}$$

MODE3.1.3 (c) Positive Half Cycle: DCM Transition

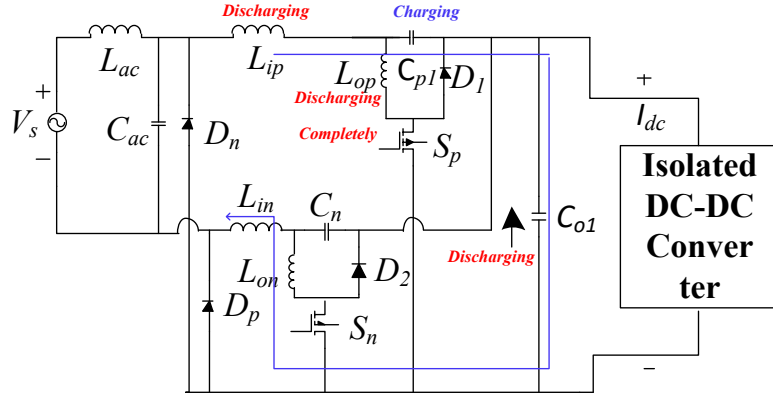


Figure 3.3 Mode Positive III

L_{ip} Discharging, L_{op} Discharging Completely, C_p Charging, C_o Discharging

Active devices : D_n , D_p conducting; L_{op} current reaches zero **Key condition:**

$$i_{Lop} \rightarrow 0 (\text{complete discharge})$$

KVL Loop 1 AC Input:

$$\frac{di_{Lac}}{dt} = \frac{1}{L_{ac}} (V_s - v_{Cac}) \quad (3.19)$$

KVL Loop 2 C_{ac} :

$$\frac{dv_{Cac}}{dt} = \frac{1}{C_{ac}} (i_{Lac} - i_{Lip}) \quad (3.20)$$

KVL Loop 3 L_{ip} Discharging via D_n , L_{in} :

$$v_{Cac} - L_{ip} \frac{di_{Lip}}{dt} - v_{Co1} = 0 \quad (3.21)$$

$$\frac{di_{Lip}}{dt} = \frac{1}{L_{ip}} (v_{Cac} - v_{Co1}) \quad (3.22)$$

Condition: L_{op} Completely Discharged:

$$i_{Lop} = 0 \Rightarrow \frac{di_{Lop}}{dt} = 0 \quad (3.23)$$

The resonant condition between L_{op} and C_{p01} :

$$\omega_r = \frac{1}{\sqrt{L_{op} \cdot C_{p01}}} \quad (3.24)$$

$$v_{Cp01}(t) = V_{Cp01} \cos(\omega_r t) + \sqrt{\frac{L_{op}}{C_{p01}}} \cdot i_{Lop0} \sin(\omega_r t) \quad (3.25)$$

KCL at C_{p01} — Charging toward v_{Co1} :

$$\boxed{\frac{dv_{Cp01}}{dt} = \frac{i_{Lop}}{C_{p01}} = 0} \text{ (after complete discharge)} \quad (3.26)$$

KCL at C_o — Discharging:

$$\boxed{\frac{dv_{Co1}}{dt} = \frac{1}{C_{o1}} (i_{Lip} - I_{dc})} \quad (3.27)$$

MODE3.1.4 (d) — Negative Half Cycle: S_n ON

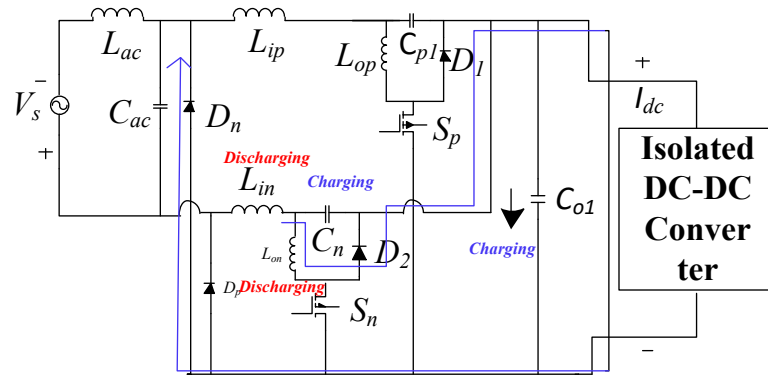


Figure 3.4 Mode Negative I

L_{in} Charging, L_{op} Charging, C_n Discharging, C_{o1} Discharging

Active devices : S_n ON, D_p conducting **Inactive:** S_p , D_n , D_1 , D_2 all OFF

KVL Loop 1 AC

$$-V_s - L_{ac} \frac{di_{Lac}}{dt} - v_{Cac} = 0 \quad (3.28)$$

$$\boxed{\frac{di_{Lac}}{dt} = \frac{1}{L_{ac}} (-|V_s| - v_{Cac})} \quad (3.29)$$

KVL Loop 2 C_{ac} :

$$\boxed{\frac{dv_{Cac}}{dt} = \frac{1}{C_{ac}} (i_{Lac} + i_{Lin})} \quad (3.30)$$

KVL Loop 3 L_{in} Charging through D_p, S_n :

$$|v_{Cac}| - L_{in} \frac{di_{Lin}}{dt} = 0 \quad (3.31)$$

$$\boxed{\frac{di_{Lin}}{dt} = \frac{1}{L_{in}} (|v_{Cac}|)} \quad (3.32)$$

KVL Loop 4 L_{op} Charging, C_n Discharging:

$$v_{Cn} - L_{op} \frac{di_{Lop}}{dt} = 0 \quad (3.33)$$

$$\boxed{\frac{di_{Lop}}{dt} = \frac{v_{Cn}}{L_{op}}} \quad (3.34)$$

KCL at C_n node Discharging:

$$\boxed{\frac{dv_{Cn}}{dt} = -\frac{i_{Lop}}{C_n}} \quad (3.35)$$

KCL at C_{o1} node Discharging:

$$\boxed{\frac{dv_{Co1}}{dt} = -\frac{I_{dc}}{C_{o1}}} \quad (3.36)$$

Mode (d) State-Space Matrix:

$$\frac{d}{dt} \begin{bmatrix} i_{Lac} \\ i_{Lin} \\ i_{Lop} \\ v_{Cac} \\ v_{Cn} \\ v_{Co1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -\frac{1}{L_{ac}} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_{in}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{L_{op}} & 0 \\ \frac{1}{C_{ac}} & \frac{1}{C_{ac}} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{C_n} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{Lac} \\ i_{Lin} \\ i_{Lop} \\ v_{Cac} \\ v_{Cn} \\ v_{Co1} \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_{ac}} \\ 0 \\ 0 \\ 0 \\ 0 \\ -\frac{1}{C_o} \end{bmatrix} \begin{bmatrix} |V_s| \\ I_{dc} \end{bmatrix}$$

MODE 3.1.5 Negative Half Cycle: S_n OFF (Transition)

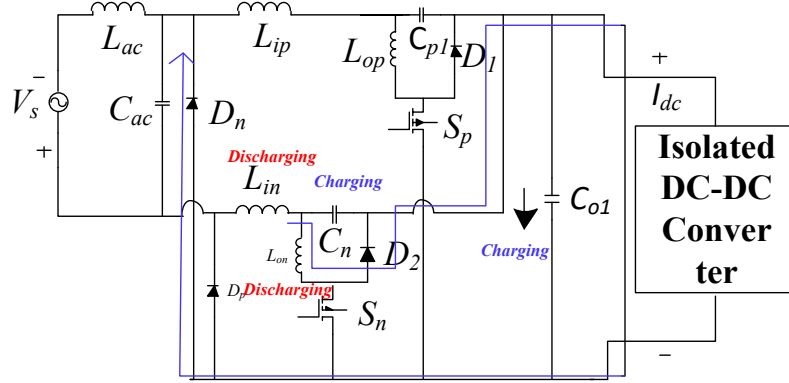


Figure 3.5 Mode Negative III

L_{in} Discharging, L_{op} Discharging, C_n Charging, C_{o1} Charging

Active devices: D_2 conducting, D_p conducting **Switches:** Both OFF

KVL Loop 1:

$$\frac{di_{Lac}}{dt} = \frac{1}{L_{ac}} (-|V_s| - v_{Cac}) \quad (3.37)$$

KVL Loop 2 C_{ac} :

$$\frac{dv_{Cac}}{dt} = \frac{1}{C_{ac}} (i_{Lac} + i_{Lin}) \quad (3.38)$$

KVL Loop 3 — L_{in} Discharging to output via D_2 :

$$|v_{Cac}| - L_{in} \frac{di_{Lin}}{dt} - v_{Co1} = 0 \quad (3.39)$$

$$\frac{di_{Lin}}{dt} = \frac{1}{L_{in}} (|v_{Cac}| - v_{Co1}) \quad (3.40)$$

KVL Loop 4 — L_{op} Discharging, C_n Charging:

$$-L_{op} \frac{di_{Lop}}{dt} - v_{Cn} + v_{Co1} = 0 \quad (3.41)$$

$$\frac{di_{Lop}}{dt} = \frac{1}{L_{op}} (v_{Co1} - v_{Cn}) \quad (3.42)$$

KCL at C_n — Charging:

$$\boxed{\frac{dv_{Cn}}{dt} = \frac{i_{Lop}}{C_n}} \quad (3.43)$$

KCL at C_o — Charging:

$$\boxed{\frac{dv_{Co}}{dt} = \frac{1}{C_{o1}} (i_{Lin} + i_{Lop} - I_{dc})} \quad (3.44)$$

Mode (e) State-Space Matrix:

$$\frac{d}{dt} \begin{bmatrix} i_{Lac} \\ i_{Lin} \\ i_{Lop} \\ v_{Cac} \\ v_{Cn} \\ v_{Co1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -\frac{1}{L_{ac}} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_{in}} & 0 & -\frac{1}{L_{in}} \\ 0 & 0 & 0 & 0 & -\frac{1}{L_{op}} & \frac{1}{L_{op}} \\ \frac{1}{C_{ac}} & \frac{1}{C_{ac}} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{C_n} & 0 & 0 & 0 \\ 0 & \frac{1}{C_{o1}} & \frac{1}{C_{o1}} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{Lac} \\ i_{Lin} \\ i_{Lop} \\ v_{Cac} \\ v_{Cn} \\ v_{Co1} \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_{ac}} \\ 0 \\ 0 \\ 0 \\ 0 \\ -\frac{1}{C_{o1}} \end{bmatrix} \begin{bmatrix} V_s \\ I_{dc} \end{bmatrix}$$

MODE 3.1.6 Negative Half Cycle: DCM Transition

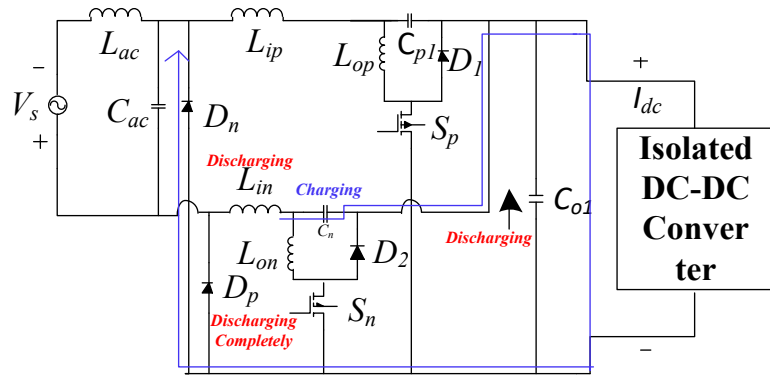


Figure 3.6 Mode Negative III

L_{in} Discharging, L_{op} Discharging Completely, C_n Charging, C_o Discharging

Active devices: D_n, D_p conducting; $i_{Lop} \rightarrow 0$

KVL Loop 1:

$$\boxed{\frac{di_{Lac}}{dt} = \frac{1}{L_{ac}} (-|V_s| - v_{Cac})} \quad (3.45)$$

KVL Loop 2:

$$\boxed{\frac{dv_{Cac}}{dt} = \frac{1}{C_{ac}} (i_{Lac} + i_{Lin})} \quad (3.46)$$

KVL Loop 3 L_{in} Discharging:

$$\boxed{\frac{di_{Lin}}{dt} = \frac{1}{L_{in}} (|v_{Cac}| - v_{Co})} \quad (3.47)$$

Resonant condition (L_{op} - C_n):

$$\omega_r = \frac{1}{\sqrt{L_{op}C_n}} \quad (3.48)$$

$$i_{Lop}(t) = I_{Lop0} \cos(\omega_r t) - \frac{v_{Cn0}}{\sqrt{L_{op}/C_n}} \sin(\omega_r t) \quad (3.49)$$

After complete discharge ($i_{Lop} = 0$):

$$\boxed{\frac{di_{Lop}}{dt} = 0}, \boxed{\frac{dv_{Cn}}{dt} = 0} \quad (3.50)$$

KCL at C_o :

$$\boxed{\frac{dv_{Co1}}{dt} = \frac{1}{C_{o1}} (i_{Lin} - I_{dc})} \quad (3.51)$$

UNIFIED AVERAGED MODEL (All 6 Modes Combined)

Using **state-space averaging** with duty cycles d_p (positive) and d_n (negative):

$$d_p + d_n \leq 1, d_p = \frac{t_{on,p}}{T_s}, d_n = \frac{t_{on,n}}{T_s} \quad (3.52)$$

The averaged system matrix:

$$\mathbf{A}_{avg} = d_p \mathbf{A}_a + (d'_p) \mathbf{A}_b + d_n \mathbf{A}_d + (d'_n) \mathbf{A}_e \quad (3.53)$$

where $d'_p = 1 - d_p$ and $d'_n = 1 - d_n$.

Averaged Equations (Positive half, by symmetry negative half is analogous):

$$\boxed{L_{ip} \frac{d\langle i_{Lip} \rangle}{dt} = d_p \langle v_{Cac} \rangle - (1 - d_p) \langle v_{Co1} \rangle} \quad (3.54)$$

$$\boxed{L_{op} \frac{d\langle i_{Lop} \rangle}{dt} = d_p (\langle v_{Cac} \rangle + \langle v_{Cp} \rangle) - (1 - d_p) (\langle v_{Co1} \rangle - \langle v_{Cp} \rangle)} \quad (3.55)$$

$$\boxed{C_p \frac{d\langle v_{Cp} \rangle}{dt} = (1 - d_p) \langle i_{Lop} \rangle - d_p \langle i_{Lop} \rangle} \quad (3.56)$$

$$\boxed{C_{o1} \frac{d\langle v_{Co1} \rangle}{dt} = (1 - d_p) \langle i_{Lip} \rangle + (1 - d_p) \langle i_{Lop} \rangle + (1 - d_n) \langle i_{Lin} \rangle - I_{dc}} \quad (3.57)$$

TRANSFER FUNCTION DERIVATION

Step 1: Find DC Steady -State Operating Point

At steady state, all derivatives = 0. From averaged equations:

From inductor volt-second balance on L_{ip} :

$$D_p V_{Cac} = (1 - D_p) V_{Co1} \quad (3.58)$$

$$\boxed{V_{Co1} = \frac{D_p}{1 - D_p} V_{Cac} = \frac{V_{Cac}}{1 - D_p}} \quad (3.59)$$

Steady-state duty cycle:

$$\boxed{D_p = 1 - \frac{V_{Cac}}{V_{Co1}}} \quad (3.60)$$

Steady-state inductor current:

$$I_{Lip} = \frac{P_{in}}{V_{Cac}} = \frac{V_{Co1} I_{dc}}{V_{Cac}} \quad (3.61)$$

Step 2: Perturbation and Linearisation

Let every variable = DC value + small-signal perturbation:

$$d_p = D_p + \hat{d}, v_{Co1} = V_{Co1} + \hat{v}_{Co1}, i_{Lip} = I_{Lip} + \hat{i}_{Lip}, v_{Cac} = V_{Cac} + \hat{v}_{Cac} \quad (3.62)$$

Substituting into averaged equations and **neglecting second-order (product of two small-signal) terms**:

Linearised L_{ip} equation:

$$L_{ip} \frac{d\hat{i}_{Lip}}{dt} = D_p \hat{v}_{Cac} - (1 - D_p) \hat{v}_{Co1} + (V_{Cac} + V_{Co1}) \hat{d} \quad (3.63)$$

$$\boxed{L_{ip} \frac{d\hat{i}_{Lip}}{dt} = D_p \hat{v}_{Cac} - (1 - D_p) \hat{v}_{Co1} + \frac{V_{Co}}{1 - D_p} \hat{d}} \quad (3.64)$$

Linearised C_{o1} equation:

$$C_{o1} \frac{d\hat{v}_{Co1}}{dt} = (1 - D_p) \hat{i}_{Lip} - I_{Lip} \hat{d} - \hat{I}_{dc} \quad (3.65)$$

$$\boxed{C_{o1} \frac{d\hat{v}_{Co1}}{dt} = (1 - D_p) \hat{i}_{Lip} - \frac{V_{Co}}{R_o(1 - D_p)} \hat{d} - \frac{\hat{v}_{Co1}}{R_o}} \quad (3.66)$$

where $R_o = \frac{V_{Co1}^2}{P_o}$ and $I_{dc} = \frac{v_{Co1}}{R_o}$.

Step 3: Take Laplace Transform

$$sL_{ip} \hat{I}_{Lip}(s) = D_p \hat{V}_{Cac}(s) - (1 - D_p) \hat{V}_{Co1}(s) + \frac{V_{Co1}}{1 - D_p} \hat{D}(s) \quad (3.67)$$

$$sC_{o1} \hat{V}_{Co1}(s) = (1 - D_p) \hat{I}_{Lip}(s) - \frac{\hat{V}_{Co1}(s)}{R_{o1}} - \frac{V_{Co1}}{R_{o1}(1 - D_p)} \hat{D}(s) \quad (3.68)$$

Step 4: Solve for Control to Output Transfer Function

Set $\hat{V}_{Cac} = 0$, $\hat{I}_{dc} = 0$ (input perturbation = 0)

From equation (3.67) :

$$\hat{I}_{Lip}(s) = \frac{-(1 - D_p) \hat{V}_{Co1}(s) + \frac{V_{Co1}}{1 - D_p} \hat{D}(s)}{sL_{ip}} \quad (3.69)$$

Substitute (3.68) into (3.67):

$$sC_{o1} \hat{V}_{Co1} = (1 - D_p) \left[\frac{-(1 - D_p) \hat{V}_{Co1} + \frac{V_{Co1}}{1 - D_p} \hat{D}}{sL_{ip}} \right] - \frac{\hat{V}_{Co1}}{R_{o1}} - \frac{V_{Co1}}{R_{o1}(1 - D_p)} \hat{D} \quad (3.70)$$

Multiply through by sL_{ip} :

$$s^2 L_{ip} C_{o1} \hat{V}_{Co1} = -(1 - D_p)^2 \hat{V}_{Co1} + V_{Co1} \hat{D} - \frac{sL_{ip}}{R_{o1}} \hat{V}_{Co} - \frac{sL_{ip} V_{Co1}}{R_{o1}(1-D_p)} \hat{D} \quad (3.71)$$

Collecting $\hat{V}_{Co1}$ terms:

$$\hat{V}_{Co1} \left[s^2 L_{ip} C_{o1} + \frac{sL_{ip}}{R_{o1}} + (1 - D_p)^2 \right] = V_{Co1} \hat{D} \left[1 - \frac{sL_{ip}}{R_{o1}(1-D_p)} \right] \quad (3.72)$$

Step 5: Final Transfer Function

$$G_{vd}(s) = \frac{\hat{V}_{Co1}(s)}{\hat{D}(s)} = \frac{V_{Co1} \left(1 - \frac{sL_{ip}}{R_{o1}(1-D_p)} \right)}{s^2 L_{ip} C_{o1} + \frac{sL_{ip}}{R_o} + (1-D_p)^2} \quad (3.72)$$

3.2 Operation of Bridgeless Modified Boost Converter

Operating modes of DC to DC converter

There are two modes of operation depending on the property of the inductor current flow during one entire switching cycle. The modes are given below:

1. Discontinuous conduction mode (DCM)
2. Continuous conduction mode (CCM)

Discontinuous conduction mode (DCM)

In the discontinuous conduction mode, one switching edge of inductor remain idle in an entire switching cycle of zero inductor current with no charging and discharging takes place. There are three intervals in the switching cycle; they are DT, DT and DT, so that $D + D + D = 1$. The first two intervals have increase and decrease of inductor current as usual while the last interval does not affect anything.

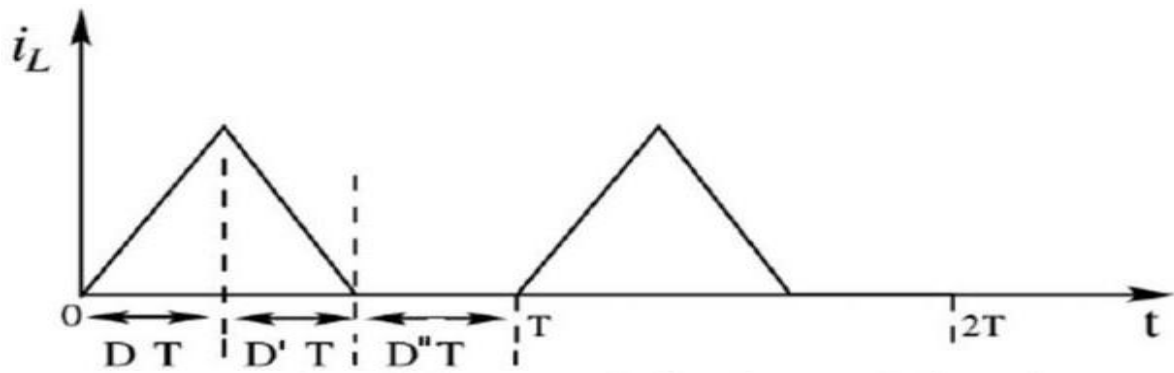


Fig3.7:DCM of Modified BL Boost Converter

Continuous Conduction Mode (CCM)

This problem comes from continuity of the inductance of the current weft price and of the output of all components in one switching period. The CCM assumes that each switching cycle consists of two periods: DT and DT such that $D + D=1$. An increasing part of the inductance mode will arise in the primary and secondary modes when both of DT and DT are shortened.

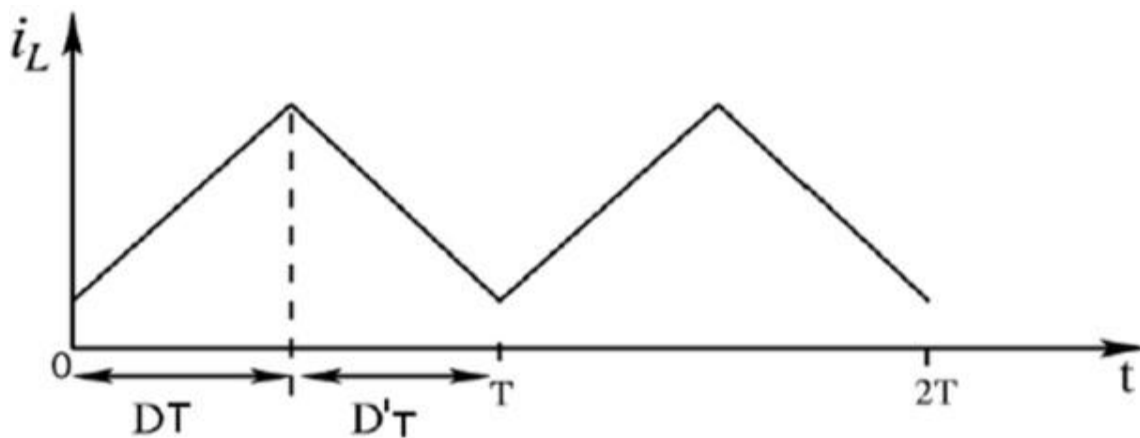


Figure 3.8 CCM of Modified BL Boost Converter

For you to be able to conceptualize this process and understand how the converter actually functions, you can view this system to be symmetrical with mirrors facing each other. One would need to visualize the arrangement of components that is activated; one set on the first positive half cycle (inductor, switch, and diode), and another one on the second negative half cycle.

Mode Positive I

Upper/Positive Path: Upper path of the converter works on the positive half cycle of AC Supply where as the lower path is blocked at this time.

Input Filter Lac-Cac: This filter will help to smooth the waveform so that start-up noise of the current will be suppressed. When the positive switch (S_p) conduct then current will flow through the input inductor (L_{ip}) and the Boost inductor (L_{op}) towards the AC Source. In this condition both the input inductor (L_{ip}) and the Boost inductor (L_{op}) stores the magnetic energy in their magnetic field and so current in these inductors increases with time. With the help of gradual increase in current we can measure input current. And at this moment DC link capacitor stores energy from intermediate capacitor (C_{p01}) that provide the required energy for load and the forthcoming DC-DC conversion. Energy cannot flow to DC link capacitor via L_{ip} and L_{op} because of reverse biased nature of output diode D_1 . DC link capacitor (C_{o1}) will provide power to the DC-DC converter at this instant. The objective of positive Mode-I is mainly charging of inductors.

Mode Positive II

As AC input positive half cycle is present, the converter comes into Positive Mode-II immediately the main switch S_p is turned OFF. Now as the L_{op} is discharged through the output diode D_1 no more energy can be stored in the boost inductor L_{op} and energy is delivered from boost inductor L_{op} to the DC-link capacitor C_{o1} . The C_{p01} will be charged which aids the filtering and input inductor L_{ip} aids in the delivery of energy to ensure the input current becomes sinusoidal. As no more diode bridge rectifier will be required and the current would be passing through the semiconductor devices. The energy will be fed to the DC-link capacitor C_{o1} which is now supplying the isolated DC-DC converter which used for the EV battery charging. So this is the point power is delivered and therefore power delivered from the AC to battery charging is manifested.

Mode Positive III

The Mode III starts when energy transfer is completed for one switching period during the positive half cycle of ac source. During this mode, boosted inductor L_{op} is completely loaded with energy, the current is zero, and the mode is switched over to DCM mode. Thus, no energy

is available to transfer from the source because there is no current in the inductor. Power delivery to isolated DC-DC converter that will deliver to battery is handled by dc-link capacitor $Co1$, which has the smooth energy delivery for a constant amount of power deliver to isolated DC-DC converter. Intermediate capacitor $Cp01$ accepts charge and keeps voltage of the dc-link level. This introduces a necessary dead-time which reduce the strain on switching semiconductor devices and also avoid losses. Using Lop in mode III of DCM is beneficial in EV charging because the current ripple is smaller.

Mode Negative I

The other half cycle of the AC supply input voltage implies a operation in negative Mode-I of the converter circuit where a lower switch leg is activated with an opened higher switch leg. In negative Mode-I of AC-to-DC converter circuit operation, the lower switching switch S_n is turned ON so the conducting path is created solely at the negative side. It can be observed that the current from input flow towards input filter and in to lower side input inductor L_{in} that it denotes a start to the charging stage. In this instant, inductor L_{on}/L_{op-n} starts getting charged from magnetic field energy and not from an instantaneous spike.

Energy transfer capacitor C_n during this time is being discharged and supports in charging the inductor and the output diode $D2$ is reverse biased. The independent supply to DC-DC converter is provided by DC link capacitor Co . Fewer power semiconductor switches compared to bridge rectifier mode of operation which supports in decreasing losses of the converter circuit is found. This mode mainly indicates the stage where energy is stored, and input current waveform shape is made in correspondence to input voltage waveform so that power factor of the converter is equal to unity.

Mode Negative II

This works in the negative half cycle after the storing process is complete where switch S_n gets switched off. When switch S_n is OFF the energy cannot be stored any more in the lower boost inductor L_{op-n} . This is being charged through output diode $D2$ and so magnetic energy is forwarded from L_{op-n} and it starts charging the DC link capacitor $Co1$. This mode will charge up the energy transfer capacitor C_n . The input inductor L_{in} ensures that current moves towards source side in a continuous fashion. Therefore the input current is smooth as no diode bridge is present and the number of conducting switches is also lower and hence conduction losses

reduced. DC-link capacitor C_o which is also known as bulk capacitor stores the energy and supplied to the isolation DC-DC converter which provides to the EV battery. This mode has significant portion of the negative cycle current delivery phase same as that of Positive Mode-II. Negative Mode-II therefore has an essential part to play in an effective energy transmission with the lowest harmonics distortion and highest power factor approaching unity.

Mode Negative III

The Negative Mode-III. Negative Mode-III occurs after the completion of energy transfer during the negative half-cycle; it occurs when the whole stored energy in the lower boost inductor L_{op-n} is transferred to the circuit and hence the inductor current falls to zero, indicating that the system is in DCM. Since the inductor current falls to zero, the energy will not be drawn from the AC source. Subsequently, energy will be transferred from the DC-link capacitor C_o to provide a continuous power supply to the isolated DC-DC converter which charges the EV battery. The energy transfer capacitor C_n is being charged at this instant and maintains the voltage. The input inductors provide a smooth transition by suppressing sharp

peaks of current; hence the input current is still sinewave as there is no switch used. As usual this mode allows recovery without any extra losses or stress in semiconductor switches; moreover this mode improve efficiency, life time and robustness of components. Hence this mode finishes the negative half-cycle with high power factor and very small current distortion. The Negative Mode-III. Negative Mode-III occurs after the completion of energy transfer during the negative half-cycle; it occurs when the whole stored energy in the lower boost inductor L_{op-n} is transferred to the circuit and hence the inductor current falls to zero, indicating that the system is in DCM. Since the inductor current falls to zero, the energy will not be drawn from the AC source. Subsequently, energy will be transferred from the DC-link capacitor C_o to provide a continuous power supply to the isolated DC-DC converter which charges the EV battery. The energy transfer capacitor C_n is being charged at this instant and maintains the voltage. The input inductors provide a smooth transition by suppressing sharp peaks of current; hence the input current is still sinewave as there is no switch used. As usual this mode allows recovery without any extra losses or stress in semiconductor switches; moreover this mode improve efficiency, life time and robustness of components. Hence this mode finishes the negative half-cycle with high power factor and very small current distortion.

Chapter 4

Designing and component sizing

4.1 Design Parameters

The circuit parameters for the boost converter are designed using the equations provided below:
 $V_{in} = 220V$, $V_o = 865V$, $F_s = 20KHz$, $P = 6800W$.

The duty ratio of the gate signals provided to the boost converter switch is provided as

$$D = \frac{V_o - V_{in}}{V_o}.$$

D=0.74

The following equation provides the inductor of the boost converter:

$$L_{ip}(= L_{in}) = \left(\frac{V_{smin}^2}{P_i} \right) \frac{1}{0.2 * f_{sL}} \frac{V_o - V_s}{V_o}$$

=566μH

$$L_{op}(= L_{on}) = \left(\frac{V_{smin}^2}{P_i} \right) \frac{D_a}{2 * f_{sL}}$$

=40μH

The energy transfer capacitor value is provided below:

$$C_{p01}(= C_{n01}) = \frac{P_i(V_o - \sqrt{2}V_{smax})}{\gamma\sqrt{2}V_{smax}f_{sL}V_o^2}$$

=80μF

The design of intermediate dc-link capacitor is C_{o1} is provided below:

$$C_{o1} = \frac{I_o}{2w_L\Delta V_o}$$

=0.07mF

The output capacitor ripple voltage is calculated using following relation:

$$\Delta V_{oc} = 2\% \text{ of } V_o$$

ΔVc= 18V

Design of Filter capacitor:

In power supply circuits, this capacitor can be calculated to ensure the least ripple at the output. The formula is

$$C = I/2fV_{pp}$$

From the equation above, 'I' is load current, 'f' is i/p frequency of AC and 'Vpp' is the minimum ripple that may be acceptable. The capacitor value is calculated as **0.6 mF**.

4.2 Control strategy of PFC Boost converter

The bridgeless boost converter uses a single loop voltage control strategy to regulate the DC link voltage

and improve the input power factor. The output voltage (V_o) is continuously measured and compared with a predefined reference voltage (V_{ref}). The difference between these two values generates an error signal:

$$e(t) = V_{ref} - V_o$$

This error signal is processed by a Proportional-Integral (PI) controller, which produces a control signal according to:

$$u(t) = K_p e(t) + K_i \int e(t) dt$$

The output of the PI controller determines the duty cycle of the converter switches. This duty cycle is compared with a high frequency sawtooth carrier waveform to generate PWM pulses for switches S_p and S_n .

The duty cycle controls the boost converter output voltage to:

$$D = \frac{V_o - V_{in}}{V_o}$$

Where D is the duty ratio. If the output voltage drops below the reference value, the controller increases the duty cycle allowing more energy to be stored in inductors and transferred to the output. Similarly when the output voltage exceeds the reference value, the duty cycle is reduced to maintain a stable DC link voltage.

The converter is designed such that the input current follows the shape of the input voltage. As a result the source current remains nearly sinusoidal and in phase with the source voltage, leading to power factor near unity:

$$PF = \frac{P}{V_{rms} I_{rms}} \approx 1$$

This approach eliminates the need for an additional current control loop or phase locked PLL, making the control switches simpler while achieving effective power factor correction and output voltage regulation

4.1 Control Principle

Output of this regulator is DC and varies neither with the load current nor with input voltage. Stability of output voltage is because of the drifting of the component values of

regulator over time and with change in temperature and pressure. Following are the most popular two closed loop control strategies used in PWM regulators. 1) Voltage-mode control 2) Current-mode control

i) Voltage Mode Control

In this type of control system, the feedback circuit of resistive voltage divider is used for the control of the output voltage of the DC-DC converter. Feedback voltage is compared with the reference voltage which is externally given and known as V_{ref} with the help of a voltage error amplifier. With the help of the voltage error amplifier a control voltage is obtained and this voltage is then compared with a constant magnitude sawtooth signal and finally the PWM signal which is used to drive the switch of the DC-DC converter is obtained from the comparator or the PWM modulator.

ii) Current Mode Control

The method to be used is Current Mode Control. There are a number of advantages when using Current Mode Control rather than a voltage mode control technique. As voltage is dependent on accumulated flux, which is a lagged effect, greater development has been carried out regarding the switch mode power supplies using Current Mode Control. Current Mode Control is designed to operate using the peak and average current values of the feedback path of the converters.

PI controller's uses in industry are very common where fast response system is not required. PI controller is implemented in following conditions:-

- a) If there is no need of fast response system;
- b) if the disturbance and noises in the system are in a high order;
- c) If the storage element for the process is one; and
- d) if there is lag in the process.

The use of both proportional and integral control action is mainly due to the elimination of static errors obtained with only the use of the proportional controller. Though stability of the system and speed of response might get affected with their use; they are widely used if there is no requirement of speed response system. This type of control action is not able to predict future system errors, so it can never improve the rise time and oscillations.

Manual Tuning Method

This kind of tuning occurs by adjusting the process variables according to the behavior of the process. Adjusting is made due to deviation between ideal and actual behavior of the system. The way to control oscillation: decrease the proportional, derivative constants to 0 while increase the integral constant to 100. In such conditions, increase the proportional gain until reaches 100 and the system behaves as we desire. If process behaves desired, we can adjust the setpoint. If not, decrease the proportional gain, as soon as oscillate system, adjust it; and increases derivative constant to 100. continue to process as above by decreasing and increasing the value of integral constant from 0 to 100 until it reaches as we desire, after tuning with integral gain adjust proportional gain until value 100.

Finally, lower the value of the proportional gain to 100.0 and then lower the value of the integral gain by 10% or 20%. Although the process for tuning looks very straight forward but it take quite an amount of time & effort & knowledge of an operator. PI control was one of the earliest control algorithm that has been used in industry. It has various advantage over many other control algorithm due to it: economic price; easy to tune, easy to implement, easy to maintain, & robustness. Actually PI controller algorithm has proven very effective on industrial applications as this algorithm does not have a specific model so, it could also be implemented for various types of non-model dependent processes such as complex & hard to model processes. But the algorithm has some disadvantages which include:

Proportional Controller

A proportional (P) controller produces an output signal which is proportional to the difference between the reference value and the measured output. For example, if the difference increases, the output signal of the controller increases in proportion to make the system reach the operating point. The gain is adjusted proportional to get quicker error correction but too large gain can cause instability in the system which creates oscillations. A proportional controller is not able to fully eliminate the steady state error and some residual offset can remain so an integral term usually added.

Integral Controller

The integral controller (I) produces an output proportional to both the magnitude and duration of the error. It calculates an integral of the error as a function of time and the

control signal is varied until the error is zero at steady state. Therefore, with an integral controller, the system output can follow the setpoint with no steady state offset. The disadvantage of integral control is that it tends to reduce system response time and it causes oscillations if the integral gain is set too high. For this reason it is usually employed with proportional control. Integral control action offers a very good low-frequency gain.

Chapter 5

Simulation Analysis

5.1 Simulation Setup of Modified BL Boost Converter

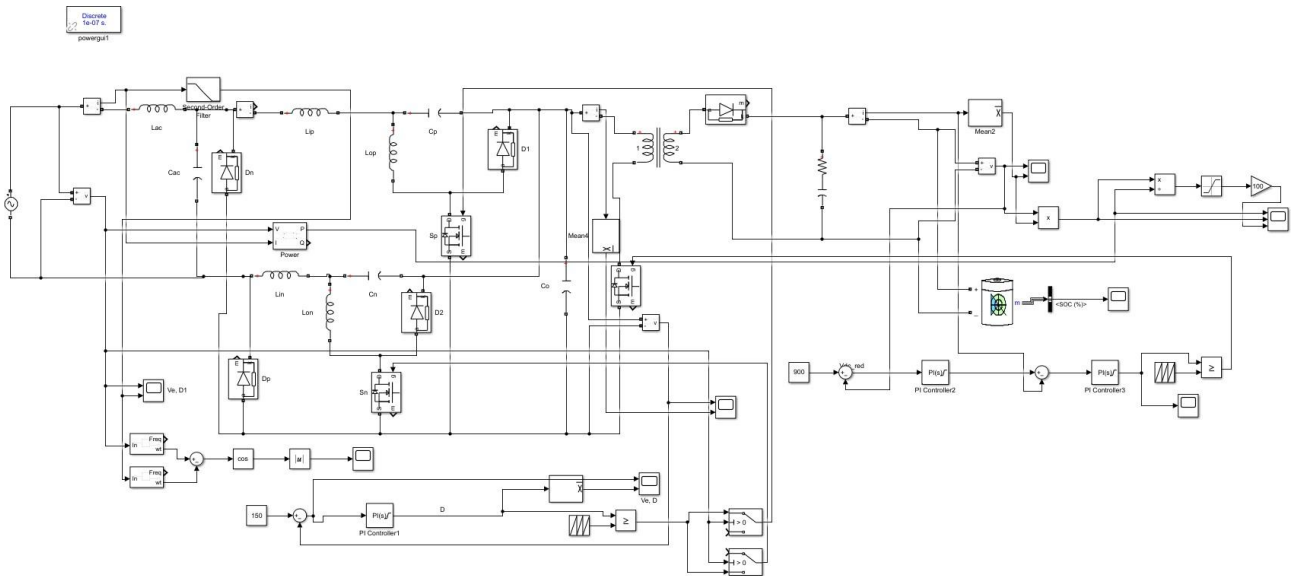


Fig 5.1: Simulation Setup Modified BL Boost Converter

5.2 Simulation Parameters for BL Modified Boost Converter

Parameters	Values
Switching frequency	20KHz
Load Power (in watts)	6.5KW
Input Voltage	230V
OutputVoltage	859V
Battery Capacity	7.5Ah
Flyback Converter output voltage	389V
Flyback Converter output current	16A

Table 1: List of parameters for BL Modified Boost Converter

5.3 Simulation Results

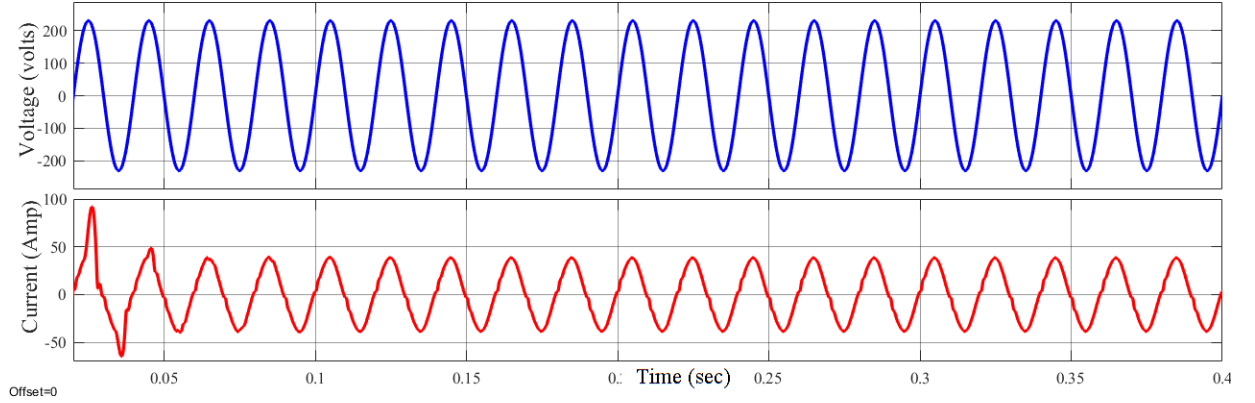


Fig 5.2: Waveform of input voltage & current

Figure 5.2 shows the input voltage and input current waveforms of the proposed bridgeless modified boost converter when operating in steady state. The waveform shows that the input voltage waveform has a sinusoidal shape with 50Hz and magnitude of roughly 230V. It can also be observed that the input current waveform is very similar to the input voltage waveform; that is, they are in phase. There is an initial spike on the current waveform at the beginning; nevertheless it reaches steady state operation soon. Hence, with the source current in sinusoidal waveform form, power factor correction is well done as it is close to one.

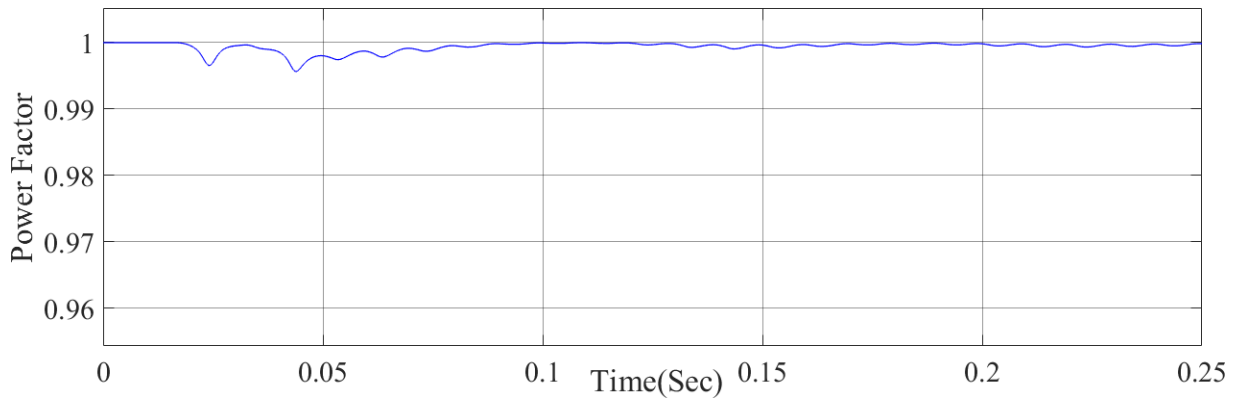


Figure 5.3 Waveform of achieving unity power factor

As shown in Figure 5.3, there is good quality of power, with a power factor staying above 0.99 for the entire period of 0.25 seconds monitored. There are some transient dips within the range of around 0.02 to 0.05 seconds, during which the power factor drops to about

0.996, but there is very fast restoration to normal thereafter.

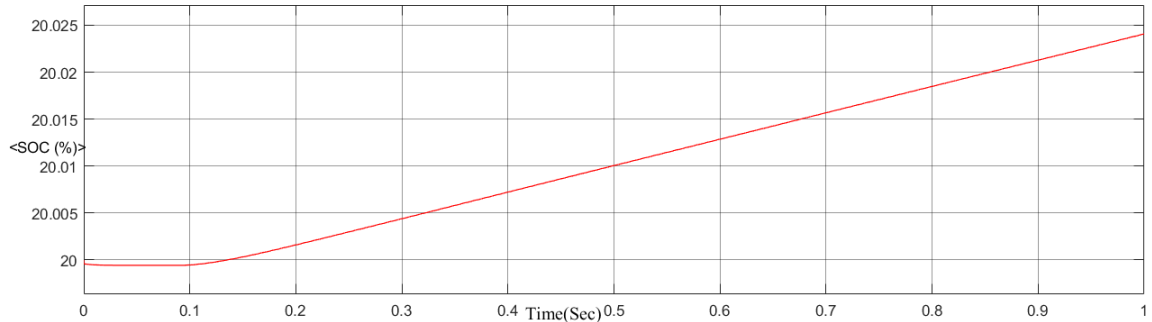


Fig 5.4: Waveform of State of Charge

The State of Charge (SOC) of the battery while charging takes place is shown in the Fig 5.3. The battery has initial SOC value nearly 20% before the charging process. The battery SOC continuously increase with time, an initial transient time period can be observed where the SOC increase with steep slope then SOC increase with constant slope.

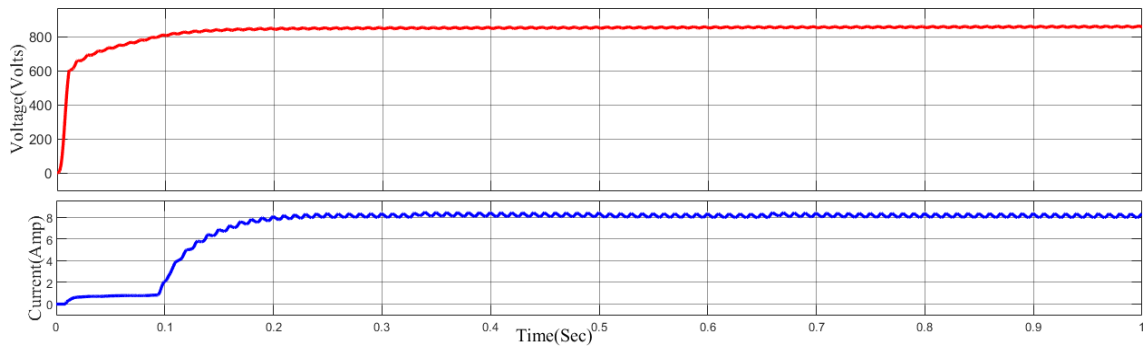


Fig 5.5 Output voltage and current of BL Boost Converter

Figure 5.5 above shows the waveform diagram of the output voltage and output current when the converter is in steady state. As can be seen in Figure 5.5, the output voltage rises sharply at startup time until it is stable around 859V. It is noticeable that there is a good control over the output voltage as it has low ripple on the waveform. Similarly, output current is rising at a slow rate until it reaches a steady state at around 8.04A. It is noted that there are relatively small ripples

present on both the current and voltage waveform because of switching action of the circuit.

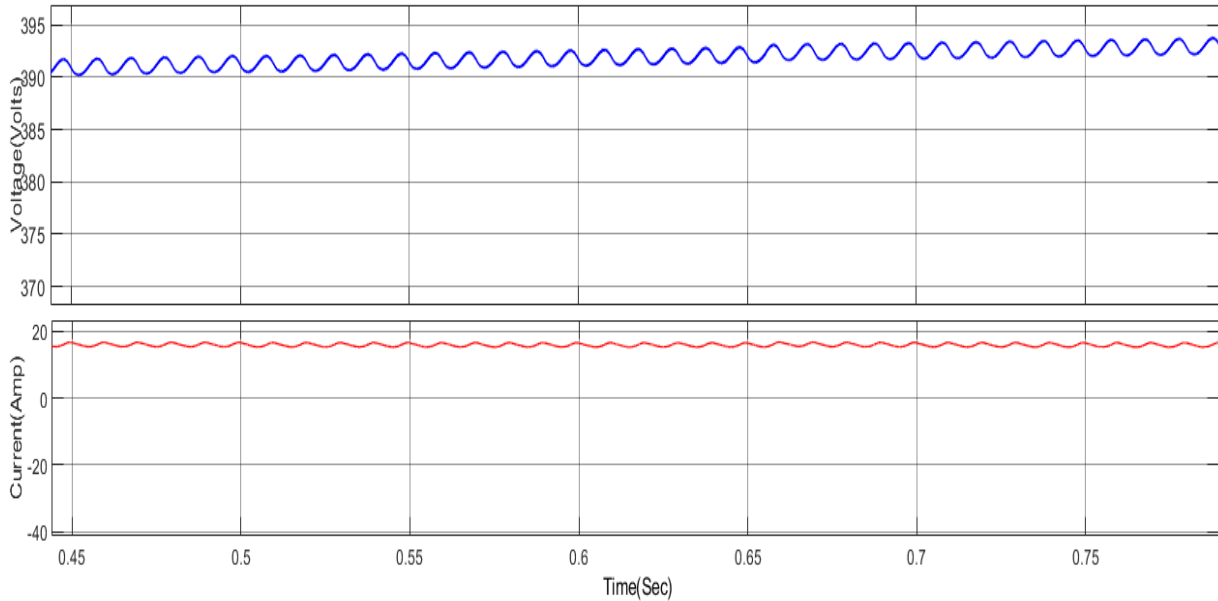


Fig5.6 Output voltage and current of Flyback Converter

Figure 5.6 shows waveforms of the battery voltage and charging current generated from the charging. As can be observed the battery voltage is approximately constant 389V and the voltage regulation using flyback converter is achieved. Meanwhile the charging current is also stable approximately 16A. In each of the waveform, small ripples can be detected due to the switching function of the converter and the energy transfer through the transformer. Very little ripple is present in the voltage, the charging voltage is therefore stable while in acceptable level of current ripple.

Chapter 6

Conclusion and Future Scope

6.1 Conclusion

All design aspects of the bridgeless modified boost PFC converter are thoroughly analyzed in this chapter. All components, as well as all control strategies, were carefully chosen to ensure adequate power quality, regulation of voltage and overall good operation under various scenarios.

Chapter is initiated with an overview of the design requirements and design concepts, the ones being to regulate the d.c. Link voltage, obtain low THD, and make sure that the system operation is achieved with power factor of one. According to these concepts, correct component values, as well as appropriate design techniques have been selected. Continuous conduction mode has been selected to operate input inductors due to their benefits as compared to discontinuous mode of operation. 20% ripple on input current is allowed when a sinusoidal current is to be produced. Output inductors have to be operated in discontinuous conduction mode due to easier control and the natural PF correction it makes possible.

Energy transfer capacitors are sized correctly to limit the high frequency ripples on the voltage, and allow energy to be transported between stages without problems. D.c. Link capacitor is sized such that low frequency fluctuations on voltage are limited to produce stable voltage to charge the batteries.

6.2 Future Scope

In fact, there are several good qualities of the PFC converter using the bridgeless modified boost topology that could be enhanced further. Among these qualities are good PFC, good regulating abilities and suitable harmonic mitigation. However, there are many aspects where enhancement could be provided by means of future better EVs network, advanced semiconductors or energetic efficiency.

Putting the PFC part and DC-DC converters within the same physical body definitely makes sense and offers new prospects apart from being cheap and efficient in the production. For instance, development of special algorithms could allow the mode transitions during the charging process to be as smooth as possible.

Soft switching could be beneficial to reduce the switching losses and EMI. Techniques such as zero voltage or zero current switching could reduce the losses considerably and make the whole charger run cool, which is essential for the power supply.

Considering the development speed in semiconductor materials field, it should be possible to make use of latest developments like GaN or SiC MOSFET wide band gap transistors which are superior in switching speed and operate temperature than silicon transistors.

The implementation of alternative control strategies, such as model predictive control, adaptive control, or an estimator which employ machine learning algorithms, could be considered in the future for output voltage and input current regulation to provide a fast and accurate control performance.

REFERENCES

1. K. V. Suhaskrishnan, V. Sruthy, and P. K. Preetha, "Smart grid compatible universal electric vehicle charging outlet to boost India's EV penetration rate," in Proc. IEEE 19th India Council Int. Conf., 2022, pp. 1-6.
2. Limits for Harmonics Current Emissions (Equipment Current 16 A Per Phase), IEC Standard IEC 61000-3-2, 2000.
3. IEEE Standard for Harmonic Control in Electric Power Systems, IEEE Standard 5192022 (Revision of IEEE Standard 519-2014), Aug. 2022.
4. D. Patil and V. Agarwal, "Compact onboard single-phase EV battery charger with novel low-frequency ripple compensator and optimum filter design," IEEE Trans. Veh. Technol., vol. 65, no. 4, pp. 1948-1956, Apr. 2016.
5. J.-H. Kim, C.-E. Kim, J.-K. Kim, J.-B. Lee, and G.-W. Moon, "Analysis on loadadaptive phase-shift control for high-efficiency full-bridge LLC resonant converter under light-load conditions," IEEE Trans. Power Electron., vol. 31, no. 7, pp. 4942-4955, Jul. 2016.
6. S. Sun, J. Fu, and L. Wei, "Optimization of high-efficiency half-bridge LLC resonant converter," in Proc. 40th Chin. Control Conf., 2021, pp. 5922-5926.
7. C. Shi, H. Wang, S. Dusmez, and A. Khaligh, "A SiC-based high efficiency isolated onboard PEV charger with ultrawide DC-link voltage range," IEEE Trans. Ind. Appl., vol. 53, no. 1, pp. 501-511, Jan./Feb. 2017.
8. C. Shi, Y. Tang, and A. Khaligh, "A single-phase integrated onboard battery charger using propulsion system for plug-in electric vehicles," IEEE Trans. Veh. Technol., vol. 66, no. 12, pp. 10899-10910, Dec. 2017.
9. T. P. Pandhi, A. S. Jain, and T. N. Date, "An approach for power factor correction of single-phase single-stage three-level AC-DC converter with phase shift modulation," in Proc. Int. Conf. Adv. Commun. Comput. Technol., 2018, pp. 487-491.
10. J. C. Dias and T. B. Lazzarin, "A family of voltage-multiplier unidirectional singlephase hybrid boost PFC rectifiers," IEEE Trans. Ind. Electron., vol. 65, no. 1, pp. 2322-241, Jan. 2018.

11. M. Alam, W. Eberle, S. G. Deepak, C. Botting, N. Dohmeier, and F. Musavi, "A hybrid resonant pulse-width modulation bridgeless AC-DC power factor correction converter," *IEEE Trans. Ind. Appl.*, vol. 53, no. 2, pp. 1406-1415, Mar./Apr. 2017.
12. Y. Jeong, J. K. Kim, and G. W. Moon, "A bridgeless dual boost rectifier with soft switching capability and minimized additional conduction loss," *IEEE Trans. Ind. Electron.*, vol. 65, no. 3, pp. 2226-2233, Mar. 2018.
13. A. Malschitzky, F. Albuquerque, E. Agostini, and B. N. Claudinor, "Singlestage integrated bridgeless-boost non resonant half-bridge converter for led driver applications," *IEEE Trans. Ind. Electron.*, vol. 65, no. 5, pp. 3866-3878, May 2018.
14. H. Wu, T. Mu, H. Ge, and Y. Xing, "Full-range soft-switching-isolated buck-boost converters with integrated interleaved boost converter and phase-shifted control," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 987-999, Feb. 2016.
15. A. M. Al-Gabri, A. A. Fardoun, and E. H. Ismail, "Bridgeless PFC modified SEPIC rectifier with extended gain for universal input voltage applications," *IEEE Trans. Power Electron.*, vol. 30, no. 8, pp. 4272-4282, Aug. 2015.
16. B. Singh and V. Bist, "A BL-CSC converter-fed BLDC motor drive with power factor correction," *IEEE Trans. Ind. Electron.*, vol. 62, no. 1, pp. 172-183, Jan. 2015.
17. H.-T. Yang, H.-W. Chiang, and C.-Y. Chen, "Implementation of bridgeless Cuk power factor corrector with positive output voltage," *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 3325-3333, Jul./Aug. 2015.
18. J. P. R. Balestero, F. L. Tofoli, R. C. Fernandes, G. V. Torrico-Bascope, and F. J. Mendes de Seixas, "Power factor correction boost converter based on the three-state switching cell," *IEEE Trans. Ind. Electron.*, vol. 59, no. 3, pp. 1565-1577, Mar. 2012.
19. P. J. S. Costa, T. B. Lazzarin, and C. H. I. Font, "Hybrid bridgeless DCM SEPIC rectifier integrated with a modified switched capacitor cell," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2016, pp. 2376-2381, doi: 10.1109/APEC.2016.7468198.
20. A. T. Al-Awami, E. Sortomme, G. M. A. Akhtar, and S. Faddel, "A voltage-based controller for an electric-vehicle charger," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 4185-4196, Jun. 2016.