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ABSTRACT

In the proposed system, the Bridgeless Boost PFC converter is utilized as the front end AC-DC conversion stage to improve input power quality and reduce conduction losses associated with conventional bridge rectifier based topologies. The elimination of the diode bridge from the main conduction path contributes to improved efficiency and better thermal performance while maintaining an improved input power factor. The PFC stage is designed to generate a regulated intermediate DC bus voltage of approximately 400 V**.** The second stage employs a Full Bridge LLC Resonant Converter for isolated DC-DC conversion and output voltage regulation. The LLC resonant topology is selected due to its ability to achieve soft switching operation, particularly Zero Voltage Switching (ZVS)**,** which helps reduce switching losses and improve overall conversion efficiency. The converter is designed to regulate the output voltage suitable for 48 V battery charging applications**.** The complete charging system is modeled and simulated using MATLAB Simulink to analyze the operational performance of both converter stages. The simulation results demonstrate improved input power quality, regulated DC bus voltage, stable output voltage performance, and effective integration of both converter stages for battery charging applications. The proposed converter configuration offers an efficient and reliable solution for medium-power battery charging systems, making it suitable for future applications requiring improved energy efficiency and enhanced power quality.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Global warming and the depletion of fossil fuels are two extraordinary crises that the world is currently facing [1]. People are starting to prioritize energy conservation. Electric cars (EVs) have been introduced as a solution to the crises and are regarded as the future's unavoidable trend in vehicle development.

Modern electronic equipment increasingly relies on compact, efficient, and reliable off-line power supplies. Devices such as chargers, communication equipment, LED drivers, industrial control systems and electric mobility subsystems draw power directly from the AC grid [2]. However, most switch-mode power converters exhibit a highly non-linear input current because they charge intermediate capacitors in short pulses. This pulsed current reduces the power factor, introduces significant harmonic distortion, and places unnecessary stress on the distribution network. To comply with international standards such as IEC 61000-3-2, power supplies beyond a certain power level are required to actively shape the input current so that it closely follows the input voltage waveform [2].

As a nonlinear load, the larger the output capacitance and the heavier the load of a diode rectifier circuit, the smaller the conduction angle of its rectifier bridge diode, and the higher the amplitude of the pulsating current extracted from the AC source during the conduction time [3]. The result is that the input current is a non sinosoidal waveform carrying a large number of low order harmonics and high distortion, which means the power factor on the AC side is extremely low. Excessive current harmonics generate serious electromagnetic interference, posing a significant threat to the normal operation of surrounding control equipment. At the same time, device selection is difficult, and available devices have large volumes and losses, seriously affecting the service life of devices and AC side equipment.

A power supply system without a Power Factor Correction (PFC) stage at the front end typically draws input current only during the interval when the rectified input voltage exceeds the voltage across the DC link capacitor. Due to this behavior, the input current waveform becomes highly pulsating in nature and contains a significant amount of harmonic components. The presence of these harmonics increases power losses within the converter and results in inefficient utilization of electrical energy. In practical systems, excessive harmonic distortion may lead to overheating, premature degradation, and unreliable operation of electronic equipment. Furthermore, the reduction in power factor causes additional power loss and introduces electrical interference to other devices connected to the same utility line. In nonlinear loads, the overall power factor is mainly affected by both the distortion factor and the displacement power factor, which play an important role in determining system performance [3].To overcome these limitations, Power Factor Correction (PFC) techniques were developed in accordance with harmonic reduction standards. The main objective of a PFC circuit is to shape the input current waveform so that it follows the input voltage waveform and remains nearly in phase with it. As a result, the converter behaves similarly to a resistive load and achieves a power factor close to unity, even when supplying nonlinear loads.

Conventionally, harmonic reduction can be achieved using large passive filter components such as bulky inductors. Based on implementation, PFC techniques are generally categorized into passive PFC and active PFC methods. Compared to passive approaches, active PFC converters offer improved power factor, compact size, reduced weight, and better overall performance [3]. Several DC-DC converter topologies can be utilized for PFC applications, including boost, buck, Cuk, and flyback converters. Among these, the boost converter is most commonly preferred because of its simple configuration, lower cost, and straightforward control mechanism. A highly effective approach for achieving superior power quality is the two-stage PFC architecture, where the first stage performs power factor correction and the second isolated DC-DC stage regulates output voltage.

A two-stage battery charger generally consists of an AC-DC converter stage followed by an isolated DC-DC converter stage. The primary function of the first stage is to improve input-side power quality by minimizing harmonic distortion and maintaining near-unity power factor

[3]. The second stage performs voltage conversion and regulation according to the charging requirements of the battery while ensuring galvanic isolation and operational safety.

12 In the present work, a two-stage battery charging architecture consisting of a **Bridgeless Boost Power Factor Correction (PFC) converter** as the front-end stage and a **Full Bridge LLC Resonant Converter** as the second stage has been proposed for charging a **48 V battery system**. The proposed charger aims to achieve high conversion efficiency, improved power quality, reduced switching losses, and stable output voltage regulation.

Electric vehicle charging infrastructure is generally categorized into three charging levels, namely Level 1, Level 2, and Level 3 charging [5], [13]. Level 1 charging is commonly employed in residential environments and is considered suitable for low-power charging applications. These chargers typically operate at power ratings of up to 2 kW, resulting in comparatively slower charging performance and generally requiring nearly 10-12 hours to achieve full battery charging or 100% State of Charge (SOC).

Level 2 charging systems are widely utilized in residential complexes, workplaces, parking facilities, and public charging stations. Compared to Level 1 charging, these systems offer improved charging capability and support higher battery C-rates, thereby reducing charging duration. The power rating of Level 2 chargers generally extends up to 20 kW, allowing battery charging to be completed in approximately 4-6 hours, depending on battery capacity and operating conditions.

In recent years, Level 3 charging, commonly referred to as DC fast charging, has gained significant attention because of its high-power capability and reduced charging duration. These charging systems typically operate at power levels ranging from nearly 50 kW to several hundred kilowatts and are increasingly being deployed in urban locations and commercial charging networks. Due to their capability of delivering higher charging currents, Level 3 chargers enable electric vehicle batteries to reach nearly 80% SOC within approximately 20–30 minutes, while complete charging duration may vary up to an hour depending upon charger rating and battery characteristics. In general, Level 1 and Level 2 charging systems are classified as on-board chargers, whereas Level 3 charging systems are categorized as off-board chargers.

The various levels of charging can be classified as:

a) Level 1 charging:

Level 1 charging is considered as slow charging which is mostly used by the user at residential area and have around 2 kW power rating. Level 1 charging can take up to 12 hours for full charge.

b) Level 2 charging:

Level 2 charging is considered as moderate charging which is mostly used by the user at private or public outlets and have up to 20 kW power rating. Level 2 charging can take up to 4-6 hours for full charge based on EV charger rating.

c) Level 3 charging:

Level 3 charging is considered as DC fast charging which is available at charging stations and have around 50 kW- 100's of kW power rating. Level 3 charging can
1
take up to 30-40 minutes for charging up to 80% SoC based on EV charging station rating.

Level 1 and level 2 charging are classified as on-board charging and level 3 charging is considered as off-board charging[4]. SAE J1772 connector can be used for level 1 and level 2 charging which consists of AC pins on top for ac charging and two DC connectors at bottom for dc charging as in Fig.1.1. For level 3 charging CHAdeMO connectors are widely considered [6].

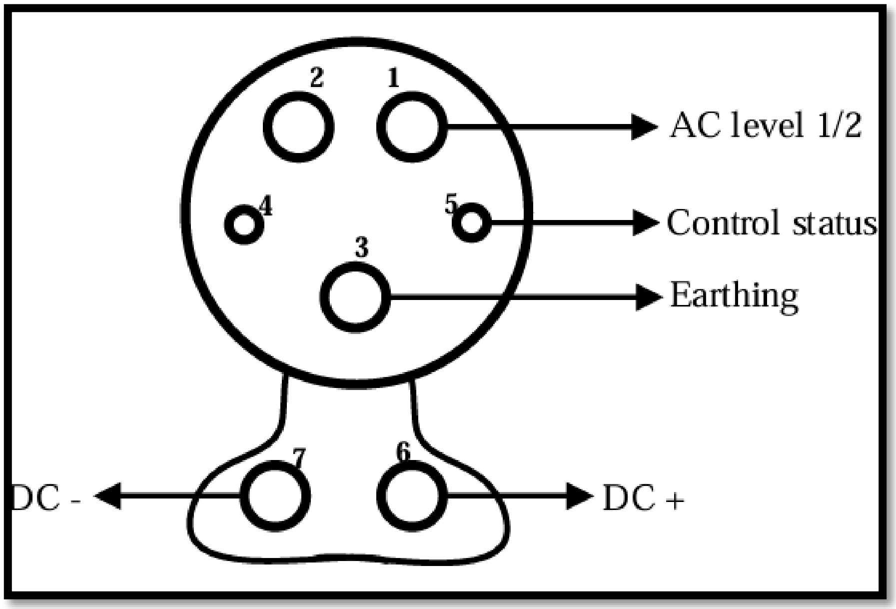

Fig.1.1. Port diagram of SAE J1772

But the main concern regarding EV charging is the availability of fast charging stations at certain distance which requires more efficient and high power density power converters. High power density can provides charging of EV battery at higher C-rate which also reduces the range anxiety among the EV users. Another concern is the grid side disturbances when charging the electric vehicles. As, AC/DC converters are used to convert AC to DC due to which the grid side current becomes distorted and THD becomes quite high which is not recommended according to EV standards in India [3]. Various power factor correction (PFC) methods are employed when designing an EV charger to make grid current in phase with the grid voltage.

The thesis work includes the front end stage which employs Bridgeless Boost PFC converter to improve the input power factor and reduce conduction losses normally associated with conventional bridge rectifier circuits. Unlike traditional boost PFC topologies, the bridgeless configuration eliminates the diode bridge from the main current conduction path, thereby reducing voltage drop and improving converter efficiency.

The second stage utilizes a Full Bridge LLC Resonant Converter to regulate the output voltage and provide isolation between input and output [10]. LLC resonant converters have become highly attractive in modern power conversion applications due to their ability to achieve soft switching operation, particularly Zero Voltage Switching (ZVS)**,** which significantly minimizes switching losses and improves overall efficiency[8]. Furthermore, the full bridge configuration makes the converter suitable for higher power applications while maintaining better voltage regulation characteristics.

The integration of these two converter stages offers several practical advantages, including improved efficiency, lower harmonic distortion, near-unity power factor, reduced thermal stress, and reliable voltage regulation. Therefore, the proposed converter architecture presents an effective solution for efficient battery charging applications.

1.2 BACKGROUND

Due to the increase in the usage of battery-operated systems in sectors like electric automobiles, energy storage, telecommunications, and industry control, there has been a rise in demand for effective battery chargers. Among many kinds of batteries, the most commonly used are 48V battery systems due to their applicability in medium-power applications and safe operation.

The battery charger is a key component when it comes to charging efficiency and performance in general. Common charging methods usually involve rectifiers followed by power converters; however, these chargers have their drawbacks, such as low power factors, high harmonic content, and inefficiency due to switching losses. These disadvantages are even more apparent in higher power chargers.

In order to address these challenges, sophisticated power electronics converters are gaining increased importance in recent charging systems. The two-stage converter concept seems to be a practical solution, wherein the first stage enhances input power quality and the second stage controls the output voltage based on the battery specifications.

For this study, a 48 V battery charger comprising Bridgeless Boost Power Factor Correction (PFC) and Full Bridge LLC resonant converter stages is recommended. Bridgeless Boost PFC helps in enhancing the input power factor and minimizing conduction losses, whereas Full Bridge LLC performs voltage control in an efficient manner using soft switching techniques. This entire design will be modeled in MATLAB Simulink.

1.3 THESIS MOTIVATION

This research is motivated by the rising demand for more efficient and effective battery charging solutions. Generally, traditional battery charging solutions experience problems such as poor power factors, excessive harmonic distortions, and increased switching losses that decrease their efficiency.

To achieve better charging efficiency, the Bridgeless Boost PFC is chosen as the front-end conversion solution owing to its ability to enhance power quality at the input while reducing conduction losses. The Full Bridge LLC Resonant Converter, on the other hand, is selected for its output voltage regulation due to its advantages of soft switching, low switching losses, and increased efficiency.

As such, the adoption of the two converters will enable a good solution for improving power quality at the input and enhancing the stability of the output voltage. Consequently, this study will investigate a high-efficiency 48 V battery charger solution using MATLAB Simulink.

1.4 THESIS OBJECTIVE

The primary objective of this thesis is to design and analyze an efficient two-stage battery charging system for 48 V battery applications using a Bridgeless Boost Power Factor Correction (PFC) converter and a Full Bridge LLC Resonant Converter. The proposed system aims to achieve improved power quality, high conversion efficiency, and reliable output voltage regulation.

The specific objectives of the present work are listed as follows:

1. To design and model a Bridgeless Boost PFC converter for improving the input power factor and reducing harmonic distortion at the AC supply side.
2. To develop a regulated DC bus voltage stage capable of providing a stable intermediate voltage for efficient operation of the DC-DC converter.
3. To design a Full Bridge LLC Resonant Converter for achieving efficient voltage conversion and regulation suitable for 48 V battery charging applications.
4. To reduce switching and conduction losses by utilizing soft-switching characteristics of the LLC converter and reduced conduction path of the bridgeless PFC topology.
5. To implement and analyze the complete charging system in MATLAB Simulink for performance evaluation.

CHAPTER 2

POWER FACTOR CORRECTION TECHNIQUES

2.1 INTRODUCTION TO POWER FACTOR CORRECTION

With the evolution of advanced electric and electronic systems, power quality issues have gained prominence because of the introduction of nonlinear loads like battery charger systems, switching modes power supplies, motor drives, and electronic converters. These loads consume distorted current from the main supply line, thus making the power factor lower and creating more harmonics distortion. The importance of achieving quality power in battery charging systems is due to the fact that this is the direct interface between the battery system and the AC mains.

19 In power conversion techniques, the power factor is referred to as the relationship between the power drawn by the load and the total power available at the point of consumption. Ideally, a power system is required to run with the power factor equaling one so as to realize maximum efficiency. However, when power factor correction techniques are not applied, the input current drawn by the diode bridge rectifier becomes non-sinusoidal and out of phase with the input voltage.

To overcome these issues, Power Factor Correction (PFC) techniques are employed. The primary objective of PFC is to shape the input current waveform in such a way that it follows the input voltage waveform, thereby improving power factor and minimizing harmonic distortion. Depending upon the implementation method, PFC techniques are generally classified into Passive Power Factor Correction and Active Power Factor Correction methods.

2.2 PASSIVE POWER FACTOR CORRECTION TECHNIQUE

One of the simplest ways to achieve good input power factor correction is by using Passive Power Factor Correction method. This is an approach that utilizes passive components like inductors, capacitors, and filters to improve input current waveform and eliminate harmonics from the input voltage.

In this case, a low frequency inductor or LC filter is employed on the input side of the supply to achieve higher power factor. As there are no active components involved in the process of passive power factor correction, it is easier and less costly to implement the design.

Some of the main strengths of the Passive PFC methods include simplicity in circuit design, reduced cost, better reliability since fewer active components are employed, and less complex control design. However, there are certain disadvantages associated with this approach. First of all, passive PFC leads to bulky equipment because low frequency inductors are needed to be incorporated into the design. Secondly, it provides limited improvement of the power factor and is not very effective in meeting the requirements related to harmonics content of the input waveform. Passive PFC is usually not recommended in high-power battery charging circuits due to inefficiency.

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2.3 ACTIVE POWER FACTOR CORRECTION TECHNIQUE

Active Power Factor Correction is a more advanced and widely adopted technique used in modern power electronic systems. Unlike passive methods, active PFC employs

6 controlled switching devices such as MOSFETs along with dedicated control algorithms to shape the input current waveform.

The main objective of active PFC is to force the input current to follow the shape of the input voltage waveform so that both remain in phase. This significantly improves power factor while reducing harmonic distortion.

Active PFC converters typically switch at high frequencies, thereby enabling the use of small passive components. In view of its excellent performance characteristics, the active PFC technology is widely applied in battery chargers, EV charge controllers, industrial power systems, and high-end electronics.

Benefits of active PFC technology include: almost ideal power factor, minimal harmonic distortion, reduction in the size of passive components, increased efficiency, voltage stabilization, conformance to harmonics specifications. Nevertheless, the disadvantages of the active PFC technology are the complex design of circuits and the need for a control system to make it work. In spite of this, the advantages far outweigh the disadvantages in medium to high-powered applications.

2.4 CLASSIFICATION OF ACTIVE PFC CONVERTERS

2.4.1 Boost PFC Converter

Boost converter based PFC has become one of the most popular active PFC converters because of its simple construction and efficient input current shaping capacity. As mentioned above, in boost converter-based PFCs, the output DC voltage is kept higher than the input AC voltage in peak condition. This property makes boost PFC converters very useful for applications that need regulated DC high voltage output. Some of the benefits of using boost PFC converters include continuous input current operation, easy control, and high efficiency level. Unfortunately, traditional boost PFC converters normally have diode bridge rectifiers on their front end. Therefore, while conducting currents, they need to pass through several semiconductor components, causing loss in their efficiency. This problem has led researchers to develop new types like the Bridgeless Boost PFC converters.

One of the important features of the boost PFC converter is that they can offer stable DC voltage at their DC bus regardless of varying input supply conditions. This has made them quite effective in applications like switched mode power supplies, industrial machinery, servers' power management system, and battery charging applications.

2.4.2 Buck PFC Converter

Buck PFC converter produces an output voltage that is lower compared to the input voltage. Buck PFC converters are applicable in situations where a lower output voltage is necessary. Although buck PFC converters produce lower semiconductor stress as well as better short circuit protection, they tend to have poor input current, resulting in the difficulty in obtaining a high power factor.

The converter normally comprises of a switching mechanism that is controlled, an inductor, a diode, and a capacitor. Through the process of switching, energy is supplied from the source to the load at the desired level of output voltage. One of the most important characteristics of the buck PFC converter is that it is capable of stepping down the voltage. Therefore, the converter can be used in low voltage applications without any conversion stages. Besides, buck PFC converters usually have a lower voltage stress on switching devices.

However, the buck PFC converter also suffers from several limitations. One major drawback is the presence of discontinuous input current**,** which makes it comparatively difficult to achieve high-quality current shaping and near-unity power factor. This discontinuous nature often increases harmonic distortion and may require additional filtering components.

Furthermore, since the output voltage can only remain lower than the input voltage, the converter lacks voltage boosting capability. This restricts its application in systems requiring higher DC bus voltages. Due to these reasons, buck PFC converters are generally less preferred in medium and high-power battery charging applications.

2.4.3 Buck-Boost PFC Converter

The buck–boost converter can be used to get output voltage which could either be greater or smaller than the input voltage depending on certain conditions. This means that it has the ability to operate under different conditions making it more efficient to use in the industry. Unfortunately, the buck–boost converter is faced by problems of high current stress and discontinuous current in input, thus making it less effective for practical power conversion.

The operation of the buck–boost converter is based on the switching process. As soon as the switch is turned ON, the energy is stored in the inductor and when the switch is off the energy is discharged through the output circuitry of the converter. With variation of duty cycle, the converter is able to step up or step down output voltage.

An important advantage of buck–boost PFC converter is its great operating flexibility. As the buck-boost converter can operate at both lower and higher voltages compared to the input, it is highly suitable for fluctuating supply conditions.

However, despite its flexibility, the buck–boost converter also presents certain disadvantages. One important limitation is the presence of higher current stress on semiconductor devices and passive components. Additionally, the input current often becomes discontinuous, which can negatively affect harmonic performance and increase electromagnetic interference. Another practical drawback is that the conventional buck boost converter generally produces an output voltage with reversed polarity, which may require additional circuit arrangements depending upon the application.

Due to increased component stress and relatively complex operation, buck–boost PFC converters are less commonly adopted in high-efficiency battery charging systems compared to boost-based topologies. However, they still remain valuable for specialized applications where flexible voltage conversion is required.

2.4.4 SEPIC PFC Converter

One of the main characteristics of the SEPIC PFC Converter topology is that it can generate output voltages which are either lower or higher than the input voltages without altering the polarity of the output. The SEPIC PFC converters are more flexible in controlling the voltage level; however, they are complex due to the use of large numbers of passive devices.

The converters, in the case of SEPIC PFC, shape the waveform of the current based on the input voltage, making it easier to regulate the power factor. As a result, harmonic distortion levels are reduced, and a higher power factor is maintained. The typical circuit design of a SEPIC converter contains two inductors, one coupling capacitor, a switching device, a diode, and an output capacitor.

The most distinguishing aspect of the SEPIC PFC converter is that its operation is not affected by variations in the input voltage supply since it can maintain the regulation of the output voltage. In addition, the input current ripple levels are low, making the converter ideal for high-performance applications.

Despite these advantages, the SEPIC converter also presents certain limitations. The presence of additional passive components increases circuit complexity and component count. Moreover, energy transfer through the coupling capacitor can introduce additional losses, which may slightly reduce efficiency compared to conventional boost PFC converters. Due to these factors, SEPIC PFC converters are generally preferred in applications requiring flexible voltage conversion rather than very high efficiency. In battery charging and renewable energy systems, SEPIC converters can provide stable operation under varying supply conditions, making them suitable for moderate power applications where voltage flexibility is required.

2.4.5 CUK PFC Converter

The Cuk Converter is yet another converter topology that finds application in PFC circuitry owing to its smoothness of the input and output current shapes. The Cuk converter is distinct from the normal boost and buck circuits in that the Cuk circuit uses the capacitor for transferring the energy across; hence, resulting in the reduction of ripple content and improvement of the waveform shape. One notable benefit associated with the Cuk converter is its ability to work in situations where stepping up or stepping down of the voltage level is required. Hence, the voltage can be converted using the Cuk converter within a wide range of voltage levels.

In power factor correction circuitry, the Cuk converter provides better performance than the normal DC/DC converters because the current on both the input and output sides of the converter is continuous. Continuous operation of current in the circuitry is known to increase the power quality by reducing the ripple content of the circuitry.

One other benefit associated with the Cuk converter is the reduction of current ripple on both sides of the circuit, hence making it more stable and minimizing the load to be handled by the filters.

However, despite its attractive characteristics, the Cuk converter is less commonly adopted in high-power battery charging systems due to increased circuit complexity and higher component count. The topology requires additional capacitive energy transfer elements, which can increase system size and introduce extra losses. Moreover, higher voltage stress across components may complicate practical implementation.

Nevertheless, the Cuk PFC converter remains an effective solution for applications requiring improved current quality and flexible voltage conversion. Its smooth current profile and harmonic reduction capability make it a valuable alternative in specialized power electronic systems.

2.5 BRIDGELESS POWER FACTOR CORRECTION TECHNIQUES

Although conventional boost PFC converters provide improved power factor, they still experience conduction losses due to the presence of a front-end diode bridge rectifier. To reduce these losses and improve efficiency, bridgeless PFC topologies have been introduced.

2.5.1 Conventional Bridgeless Boost PFC

The Conventional Bridgeless Boost Power Factor Correction (PFC) converter is an improved version of the traditional boost PFC topology developed to overcome the efficiency limitations associated with conventional diode bridge rectifier-based systems. In modern power electronic applications, particularly battery chargers, electric vehicle charging systems, switched-mode power supplies, and industrial converters, efficiency improvement and power quality enhancement are major design objectives. The Bridgeless Boost PFC converter has therefore emerged as an attractive solution due to its capability to reduce conduction losses while maintaining effective power factor correction.

In the traditional boost PFC converter, the AC voltage input is fed into the circuit by passing through the diode full bridge rectifier before being converted using the boost conversion section. While this configuration enhances the input power factor and maintains the DC bus voltage regulation, it creates extra power losses since the input current flows through more semiconductor elements during the conductive state. Generally, while operating, the current has to flow through a minimum of two bridge diodes besides the boost diode and boost switch.

In order to solve the above problem, the Bridgeless Boost PFC converter technology incorporates a design where the diode bridge rectifier of the traditional design is eliminated in the main power flow path while integrating the rectifying process in the converter itself. With the elimination of unnecessary diode current flow paths, the bridgeless boost PFC converter lowers its voltage drop, which increases energy conversion efficiency.

The converter generally consists of two inductors, two active power switches, diodes, and output filtering components arranged in such a way that separate conduction paths exist for positive and negative half cycles of the AC supply. Unlike conventional boost converters, where the same power path operates continuously, the Bridgeless Boost PFC converter functions differently depending on the polarity of the input AC waveform.

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2.5.2 Totem Pole PFC Converter

Totem Pole Power Factor Correction (PFC) Converter is an advanced version of a bridgeless converter which has attracted substantial attention in recent times because of its capability to provide a very high efficiency level. It should be noted that compared to traditional boost PFC converters which have a full bridge diode rectifier as their input, the totem pole configuration does not use any diodes for rectifying the input AC voltage, but achieves the purpose through switching.

Typically, a totem pole converter contains two high frequency and two low frequency switching devices, all of which are connected in the form of a totem pole arrangement. During operation, the converter carries out rectification as well as power factor correction at the same time. In particular, the low frequency switches act as per the polarity of input AC voltage, while high frequency switches are used for carrying out boosting action and current shaping.

For the positive half cycle of input AC voltage, one path conducts, enabling the current flow across the respective switching devices and inductor, while in case of negative half cycle, the other switching path becomes operational.

One of the most important advantages of the Totem Pole PFC converter is the reduction in conduction losses due to the absence of the conventional diode bridge rectifier. Since fewer semiconductor devices participate in the current conduction path, voltage drop across the converter is reduced, leading to improved efficiency. Moreover, the topology supports higher switching frequency operation, enabling the use of smaller passive components and resulting in increased power density.

11 The introduction of wide bandgap semiconductor devices, such as silicon carbide (SiC) and gallium nitride (GaN) switches, has further enhanced the performance of Totem Pole PFC converters. These devices exhibit lower switching losses and superior high-frequency characteristics, making them highly suitable for high-efficiency converter applications.

2.5.3 Interleaved Bridgeless Boost PFC Converter

The Interleaved Bridgeless Boost Power Factor Correction circuit represents the advanced form of the Bridgeless Boost power converter, in which various phases of boost converters work together in parallel but with phase shifted switching signals. Such techniques have been used primarily for reducing current ripple, improving heat dissipation, and enhancing converter performance.

Unlike the basic Bridgeless Boost Power Factor Corrector circuit in which only one inductor and one switch actively work in boosting in one particular half cycle, the Interleaved version has the advantage of having two or more parallel boost converters in a single converter circuit. Although the efficiency of the circuit is considerably enhanced due to absence of the bridge, higher current stress and increased ripple current is possible at high power levels.

In order to address such shortcomings, in an Interleaved Bridgeless Boost circuit, two or more boost circuits with 180 degree phase difference are operated in parallel. As the two switches are turned on at a different point of time, the current ripple gets minimized.

The working principle of the interleaved bridgeless boost PFC converter is based on current sharing among parallel phases. During converter operation, each phase handles a portion of the total input current. As a result, current stress on individual semiconductor devices and magnetic components decreases considerably. This helps improve converter reliability and thermal performance.

One of the major advantages of using the interleaving method is the cancelling effect on the ripple current. The current ripples created by individual phases tend to offset each other in such a way that the total ripple effect experienced at the input end becomes relatively lower. The improvement in ripple levels leads to better input currents as well as low electromagnetic interference.

Apart from that, the interleaved structure also ensures more uniform heat distribution, whereby the dissipated energy is distributed among several stages instead of being concentrated in one switch stage.

2.6 SELECTION OF BRIDGELESS BOOST PFC FOR PRESENT WORK

Of the various PFC circuit topologies, the Bridgeless Boost PFC converter is chosen to be used in the battery charger being developed because of its enhanced efficiency and lower conduction losses. With the absence of the diode bridge rectifier in the principal current flow path, there will be less number of semiconductor components involved in current conduction, which results in lower energy dissipation.

Furthermore, it also offers better input current shaping and higher power factor than that of the conventional boost PFC converters. Hence, it is very suitable for the proposed 48V battery charging application.

Accordingly, the Bridgeless Boost PFC converter will be employed as the first stage of the overall circuit design to provide a DC bus voltage for the next level of conversion.

CHAPTER 3

RESONANT CONVERTER TECHNOLOGIES

3.1 INTRODUCTION TO RESONANT CONVERTERS

As a result of the high efficiency demands from power conversion systems, there has been a trend away from traditional hard switched converters towards more sophisticated soft switched converters. There is an urgent need to cut down the switching losses in addition to high efficiency operation in new power electronic systems, which include battery chargers, electric vehicle chargers, renewable energy converters, and telecommunications power supplies. Resonant converter technology is seen as the best way forward in fulfilling these criteria.

Traditional PWM converters switch ON/OFF their switches under high-voltage and high-current operating conditions. Such actions result in huge losses in the form of switching losses, thermal stresses, and electromagnetic interference (EMI). With higher switching frequencies to minimize size, these losses increase even further.

In order to solve these issues, resonant converters use resonant components such as inductors and capacitors that help them achieve soft switching behavior. Soft switching refers to the mode of switching where semiconductor switches operate in the states of ZVS or ZCS and thus reduce switching losses.

Resonant converters work on the basic concept of energy exchange between inductive and capacitive components. These components create an oscillating wave within the resonant tank circuit, allowing the conversion of power more effectively and easing the working of switching components. Due to these features, resonant converters have gained great popularity in medium-to-high-power applications.

3.2 SERIES RESONANT CONVERTER

The Series Resonant Converter (SRC) is among the oldest and basic topologies of resonant converters. In the case of SRC, both the resonant inductor and capacitor are connected in series with the load and form an LC resonant tank through which the load current passes.

The principle of operation of this circuit depends on the switching frequency compared to the resonant frequency of the LC circuit. Operation at resonant frequencies ensures efficient energy transfer since there will be resonance between the inductor and capacitor.

There are several benefits that make the SRC topology unique, among them the ability to have soft switching with low losses. This converter allows for the natural achievement of Zero Current Switching (ZCS) thus ensuring less stress in switching. Besides, high-frequency operation is possible due to the minimal losses.

Nevertheless, some limitations exist when using the SRC as well. Voltage regulation under light load can become problematic due to the limited control range of gain control. Moreover, the higher circulation current within the resonance tank increases the conduction losses. Regardless of these limitations, the SRCs are ideal for high frequency isolated power converters.

3.3 PARALLEL RESONANT CONVERTER

Parallel Resonant Converter (PRC) is yet another vital resonant converter type wherein the resonant capacitor gets connected across the load while the inductor stays inside the resonant circuit.

In this case, the mode of energy transmission turns out different from that observed in a series resonant converter. The reason is that the load continues to get connected parallel to the resonant capacitor, making it easier to regulate the output voltage depending on the changing load.

One of the key features of the parallel resonant topology is the enhanced voltage regulating capacity when there is zero or low-load operation. That is why the parallel resonant topology can be used where load changes substantially.

Nevertheless, the major limitation associated with the PRC topology is related to constant circulating currents that tend to increase conduction losses and limit the efficiency of the design. Due to the higher current stresses, component ratings need to be increased, limiting the widespread usage of PRC.

3.4 SERIES-PARALLEL RESONANT CONVERTER

This converter takes on the qualities of the series and parallel converters in order to eliminate the problems encountered by each of them. In the Series-Parallel Resonant Converter (SPRC), the resonant elements are placed in such a way that they utilize both the series and the parallel resonance principles for transferring power.

This topology helps in achieving better load regulation and also operates within a larger operating range than both the SRC and PRC topologies alone. Due to this inclusion of both the principles of energy transfer, better performance of the converter can be achieved irrespective of the operation parameters.

Efficiency under various loads is another major benefit of this type of converter. Circuit complexity is another disadvantage that this converter faces because of its use of more resonant components.

3.5 LLC RESONANT CONVERTER

One of the most popular types of resonant converters is LLC Resonant Converter owing to its highly efficient design, ability for soft switching, and effective regulation of voltage output levels. The design of the LLC converter comprises of a resonant inductor Lr, resonant capacitor Cr, magnetizing inductance of the transformer Lm. With two inductors available in the system, a number of resonance frequencies are achievable.

One of the key strengths of the LLC converter design is the possibility to provide zero voltage switching for the primary-side switches and zero current switching for the secondary side rectifiers. As a result, energy loss associated with switching operations is minimal, leading to higher energy efficiency. In contrast to hard-switched designs, an LLC converter regulates output voltage using frequency modulation technique by adjusting the frequency around the resonance point.

Advantages of LLC converters include high efficiency, low energy losses, compact design, and soft switching capability. Because of these strengths, LLC converters are extensively utilized in battery charging, electric vehicle charging systems, server power supplies, and telecommunications equipment.

3.6 LCC RESONANT CONVERTER

The LCC Resonant Converter represents yet another resonant circuit that has an extra capacitance in its resonant circuitry than the LLC Resonant Converter does.

The LCC Resonant Converter can attain higher efficiency levels and enhanced gain control when operating in certain conditions. In addition, the LCC Resonant Converter offers improved performance when higher output voltages need to vary.

Nonetheless, having several resonating elements leads to added design challenges and raises the cost of the design. Moreover, controller design also becomes complicated. This is why LCC Resonant Converters are applied in special applications only.

3.7 SELECTION OF LLC RESONANT CONVERTER FOR PRESENT RESEARCH WORK

Among many resonant converters available, the LLC Resonant Converter is chosen for the current project since it has more advantages like higher efficiency, less switching losses, and capability of having soft switching characteristics. The converter performs exceptionally well within a wider range of operations and is quite effective in charging batteries where a regulated output voltage and high power density are needed.

The Full Bridge LLC topology is chosen as it is quite suitable for both medium and high power applications. It can effectively convert the regulated DC Bus Voltage from the Bridgeless Boost PFC stage into the required output voltage level of 48V for charging batteries.

CHAPTER 4

BATTERY CHARGER TOPOLOGIES AND THEIR CLASSIFICATIONS

4.1 INTRODUCTION TO BATTERY CHARGING SYSTEMS

With the fast development of batteries in present-day electrical and electronic engineering, the role of battery charging technologies becomes especially significant. Batteries serve as the sources of energy in electric vehicles, renewable energy storage systems, telecommunications systems, uninterruptible power supplies (UPS), consumer electronics, and automated industrial processes. Given that batteries are energy storage devices, the performance and service life of a battery will highly depend on the type of charging technique used. In turn, efficient charging systems have become an area of active research within power electronics.

Battery charging systems are power electronic systems aimed at the conversion of utility electrical energy into appropriate electrical energy for charging batteries. The charging system should guarantee a safe charging process by providing energy-efficient and controlled charging with prevention of overvoltage, overheating, and excessive load on the battery. Inappropriate battery charging methods will inevitably result in decreased battery service life and other serious issues.

Traditional methods of battery charging were typically dependent on basic rectifiers with the inclusion of filter circuits in order to get the DC voltage for charging. Despite their ease of use and economical nature, these battery charging schemes had disadvantages in terms of low efficiency, bulky size, low power factor of input, and higher harmonics. Increased power needs accentuated these limitations, particularly in medium and high power applications.

Modern techniques of battery charging involve sophisticated switching converters which help boost efficiency and compactness and improve overall system performance. This helps in controlling the battery charging voltage and current. The type of battery charger depends on the requirements including the power rating of the charger, the charging time required, isolation and the type of converter used.

Battery chargers can be categorized depending on a number of characteristics including the operating concept, the structure of the converter, method of isolation, charging methodology, and power electronics converter topology.

4.2 CLASSIFICATION BASED ON POWER CONVERSION TECHNIQUE

Battery chargers can broadly be classified into two major categories based on the method of power conversion. Each charging method offers distinct operational characteristics, advantages, and limitations depending upon the application requirement.

4.2.1 Linear Battery Chargers

Linear battery chargers are one of the most elementary types of chargers used for low power consumption applications. Linear battery chargers usually consist of a transformer, rectifier circuitry, filtering circuitry, and linear voltage regulators to ensure proper charging operation.

Operation of linear chargers depends upon the dissipation of unwanted power in the form of heat in order to deliver regulated voltage or current to the batteries. As the regulation of current or voltage depends upon resistance-based or linear method, the charging process becomes rather simple and easier to implement. There are a number of merits of linear chargers and first of all, linear chargers are very simple to use. Linear chargers require less number of components, have less control requirements, and low electromagnetic interference. Also, there is less voltage ripple as compared to other types.

However, there are some major drawbacks in the linear charging process as well. First of all, efficiency becomes very poor since much of the energy is lost in the form of heat. As the level of power increases, losses increase significantly.

Moreover, linear chargers generally possess larger physical dimensions due to the use of low-frequency transformers and bulky filtering components. This reduces power density and limits their suitability for modern compact applications. Due to these disadvantages, linear battery chargers are mostly restricted to low-power systems such as small electronic devices and portable equipment where simplicity is preferred over efficiency.

4.2.2 Switch Mode Battery Chargers

A type of battery charger that operates on high-frequency switches is referred to as Switch Mode Battery Chargers or SMPS battery charger. It uses switching devices such as MOSFETs and sophisticated converters to control the charging voltage and current.

Switch mode battery chargers are different from linear chargers because of the way energy transfer takes place. In this case, energy transfer occurs via the process of on/off switching. This results in minimal power wastage since the switching transistors either remain fully turned ON or OFF.

Switch mode battery chargers have several benefits associated with them. Their most important feature is high efficiency compared to linear battery chargers. Moreover, high-frequency operation allows for smaller components (magnetic elements and capacitors), resulting in an increase in system efficiency. Contemporary switch mode battery chargers also offer good control flexibility. In other words, the output voltage and current can be carefully controlled using feedback control systems.

However, switch mode chargers involve comparatively higher design complexity and require sophisticated control mechanisms. Electromagnetic interference and switching noise may also increase due to high-frequency switching operation.

Despite these challenges, switch mode chargers have become the preferred choice in electric vehicle charging systems, renewable energy applications, industrial battery systems, and medium to high-power battery chargers due to their superior performance characteristics.

4.3 CLASSIFICATION BASED ON POWER CONVERSION ARCHITECTURE

Battery chargers can also be classified according to their power conversion structure. Depending on the number of conversion stages used for power processing, chargers are categorized as Single Stage Battery Chargers, Two Stage Battery Chargers, Multi Stage Battery Chargers.

4.3.1 Single Stage Battery Chargers

A single stage battery charger comprises integration of processes involved in rectification of input power, power factor correction, and voltage regulation into one single stage power conversion process. In these systems, there occurs simultaneous AC-DC conversion and control of battery charging process.

Simplicity is perhaps the most significant benefit of using a single stage battery charger. This is due to the fact that it requires only few stages of converters. Consequently, it becomes cheaper to manufacture as well as having small sizes.

However, the disadvantage faced by this type of charger includes inability to produce quality power supply along with effective regulation of voltage.

It follows that these systems would only suit use in situations that demand moderate power.

4.3.2 Two Stage Battery Chargers

The use of two-stage chargers has become quite popular in power electronic converters particularly for applications of medium and high power levels. Two-stage power conversion system consists of two stages, each stage having its own particular task.

The first stage of such system consists of an AC to DC Power Factor Correction (PFC) converter circuit that will maintain good quality input power as well as providing an intermediate voltage DC bus. The second stage makes use of a transformer isolated DC to DC converter circuit that regulates the output voltage and battery charge.

One of the benefits of using two-stage design system is that both input power quality and output voltage regulation can be independently controlled to achieve efficient operation and improved harmonics and battery charging control performance. Two-stage converter systems include the Boost PFC & LLC resonant converter and the Bridgeless boost PFC & Full Bridge LLC resonant converter due to their remarkable performances in today's charging circuits.

In our present study project, two stage design system would be considered where a Bridgeless Boost PFC circuit will be used in the front end stage while Full bridge LLC Resonant converter provides voltage regulation at output for battery charging.

4.3.3 Multi Stage Battery Chargers

Multi-stage battery chargers can be defined as advanced chargers that use several stages of conversion of the supplied energy into the output electricity. Using several stages of conversion allows increasing the efficiency of battery chargers, making them more efficient and flexible. Multi-stage chargers are primarily designed for applications requiring high performance, intelligent management of the charging process, several inputs and outputs, and capability to convert energy.

Each stage of a multi-stage charger is responsible for particular functions related to the work of battery chargers. Multi-stage converters differ from single and double stage converters by splitting system functionality between several stages. The first stage may deal with the input power conditioning, whereas the second stage may regulate the voltage. Other tasks like energy management, isolation, bidirectional energy conversion, and photovoltaics connection can be assigned to other stages.

The simplest multi-stage battery charger includes several stages including AC/DC rectifier, Power Factor Corrector, DC/DC isolation converter, and an energy management/battery balancing stage. To create multi-stage chargers for renewable energy systems, additional stages are required.

One of the biggest benefits of multi-stage battery chargers is that they can offer improved charging accuracy and system optimization. Being independent from one another, parameters such as voltage regulation, current regulation, power quality, and charging profile for each stage can be optimized independently. It allows for improved efficiency of charging and enhanced battery protection. Another benefit of these battery chargers is that they can implement complex and sophisticated charging algorithms. With the emergence of advanced battery technologies, especially lithium ion, there is an increasing need to use sophisticated charging algorithms in order to optimize charging and increase battery life. This can be achieved using multi-stage chargers since they allow implementing CC-CV (Constant Current – Constant Voltage), temperature dependent charging algorithms, state of charge and cell balancing algorithms.

Another benefit of multi-stage architecture is improved power quality and compatibility with the grid. Power Factor Correction stages enable maintaining a near unity power factor and low harmonics, resulting in improved energy efficiency. Similarly, isolated DC-DC converter stages ensure improved electrical safety and efficient voltage regulation according to battery needs.

Furthermore, these chargers provide superior flexibility and scalability. Since each stage is modular in nature, system designers can easily modify or upgrade specific sections without redesigning the complete charging system. This becomes particularly useful in electric vehicle charging stations and renewable energy systems where operating conditions may vary significantly.

However, despite their advantages, multi-stage battery chargers also involve certain challenges. The presence of multiple converter stages increases overall system complexity, component count, and control requirements. Additional semiconductor devices and passive components may increase converter cost and system size. Moreover, coordination among multiple control loops becomes more challenging and requires careful controller design to maintain system stability.

Due to these reasons, multi-stage chargers are generally preferred for high-performance and high-power applications rather than simple low-power charging systems. They are commonly found in electric vehicle charging infrastructure, renewable energy storage systems, smart grid applications, aerospace systems, industrial battery backup systems, and advanced energy management platforms.

Although multi-stage charging systems provide superior functionality, their implementation complexity and higher cost may not always be justified for medium-power applications.

Therefore, for many practical charging systems, a two-stage charging architecture often represents a balanced solution between performance, efficiency, and implementation complexity.

4.4 CLASSIFICATION BASED ON ISOLATION

Battery chargers can also be classified based on the presence or absence of electrical isolation between the input power source and the battery side. Isolation plays an important role in ensuring user safety, reducing electrical hazards, and protecting sensitive electronic equipment from fault conditions. Based on this criterion, battery chargers are broadly categorized into Non Isolated Battery Chargers and Isolated Battery Chargers. The selection between isolated and non-isolated chargers depends on factors such as power rating, safety requirement, application type, voltage level, and cost considerations.

4.4.1 Non Isolated Battery Chargers

The term Non-isolated Battery Chargers refers to charging systems in which galvanic isolation between input voltage source and output voltage terminals does not exist. Here electrical energy transfers directly from the input terminals to output terminals through the converter without requiring the use of any isolation transformers. Such chargers use Non-isolated converter configurations like Boost Converter, Buck Converter, Buck-boost Converter, SEPIC converter, and Cuk converter.

One of the key benefits of Non-isolated battery chargers is simplicity of circuit design. With no need for isolation transformers, the charger becomes easier to construct and smaller in size. Also, efficiency of such chargers increases with absence of transformer losses. Moreover, one of the significant benefits of Non-isolated battery chargers is smaller and cheaper sizes. Without need for transformers and other magnetic isolation components, chargers become lighter and smaller in terms of volume. Lastly, most Non-isolated battery chargers are characterized by high power density because of smaller number of components used and simpler design.

Nonetheless, there are some serious drawbacks associated with these types of chargers especially when electrical safety issues are considered. There being a physical connection between the power source and battery, any failure may result in exposure of the battery and even user to dangerous voltage values. The inability of non-isolated chargers to provide safety in such cases makes them impractical for many high voltage applications. Besides, in the lack of electrical insulation, there may be an increased risk of noise coupling and electromagnetic interference between the input and output circuitry.

Owing to these facts, non-isolated battery chargers can only be recommended in the following applications: Battery chargers requiring low power input, Electronic devices that are used portably, Consumer electronic products having small size, Low voltage DC applications.

4.4.2 Isolated Battery Chargers

Isolated battery chargers are those charging devices where there is an electrical isolation between the input source and battery output terminals. Electrical isolation in the battery charging system is done using a high frequency transformer. The use of transformers ensures no electrical connection between the input and battery terminal, and energy transfer takes place by magnetic coupling. Topologies used in isolated charger systems include Flyback converter, Forward converter, Push Pull converter, Half Bridge converter, Full Bridge converter, LLC Resonant converter.

One major benefit of the isolated battery charger is the aspect of safety during operation. With electrical isolation between input and battery, chances of electric shocks or faults being experienced during operation are eliminated. Isolated chargers are recommended for medium and high power charging needs. Another great benefit of using isolated chargers is the ability to control the voltage level through the turns ratio of the transformer. Choosing the appropriate transformer turns ratio will enable voltage stepping up and down.

Isolated chargers are characterized with increased immunity to noise and reduced common mode interference hence higher efficiency and reliability. Currently, isolated battery chargers use soft switched resonant converters like LLC converters.

There are, however, some disadvantages associated with isolated chargers. For instance, isolated chargers are complex, costly, and more difficult to design due to the addition of transformers in the circuit. Transformers become even more important in systems operating at high frequencies, and their design should be considered carefully. Despite these drawbacks, isolated chargers find application in the following areas: Electric vehicles charging systems, Industrial battery chargers, Renewable energy storage systems, Telecommunications power systems, Medical and safety-critical applications. In this project, an isolated charger topology has been used in the form of a Full Bridge LLC Resonant Converter owing to its advantages in terms of efficiency and safety.

4.5 CLASSIFICATION BASED ON CHARGING METHOD

The other classification of battery charging systems is based on the charging technique used in charging the battery. The various types of batteries require different charging techniques in order to charge the battery safely, use energy efficiently, and increase the lifespan of the battery. 18 Depending on the charging techniques, battery chargers are usually grouped into Constant Voltage Charging (CV), Constant Current Charging (CC), and Constant Current Constant Voltage Charging (CC-CV).

The charging technique refers to the technique used to provide a certain level of voltage and current to charge the battery. Charging techniques will ensure that charging is efficient and increases the performance of the battery.

4.5.1 Constant Voltage (CV) Charging

First of all, when it comes to charging in this scenario, the thing to consider is that the voltage in the battery would be low since it would already have some level of discharge. Because of this, due to the higher voltage differential between the charger and the battery, the current going into the battery would inevitably be high. Since the battery voltage increases during the process of charging, the difference between the voltage on the charger and the battery becomes lower, and, thus, the current that goes into the battery decreases. Finally, what needs to be considered is that once the battery voltage equals the charger voltage, the current would become extremely low.

When it comes to advantages, two aspects need to be emphasized. To start with, the simplicity of the method can be considered one of its advantages since it only requires voltage regulation. Another aspect to consider would be the fact that there is no risk of overvoltage.

Despite the simplicity associated with it, there are some downsides with CV charging. At the early stages of charging, the battery may require a very large current, especially when the battery is highly discharged. High charging current could cause heat generation, which would adversely affect battery lifespan. The second downside with CV charging is the slow rate of charging at the later stages since current will gradually reduce as the battery becomes more charged. Due to the above reasons, CV charging may not be ideal for top performing rechargeable batteries.

CV charging technique is applied in Lead acid batteries, Float charging, Backup power systems, Small rechargeable battery system.

4.5.2 Constant Current (CC) Charging

The constant current charging, in its turn, is one of the types of battery charging systems, where constant current charge is applied to the battery by the charger without taking into account any alterations in battery voltage during charging process. While in constant voltage charging battery charging voltage will remain unchanged, in constant current charging, on the contrary, charging current will be changed continuously regardless of the battery voltage alterations.

In case of constant current charging, the charger delivers constant current to the battery when the battery is being charged. As far as the current supplied to the battery is kept constant, the voltage of the battery also increases. Thus, in the initial period of battery charging, voltage is relatively low, while at the final stage of charging process, it reaches maximum possible level. Hence, the current remains constant throughout the process while the voltage becomes higher and higher.

It is important to note that the main advantage of constant current charging is controllability of battery charging current, which means no risk of stress related to abrupt voltage changes. Besides, fast battery charging, especially in the early stages of battery charging process, is another major feature of CC charging.

The major disadvantage of constant current charge is that overcharge can happen when charging proceeds beyond the maximum voltage of the battery. This happens because there is constant current, and the battery might be over-heated or damaged. Thus, constant current charging is not enough to completely charge a battery.

Constant current charging is applied in nickel-based batteries, lithium-ion battery charging, fast chargers, laboratory charging setup of batteries.

4.5.3 Constant Current – Constant Voltage (CC-CV) Charging

The other modern and widely accepted battery charging method that is employed is the Constant Current – Constant Voltage or CC-CV charging method which finds application in today's rechargeable batteries. In using this particular method, both features of the constant current as well as the constant voltage can be merged to produce an efficient and optimal charging process. It is an appropriate method of charging since it involves charging batteries such as the lithium-ion batteries with high precision in order to enhance their life and performance.

In this particular case, first the charger operates in the constant current region whereby a specific charging current is fed into the battery whose voltage begins increasing. The use of constant current makes the process of energy transfer fast and efficient. It ends once the battery attains its specific voltage level.

When this voltage level is attained in a battery, the charger automatically switches to constant voltage mode. In this particular region, the charger feeds a steady voltage as the current continuously falls until the battery becomes almost fully charged when the current becomes very low.

Another advanced and recognized technique of battery charging that is currently in use is the Constant Current -Constant Voltage or CC-CV method of battery charging. This technique combines both the qualities of constant current and constant voltage to give an efficient battery charging system. This is because the process of charging is done through the use of high precision in order to increase the battery life and efficiency.

The first stage in this kind of battery charging involves the use of constant current. Here, a certain amount of charge current is provided to the battery, whose voltage increases in the process. The advantage of using constant current is that energy is transferred effectively. This continues until the battery reaches its certain predetermined voltage.

Once the predetermined voltage is reached by the battery, the charger automatically shifts to constant voltage mode. Here, a constant voltage is supplied to the battery until its current level becomes very low.

CHAPTER 5
DESIGN AND ANALYSIS OF BRIDGELESS BOOST PFC

5.1 INTRODUCTION

The improvement of system efficiency and power quality have turned out to be crucial factors in power electronics system design for the purposes of medium and high-power battery chargers. In general, AC/DC converters employ uncontrolled bridge rectifier circuits and filter circuits to provide DC voltage output. Such circuits are considered cheap and easy-to-implement, although, on the other hand, there are quite a few drawbacks, among which include poor power factor, high harmonic distortions, and elevated conduction loss.

As far as battery charger applications go, especially when using medium/high power values, it is very important to keep the power factor high enough in order to improve energy consumption efficiency and comply with international requirements regarding power quality. Otherwise, low power factor will result in high consumption of reactive power, higher line and current losses, and reduced overall efficiency. Nonlinear currents used by conventional rectifier circuits lead to harmonic distortions affecting other equipment that might be connected to the utility network.

In order to compensate for these drawbacks, Power Factor Correction (PFC) methods are used extensively in AC to DC power conversion processes. The PFC converters are so designed
13 that they produce an input current waveform that tracks the input voltage waveform, thus enhancing the input power factor and minimizing the effects of harmonics. Amongst all active PFC structures, the Boost Converter based PFC is the most commonly used type because of its ease of control and ability to produce a controlled DC voltage which is greater than the input peak voltage.

However, there are certain shortcomings that come with the efficiency of conventional boost PFC converter because of the incorporation of a diode bridge rectifier in the front-end. Because of the flow of input current through different semiconductor devices, the losses during conduction increase.

As a solution to this problem, the Bridgeless Boost Power Factor Correction (PFC) converter has been developed, which provides a better approach to the design of the traditional boost PFC converters. In such a topology, the traditional diode bridge rectifier is removed from the power flow path, and the rectification function is implemented inside the converter itself. Thus, fewer semiconductor components are required for the conduction of the current.

A vital characteristic of the Bridgeless Boost PFC converter is that it can maintain a high power factor even when there are lower levels of THD. It achieves this by ensuring control of the switching process, which makes the input current sinusoid match the input voltage sinusoid. This ensures a nearly perfect power factor. Additionally, the Bridgeless Boost PFC converter works better in terms of heat. This is due to the fact that it saves on power and does away with any power loss that would have been caused by rectifiers present in other converters.

In the present work, a Bridgeless Boost PFC converter is selected as the front-end stage of the proposed **48 V battery charging system**. The converter is designed to convert the **230 V AC input supply into a regulated 400 V DC bus voltage**, which serves as the input to the subsequent **Full Bridge LLC Resonant Converter** stage. The Bridgeless Boost PFC converter operates in **Continuous Conduction Mode (CCM)** at a switching frequency of **100 kHz** to ensure improved current shaping, reduced ripple, and better converter performance. The proposed converter aims to achieve an input power factor in the range of **0.98-0.99** while maintaining approximately **2% output voltage ripple**.

Thus, the selection of the Bridgeless Boost PFC converter in the present charging architecture contributes significantly toward improving overall efficiency, input-side power quality, and converter reliability.

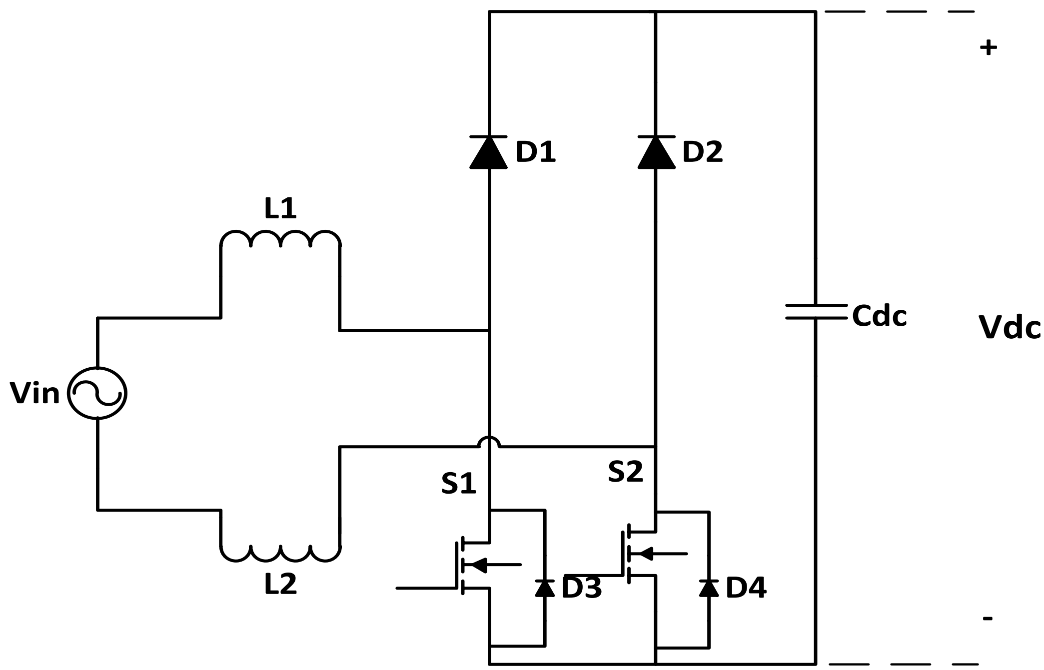


Fig 5.1 Circuit Diagram of Bridgeless Boost PFC

5.2 NEED FOR POWER FACTOR CORRECTION IN BATTERY CHARGING SYSTEMS

Increased demands on the effectiveness of modern battery charging systems have led to the need for further enhancements in the power quality of utility grids. Battery charger systems, which incorporate AC-DC converters, utilize diode bridge rectifiers followed by capacitive filters. Although these types of systems can be easily designed, they consume very distorted currents drawn from the electrical grid.

In fact, the input current of such battery chargers is non-sinusoidal and discontinuous because it draws only at certain points in time within the AC voltage waveform. Thus, these systems experience poor power factor and harmonic generation in the electrical circuit. This causes multiple problems in their operation and leads to increased losses of power, overheating of electrical conductors, loading of transformers, and ineffective energy conversion processes.

7 Power factor may be defined as the ratio of real power consumed by the load to the apparent power supplied by the source. Mathematically, it is expressed as

$$PF = \frac{P_{\mathrm{Real}}}{P_{Apparent}} \tag{5.1}$$

An ideal electrical circuit must have a power factor close to one, which means there is no wastage of electricity. But conventional battery chargers do not offer such power factors because of the presence of harmonics and phase shift between the voltage and current. There are many disadvantages associated with a poor power factor like increased rms value of the current flowing from the source, increased losses in the transmission lines, poor voltage regulation, and generation of harmonics on the input side. In order to resolve these problems, PFC methods are employed in battery chargers.

The implementation of PFC offers several important advantages Improved Input Power Factor, Reduced Harmonic Distortion, Better Energy efficiency, Reduced current stress, Improved Grid compatibility.

5.3 SELECTION OF BRIDGELESS BOOST PFC CONVERTER FOR PRESENT WORK

The selection of suitable Power Factor Correction converter plays an important role in the functioning of the battery charger. The present work involves the designing of a battery charger of 1 kW for a 48V battery bank, therefore, the choice of the front end conversion circuit must take into account different factors such as efficiency, improved power factor correction, lower harmonics in line currents, constant DC output voltage, and minimum losses in conduction. In the case of high-power converters, such as the battery charger of 1 kW, the losses associated with conduction become very significant and affect directly the performance of the converter.

In order to avoid these demerits, the Bridgeless Boost PFC converter is chosen in this study. In the bridgeless topology, the traditional diode bridge rectifier is omitted from the primary conduction pathway and the conversion is done with the help of switching elements and boost diodes. Thus, by decreasing the number of semiconducting components in the conduction pathway, both conduction losses and converter efficiency are minimized. Among several other factors that contributed to choosing the Bridgeless Boost PFC converter, the capability of achieving a near unity power factor while minimizing Total Harmonic Distortion (THD) in the input current waveform can be considered as the most crucial one. This happens because of the conversion of input current to resemble the wave shape of the supply voltage, thereby drawing near sinusoidal input currents from the AC source. Apart from all these factors, an increase in the efficiency of the converter in comparison to that of a regular boost PFC converter is another major benefit. The reason being, conduction losses have decreased substantially due to omission of diode bridges.

For the proposed battery charger system, the Bridgeless Boost PFC converter is designed to convert the available 230 V AC utility supply into a regulated 400 V DC bus voltage. This regulated DC output serves as the input to the second-stage Full Bridge LLC Resonant Converter**,** which performs isolated DC-DC conversion and voltage regulation for charging the 48 V battery system**.**

In the present work, the converter operates under Continuous Conduction Mode (CCM) at a switching frequency of 100 kHz. The CCM operation is selected because it provides lower input current ripple, smoother converter operation, reduced current stress, and improved harmonic performance. The converter is designed to achieve approximately 2% output voltage ripple while maintaining a power factor within the range of 0.98-0.99. Therefore, considering efficiency, reduced conduction loss, improved power quality, and suitability for medium-power battery charging applications, the Bridgeless Boost PFC converter is selected as the front-end stage of the proposed charging system.

5.4 WORKING PRINCIPLE AND MODES OF OPERATION

The converter operation is divided into two major intervals depending upon the polarity of the AC input supply that is Positive Half cycle operation and Negative Half cycle operation. During each half cycle, only one converter leg actively performs boost conversion while the other leg provides a return current path. This alternate switching mechanism eliminates unnecessary diode bridge conduction loss and improves overall converter efficiency. The detailed converter operation during each half cycle is explained in the following section through mode-wise analysis. In this section, the converter operation will be analyzed in detail through different modes of operation.

5.4.1 Mode 1 – (Positive Half Cycle), Switch (S1):ON , Body Diode (D4):ON

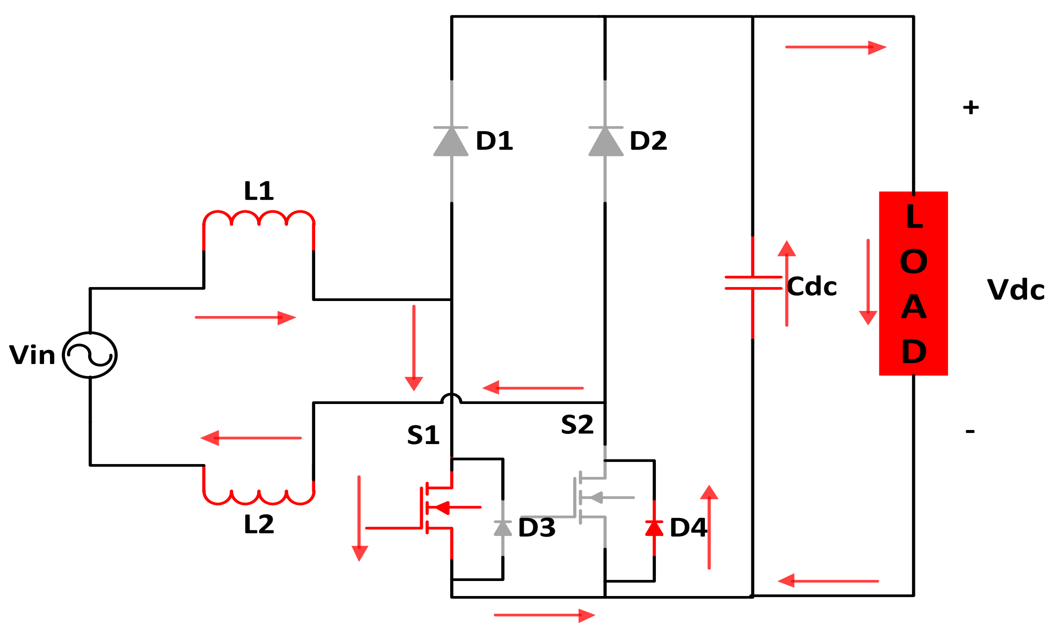


Fig. 5.4.1 Bridgeless Boost PFC operation in MODE 1

During the positive half cycle of the AC supply, the input terminal polarity becomes positive with respect to the return path. In this interval, switch S1 becomes the active switch while switch S2 remains inactive. When switch S1 is turned ON, the corresponding boost inductor L1 starts storing energy from the AC source. Since the switch provides a low resistance conduction path, the inductor current gradually increases and magnetic energy is accumulated within the inductor.

During this interval S1 conducts, L1 stores energy, D1 remains reverse biased, Output capacitor supplies load energy. At this stage, the stored energy is not yet transferred to the output because the boost diode remains reverse biased. Meanwhile, the other inductor L2 does not perform active boost action during this positive half cycle. However, it acts as a return current path and participates in maintaining circuit continuity. This is an important characteristic of bridgeless boost topology that distinguishes it from conventional boost converters.

The voltage across the inductor during switch ON condition can be expressed as

$$V_{L1} = V_{in}$$

Applying the inductor voltage-current relation

$$V_{L1} = L\frac{dI_L}{dt}$$

Thus inductor current varies as

$$\frac{dI_L}{dt} = \frac{V_{in}}{L_1} \quad (5.4.1)$$

This indicates that inductor current increases linearly during the switch ON interval. The output capacitor Co supports the load requirement during this mode and helps maintain DC bus voltage stability.

5.4.2 Mode 2 – (Positive Half Cycle), Diode (D1):ON , Body Diode (D4):ON

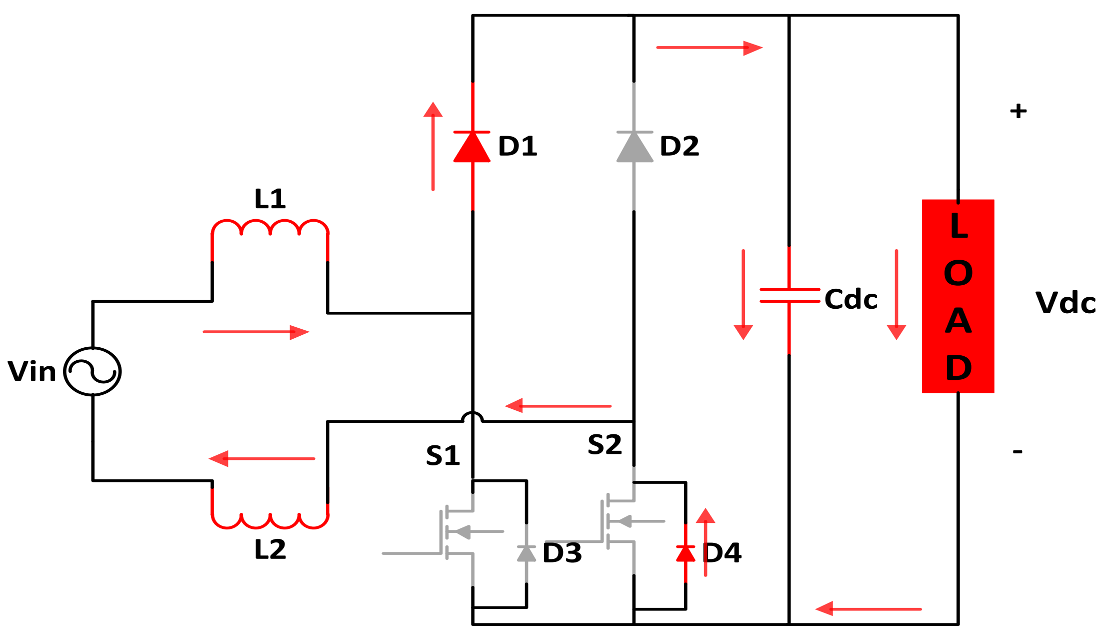


Fig. 5.4.2 Bridgeless Boost PFC operation in MODE 2

When switch S1 turns OFF, the stored energy in inductor L1 cannot collapse instantaneously because inductors oppose sudden current change.

As a result, the polarity across the inductor reverses and forward biases diode D1. The stored magnetic energy is now transferred to the output capacitor and load.

During this interval S1 remains off, D1 becomes forward biased, L1 releases stored energy, Output capacitor charges. Current path is being showed in the Fig 5.4.2 .

Since the inductor voltage reverses during energy transfer, inductor voltage becomes

$$V_{L1} = V_{in} - V_o$$

Where , Vo>Vin, thus the converter performs boost action, allowing the output voltage to become higher than the input voltage peak. The rate of inductor current change during switch OFF interval becomes

$$\frac{dI_{L1}}{dt} = \frac{V_{in} - V_0}{L_1} \qquad (5.4.2)$$

The inductor L1 current decreases gradually. The capacitor receives charging energy during this interval, thereby helping maintain the regulated 400 V DC bus voltage.

5.4.3 Mode 3 – (Negative Half Cycle), Switch (S2):ON , Body Diode (D3):ON

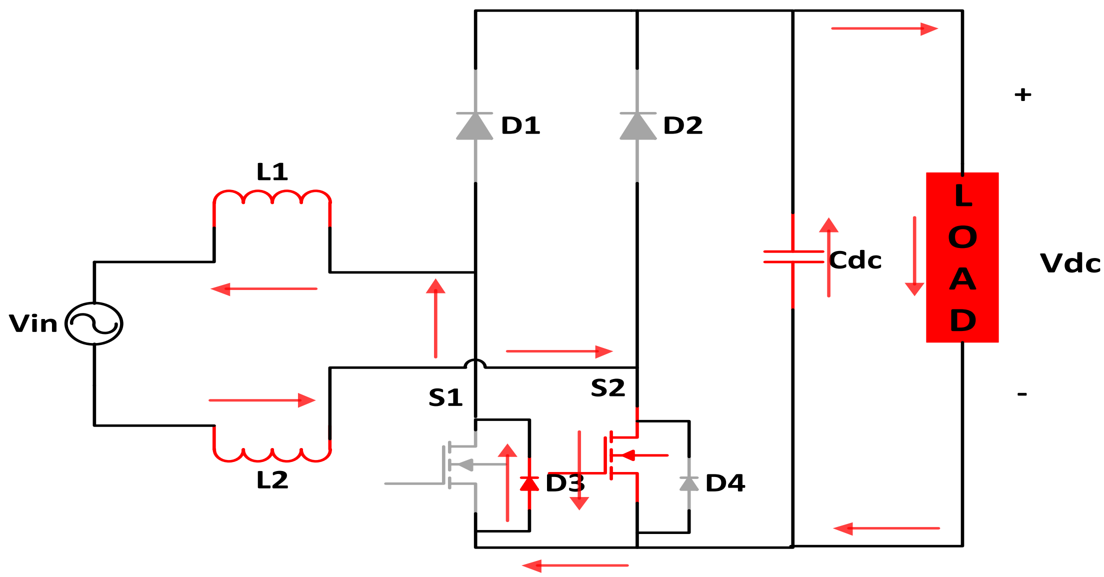


Fig. 5.4.3 Bridgeless Boost PFC operation in MODE 3

During the negative half cycle, the polarity of the AC source reverses. Consequently, switch S2 becomes the active switch while switch S1 remains inactive. When switch S2 turns ON**,** inductor L2 starts storing energy from the input source.

During this operating interval S2 conducts, L2 stores magnetic energy, D2 remains reverse biased, Output capacitor supplies load demand. The conduction path is shown in Fig. 5.4.3 . Similar to the positive half cycle, the inductor current increases linearly due to energy storage. The inductor voltage becomes

$$V_{L2} = V_{in}$$

Thus,

$$\frac{dI_{L2}}{dt} = \frac{V_{in}}{L_2} \tag{5.4.3}$$

Again, the capacitor supports the output load during the switch ON period.

The alternate operation of switches during positive and negative half cycles helps reduce semiconductor conduction losses compared to conventional bridge rectifier-based PFC converters.

5.4.4 Mode 4 – (Negative Half Cycle), Diode (D2):ON , Body Diode (D3):ON

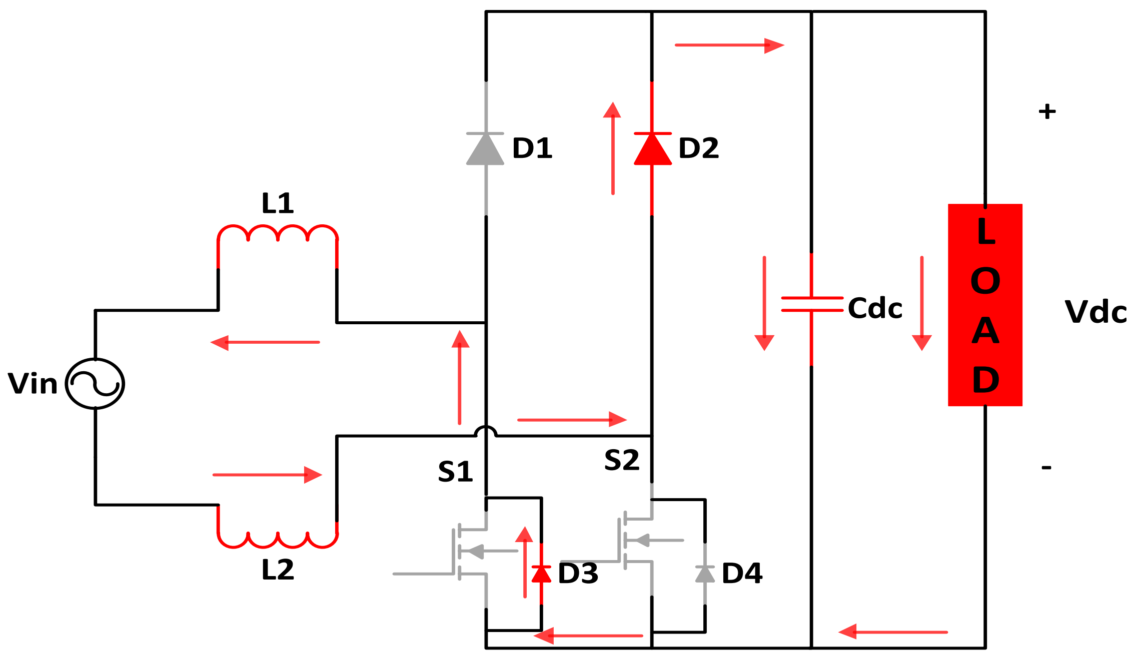


Fig. 5.4.4 Bridgeless Boost PFC operation in MODE 4

When switch S2 turns OFF, the magnetic energy stored in inductor L2 begins to transfer toward the output stage.

Since inductor current cannot change abruptly, diode D2 becomes forward biased and provides the path for energy transfer. During this interval S2 remains off, D2 conducts, L2 releases stored energy, Output capacitor charges. The corresponding conduction path is shown in Fig. 5.4.4 .

The inductor voltage is expressed as

$$V_{L2} = V_{in} - V_o$$

The inductor current decreases gradually as energy is transferred to the capacitor and load.

$$\frac{dI_{L2}}{dt} = \frac{V_{in} - V_0}{L_2} \tag{5.4.4}$$

This OFF interval also contributes to maintaining the boosted DC output voltage across the output capacitor.

5.5 CALCULATION OF BRIDGELESS BOOST PFC CONVERTER PARAMETERS

The effectiveness of operation of the Bridgeless Boost Power Factor Corrector depends on the proper selection of various parameter values. Selection of components and their sizes becomes critical for achieving high efficiency, regulated voltage at the DC bus, low voltage ripple, and higher power quality of the circuit.

In the current design study, the Bridgeless Boost PFC converter is to be designed for the purpose of providing power for a 1 kW battery charger. In the process, 230V AC input is to be converted into a regulated DC output voltage of 400 V. The converter will be made to operate in CCM at 100 kHz switching frequency, while output voltage ripple should not exceed 2% and input power factor should remain at 0.98-0.99 levels.

5.5.1 Duty Cycle Calculation (D)

The duty cycle is one of the most important parameters in a boost converter because it determines the voltage conversion ratio and controls the boosting action of the converter.

For a boost converter operating ideally in Continuous Conduction Mode, the relationship between input and output voltage is expressed as

$$V_{dc} = \frac{V_{in}}{1-D} \quad (5.5.1a)$$

Since the converter is supplied from an AC source, the maximum input voltage corresponds to the peak of the sinusoidal waveform. The peak input voltage is calculated as

$$V_{in(pk)} = V_{rms} \cdot \sqrt{2}$$
$$V_{in(pk)} = 230 \times 1.414 = 325.2\,V \quad (5.5.2b)$$

The required output voltage is 400V (Vdc), therefore using equation 5.5.1a duty cycle (D) becomes,

$$D = 1 - \frac{V_{in(pk)}}{V_{dc}}$$

On substituting values we get, D=0.187 , practically due to switching losses, voltage drops across semiconductor devices, and controller action, the duty ratio varies dynamically throughout the AC cycle. Therefore, the practical duty range generally lies between ($0.18<D<0.30$) to maintain regulated DC bus voltage.

5.5.2 Calculation of Boost Inductance (L1 & L2)

Boost inductor significantly influences the current ripple, stability of the converter, and conduction mode. Because the proposed DC-to-DC converter functions on Continuous Conduction Mode, the inductor must be chosen appropriately so as to prevent the inductor current from dropping to zero.

Improperly designed inductor will result in large ripple current, low power factor, high levels of EMI, and instability of the whole circuit. Therefore, choosing an appropriate value of inductance is vital.

The inductance is calculated using the following expression

$$L = \frac{V_{in} D}{\Delta I_L f_s} \tag{5.5.2a}$$

The average input current is calculated as

$$I_{in(avg)} = \frac{P_0}{V_{in(rms)}} = \frac{1000}{230} = 4.35\,A \tag{5.5.2b}$$

For CCM operation, ripple current is selected as 30% of average inductor current, therefore ripple current is,

$$\Delta I_L = 0.3 \times 4.35 = 1.305\,A \tag{5.5.2c}$$

Using equation 5.5.2a we get value of inductance as L= 466uH, considering practical component availability and improved ripple reduction, an inductance range of (400-600uH) is selected. For present work L=470uH is considered an appropriate practical design choice.

5.5.3 Calculation of DC Bus Capacitance (C_{dc})

The capacitor in the output stage is popularly known as the DC link capacitor. The main objective of this capacitor is to smooth out the DC output voltage, minimize ripple in the DC output voltage, and ensure that the DC bus voltage is maintained at a stable level at all times.

The objective of the DC bus capacitor is to minimize ripple in the output voltage and ensure that the DC bus voltage remains stable. When it comes to designing the capacitor for single-phase PFC converters, the double line frequency ripple is very important.

For 50Hz line frequency, ripple frequency (fr) is calculated as 100Hz, capacitor value is calculated as

$$C = \frac{P_0}{2\omega V_{dc} \Delta V_0} \tag{5.5.3a}$$

The allowable voltage ripple is 2% of Vdc that is 8V, on substituting values in equation 5.5.3a, we get C_{dc}= 995uH, hence a practical value of 1000uF, 450V is taken to maintain stable DC bus voltage. The selected capacitor value also helps reduce transient voltage fluctuations and improves output voltage regulation.

5.5.4 Selection of Power Switch Rating (S1 & S2)

The performance of a Bridgeless Boost PFC converter is highly dependent on the suitable choice of switching components. This is due to the reason that in such a converter, the switch undergoes the stress of voltage and current. Any improper selection of switch can result in overheating, decreased efficiency, switching losses, and other such problems. In high-frequency converters, MOSFET switches are preferred since they have a very fast switching speed and minimal switching losses.

Proper selection of switch involves two primary factors Voltage and current ratings of the switch.

Voltage Rating of Switch (V_{sw})

The voltage stress across the MOSFET mainly depends on the converter output voltage. During switch OFF condition, the switch must withstand nearly the entire DC bus voltage. Therefore, switch voltage stress can be approximated as $V_{sw(\max)} = V_0$, where V_0=400V , but in practical systems, voltage overshoot occurs due to parasitic inductances, switching transients, ringing effects, EMI, therefore a suitable safety margin must be included, typically $1.5 \times V_0$, is considered for reliable operation. Hence $V_{sw(\max)} = 1.5 \times 400 = 600V$ is taken.

Current Rating of Switch (I_{sw})

The switch current rating depends upon converter input power and input voltage. The average input current is calculated as 4.35A from equation 5.5.2b

Since the practical converter operation involves ripple current and transient overload conditions, the switch should be selected with sufficient current margin. Generally a factor of 2 is multiplied to get the actual current rating.

Table. 5.1 Design specification for Bridgeless Boost PFC converter

Parameters	**Value**
L-N rms Supply voltage (V_s), grid frequency (f_s)	230 V, 50 Hz
DC Bus voltage (V_{dc})	400V
Power Rating (P_{ac})	1 kW

Output Current (I_o)	2.5 A
Switching Frequency (f_{sw})	100 kHz
DC Bus Capacitance (C_{bus})	1000 µF
Boost Inductance (L_s)	470 µH
Input Current THD	< 5%

CHAPTER 6

DESIGN AND ANALYSIS OF FULL BRIDGE LLC RESONANT CONVERTER

6.1 INTRODUCTION

These days isolated DC-DC converters find wide applications in power electronics circuits. Some of the applications include EV chargers where high power density is needed, as well as efficient power converters. Such characteristics are offered by LLC resonant converters. Different from other DC-DC converters that are controlled through pulse width modulation (PWM), and thus providing duty ratio D, LLC is controlled by varying the frequency of oscillations depending on the range of frequencies obtained. The basic principle of operation of an LLC converter involves altering the output voltage depending on changing the switching frequency. It does this because the alteration of frequency changes the input impedance of the resonant circuit, and thereby changes the output voltage. There are mainly two types of LLC resonant converters: series and parallel resonant converters.

In low load conditions, high frequency is required because it is difficult to control the output as a result of high impedance of the load. The parallel resonant converter is not used for applications requiring high power density because of the high circulating currents in the circuit. These shortcomings may be solved through combining these circuits and thus achieving LLC or LCC resonant converters. The LLC resonant converters are popular because of their flexibility in regulating both the load and line. This may be done through varying the frequency slightly. They also have zero voltage switching among the primary controlled switches and thus reduced switching losses hence increased efficiency. This may only be done while running the converter in the inductive region on the gain against normalized frequency plot. Also, they have zero voltage switching among the secondary diodes of the diode bridge rectifier.

Full bridge LLC is opted before half bridge LLC resonant converter when higher power rating is required for certain application. In this work FBLLC is adopted and analyzed for off-board EV charging. FBLLC converter consists of full-bridge inverter which is utilized for generating bipolar voltage square wave having duty $D=0.5$ due to which switches $Q1$, $Q4$ are ON for positive cycle and switches $Q2$, $Q3$ are ON for negative cycle. This bipolar square voltage acts as a switching waveform for the resonant tank circuit which consists of resonating inductor (Lr), resonating capacitor (Cr) and magnetizing inductance (Lm) of high frequency transformer. This tank circuit drives power to the secondary side. Secondary side includes diode bridge rectifier which converts AC to DC and filter out using output capacitor Co and power is transferred to the load RL.

At resonant frequency f_o, the resonant tank circuit provides the minimum impedance and the maximum current or power is delivered to the load. The impedance of the resonant tank circuit depends on the switching frequency of the applied switching voltage waveform V_{sw}. In LLC resonant tank due to the influence of the transformer magnetizing inductance, L_m. The peak resonance does not occur at resonant frequency, f_o. The peak resonance occurs at f_{co} and it depends on load and range of f_{co} is, f_p □ f_c □ f_o , where,

$$f_p = \frac{1}{2\pi\sqrt{(L_r + L_m)C_r}} \tag{6.1}$$

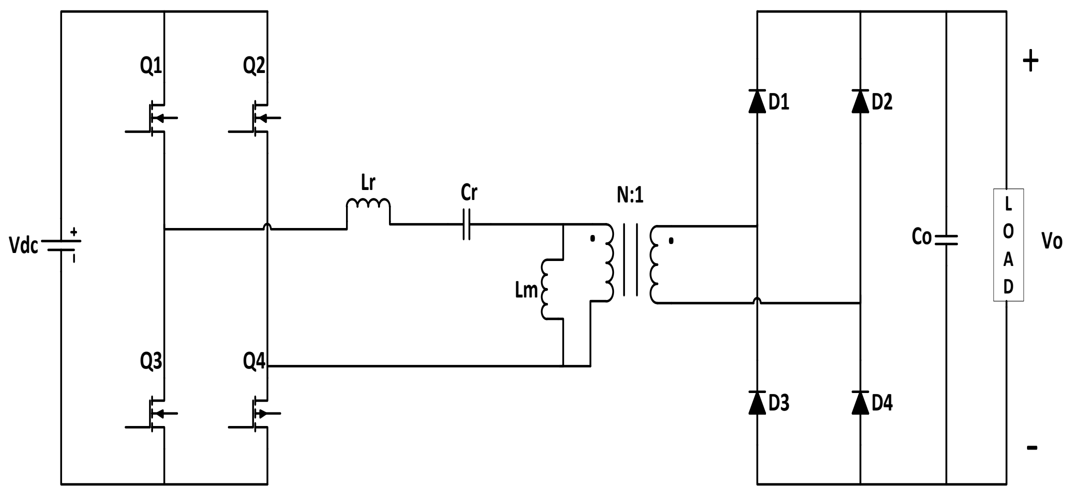


Fig. 6.1 Circuit Diagram of Full Bridge LLC Resonant Converter

Operation at resonance:

During this mode of operation as in Fig.6.2 the switching frequency is kept equal to resonant frequency, i.e. $f_{sw}=f_o$. The switches Q_1 ,Q_4 are ON for positive cycle of switching voltage, the resonant current is sinusoidal in nature. At t=t_1, when switches Q_1, Q_4 are OFF, the resonant current becomes equal to magnetizing current I_m during region t_1 to t_2. As, $f_{sw}=f_o$, wide range of operation is not possible. This delay time for switching ON the switch Q_2, Q_3 between t_1 to t_2 helps in achieving ZVS for primary side controlled switches and ZCS for secondary side diodes.

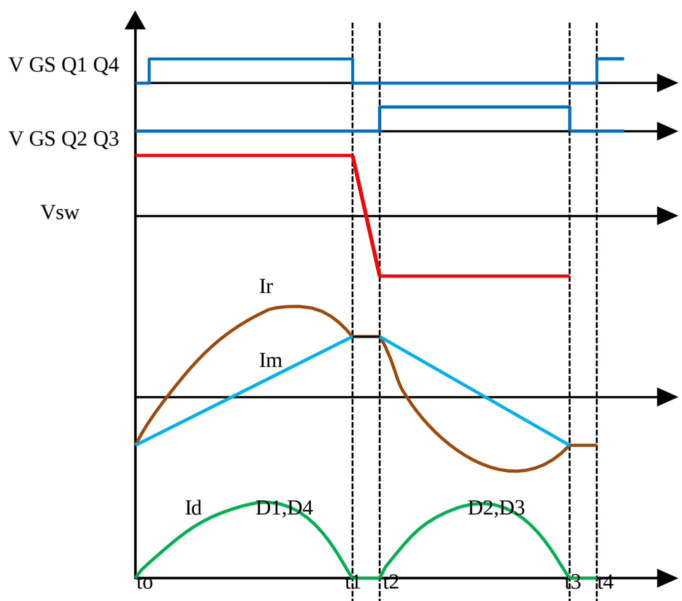


Fig. 6.2. Operation at resonance

Operation below resonance:

During this mode of operation as in Fig.6.3 the switching frequency is kept below the resonant frequency, i.e. $f_{sw}<f_o$. In this the resonant current becomes equal to the magnetizing current I_m quite before t=t1, which leads to more circulating current demand and considerable conduction losses across switches. The diode current also becomes discontinuous in this mode of

operation and switching frequency should not be reduced below a certain f_O to prevent circuit to lose ZVS.

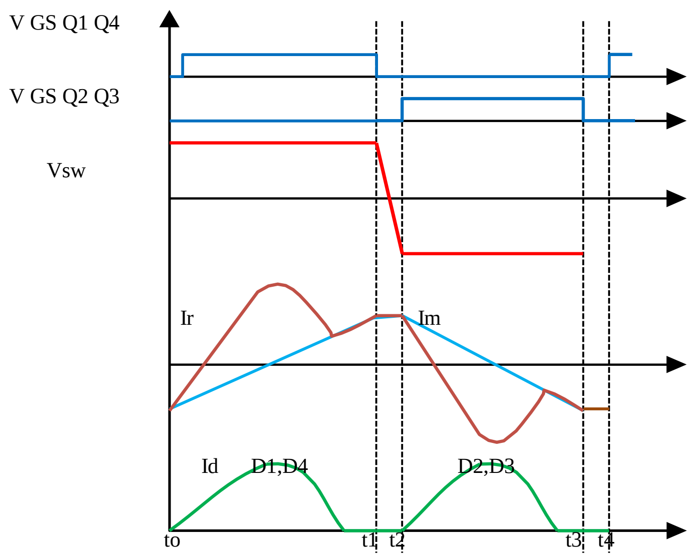


Fig. 6.3. Operation below resonance

Operation above resonance:

During this mode of operation as in Fig.6.4 the switching frequency is kept above the resonant frequency, i.e. $f_{sw}>f_o$. In this the resonant current becomes continuous and sinusoidal, which leads to less circulating current demand and very less considerable conduction losses across switches. The diode current is reduced to zero after $t=t_1$ which means secondary side diodes are not soft commutated and leads to increased reverse recovery losses.

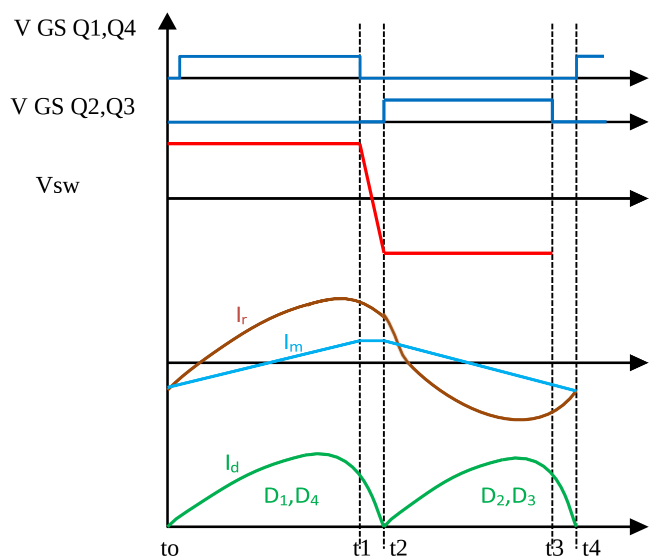
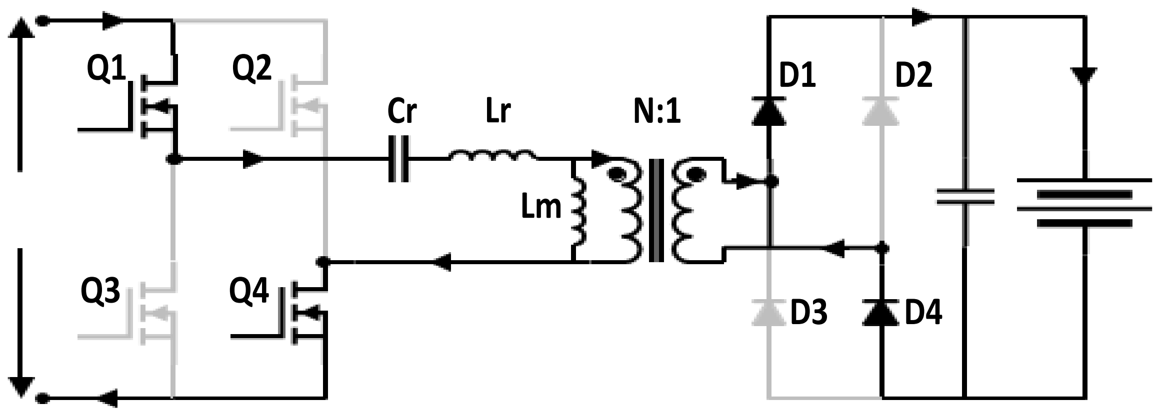


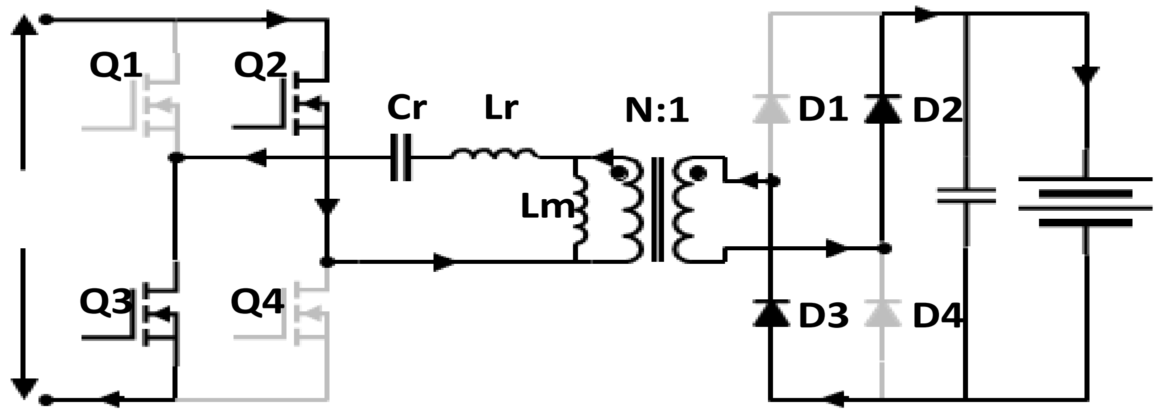
Fig. 6.4. Operation above resonance

6.2 MODES OF OPERATION OF FBLLC CONVERTER

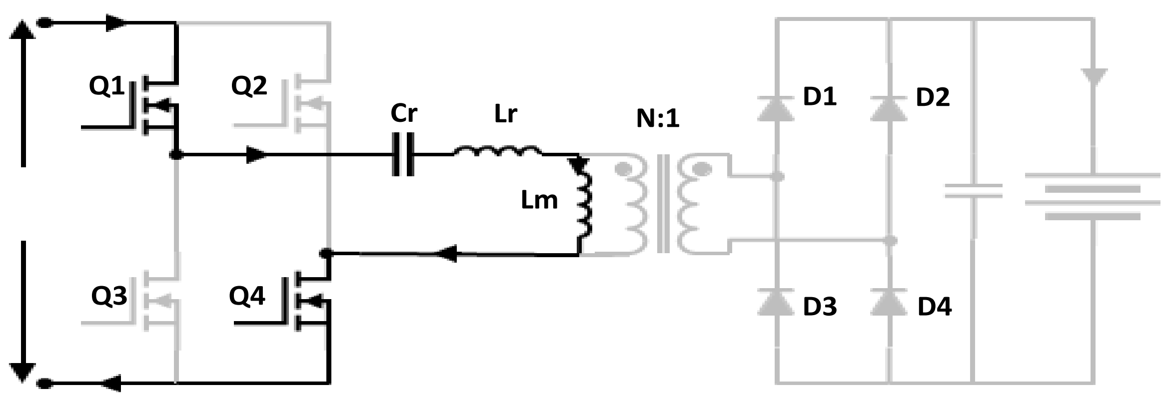
The operation of the LLC resonant converter can generally be explained through different operating intervals, starting from positive cycle operation to negative cycle operation, and freewheeling operation. During the positive cycle of operation, switching pulses are applied to the semiconductor switches Q1 and Q4, which generate a positive square waveform across the resonant tank circuit, as illustrated in Fig. 6.2(a). Similarly, during the negative cycle of operation, the switching signals are transferred to switches Q2 and Q3, resulting in the formation of a negative square waveform at the resonant network input, as shown in Fig. 6.2(b). These alternating switching intervals are primarily responsible for transferring energy from the converter primary side to the secondary side through the high-frequency transformer. The transferred power is subsequently utilized for charging the lithium-ion battery connected at the output stage. Further, Fig. 6.2(c) represents the operating condition in which the resonant current becomes equal to the magnetizing current, due to which no current transfer occurs toward the secondary side of the converter. In addition, Fig. 6.2(d) illustrates the freewheeling mode, corresponding to the condition of positive magnetizing current.



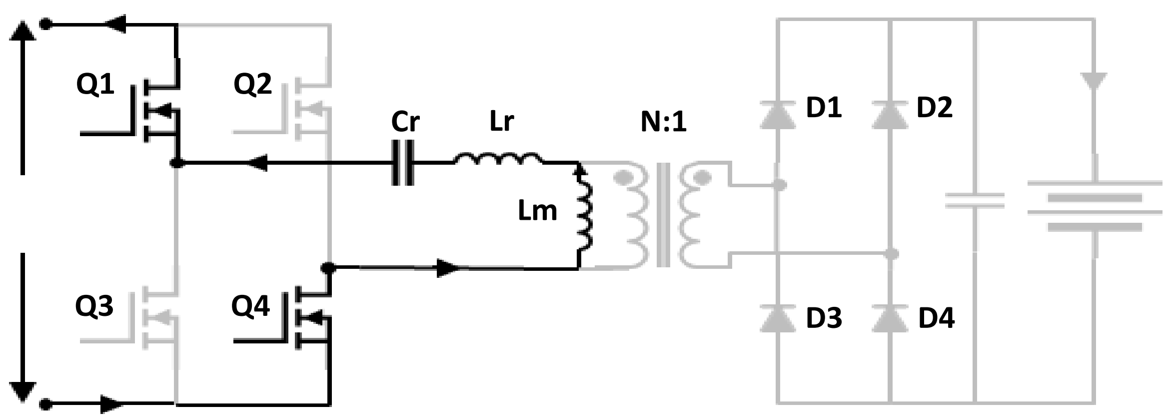
(a)


Q1
Q2
Cr
Lr
N:1
D1
D2
Lm
Q3
Q4
D3
D4

(b)


Q1
Q2
Cr
Lr
N:1
D1
D2
Lm
Q3
Q4
D3
D4

(c)


Q1
Q2
Cr
Lr
N:1
D1
D2
Lm
Q3
Q4
D3
D4

(d)

Fig. 6.5 Full Bridge LLC converter modes of operation for (a), (b) Power flow from primary to secondary (c), (d) No power flow from primary to secondary

6.3 FULL BRIDGE LLC RESONANT CONVERTER DESIGN

First Harmonic Approximation (FHA) can be used to analyze LLC resonant converter when higher order harmonics are not included as in Fig. 6.3 .

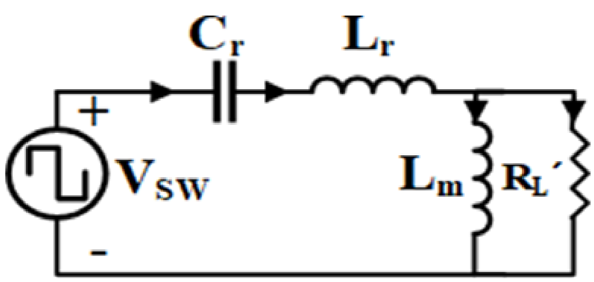


Fig. 6.6 LLC equivalent circuit model

Fig. 6.7 summarizes the designing steps followed for designing LLC converter. The gain is calculated as,

$$M_g = \frac{V_{oe}}{V_{ge}} = \left| \frac{jX_{L_m} \parallel R_e}{\left(jX_{L_m} \parallel R_e\right) + j\left(X_{L_r} - X_{C_r}\right)} \right| \tag{6.2}$$

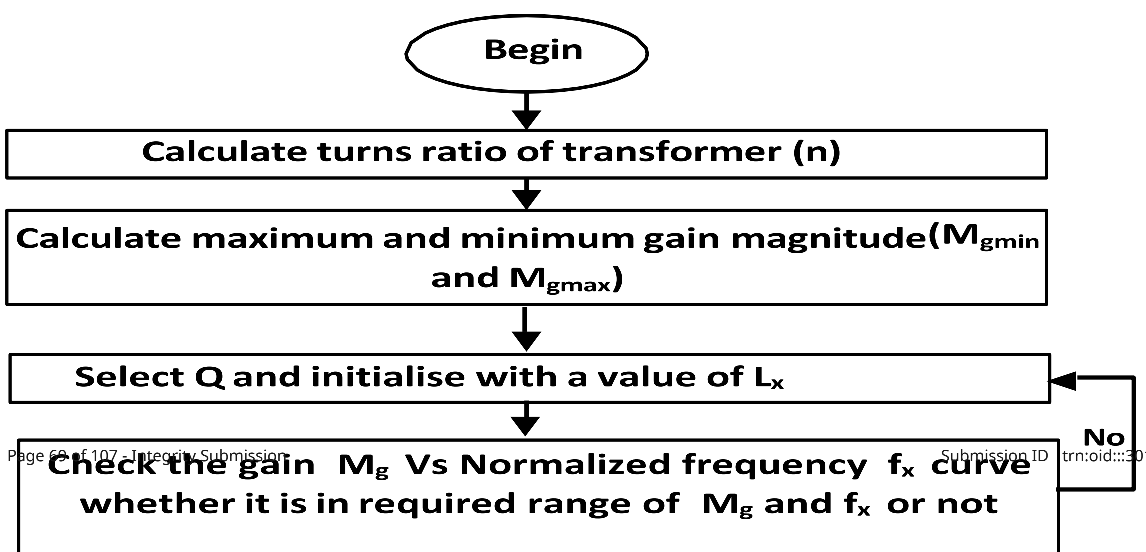


Fig. 6.7 Designing steps of LLC resonant circuit

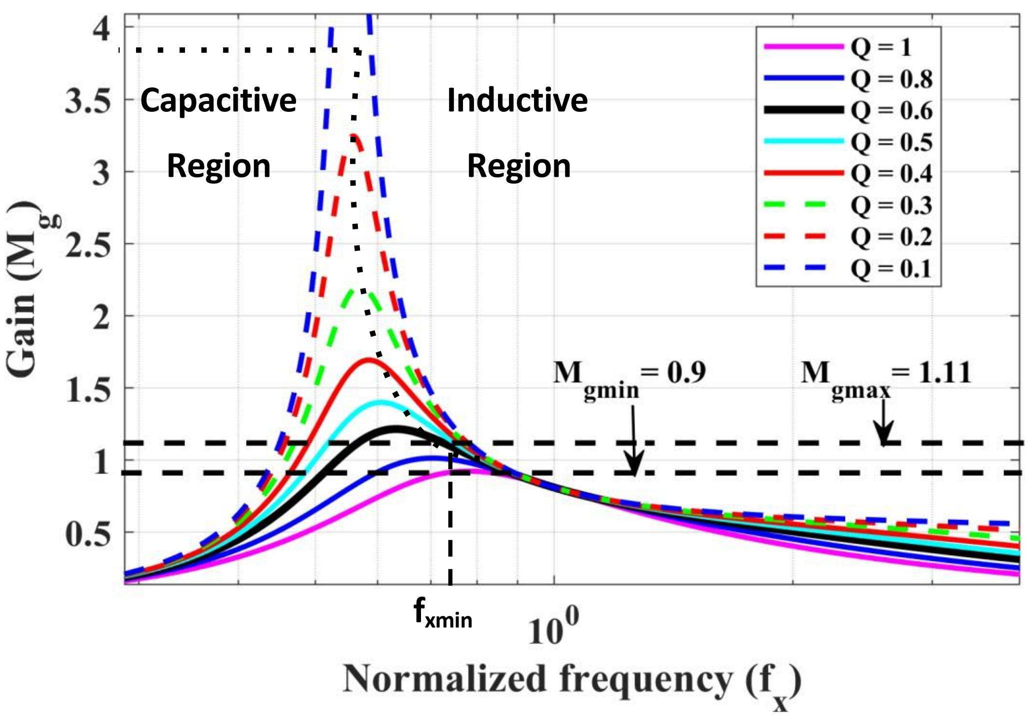


Fig. 6.8 Gain magnitude Vs normalized frequency curve

The output voltage depends on the gain magnitude,

$$V_0 = M_g \times \frac{1}{n} \times V_{dc} \tag{6.3}$$

1 Gain magnitude is the function of L_x, f_x, and Q. The optimum value of the Q and L_x can
1 be obtained using gain curve. Hence, only controlled variable left is the normalized frequency, f_x. Gain in terms of f_x can be written as,

$$M_g = \left[\frac{L_x \times f_x^{\,2}}{\left[(L_x + 1) \times f_x^{\,2} - 1 \right] + j \left[(f_x^{\,2} - 1) \times f_x \times Q \times L_x \right]} \right] \tag{6.4}$$

The quality factor is described as,

$$Q = \frac{1}{R_e} \sqrt{\frac{L_r}{C_r}} \tag{6.5}$$

The normalized frequency is described as,

$$f_x = \frac{f_{sw}}{f_0} \tag{6.6}$$

The turns ratio of transformer at gain=1 can be calculated as,

$$n = M_g \times \frac{V_{dc}}{V_0} = \frac{25}{3} \tag{6.7}$$

The maximum and the minimum gain can be calculated as,

$$M_{g\_min} = \frac{n \times (V_{0\_min} + V_D)}{V_{dc\_max}} = 0.9 \tag{6.8}$$

$$M_{g\_max} = \frac{n \times (V_{0\_max} + V_D)}{V_{dc\_min}} = 1.15 \tag{6.9}$$

The rms value of primary side load current can be calculated as,

$$I_{0\_prms} = \frac{\pi}{2\sqrt{2}} \times \frac{1}{n} \times I_0 = 2.77\,\text{A} \tag{6.10}$$

The rms value of magnetizing current at minimum f_{sw} can be evaluated as,

$$I_{m\_rms} = \frac{2\sqrt{2}}{\pi} \times \frac{nV_0}{\omega L_m} = 1.24\,\text{A} \tag{6.11}$$

The resonant current can be calculated as,

$$I_r = \sqrt{I_m{}^2 + I_{0\_prms}} = 3.03\,\text{A} \tag{6.12}$$

Equivalent load resistance can be calculated as,

$$R_e = \frac{8}{\pi^2} \times n^2 \times R_L = 129.76\Omega \tag{6.13}$$

Resonant circuit parameters can be calculated as,

$$C_r = \frac{1}{2\pi \times Q \times f_0 \times R_e} = 80.6\,\text{nF} \tag{6.14}$$

$$L_r = \frac{1}{(2\pi \times f_0)^2 \times C_r} = 31.4\,\text{uH} \tag{6.15}$$

$$L_m = L_x \times L_r = 157\,uH \tag{6.16}$$

Table 6.1. Design Specifications for LLC Resonant Converter

Parameters	**Value**
DC Bus voltage (V_{dc_min}-V_{dc_max}), Nominal bus voltage (V_{dc_nom})	380-420 V, 400 V
Output voltage (V_{o_min}-V_{o_max}), Nominal output voltage (V_{o_nom})	42-52 V, 48 V
Quality factor (Q)	0.6
Transformer turns ratio (n)	25:3
Resonating Inductance (L_r)	31.4 µH
Resonating Capacitance (C_r)	80.6 nF
Magnetizing Inductance (L_m)	157 µH
Inductance ratio	5
Resonating frequency (f_o)	100 kHz

CHAPTER 7

CONTROL SCHEME ANALYSIS

7.1 CONTROL OF BRIDGELESS BOOST PFC CONVERETR

7.1.1 Control Objective

The primary objective of a Bridgeless Boost PFC converter is not only to convert AC input into regulated DC output but also to improve power quality at the input side. In practical operation, supply voltage variation, load fluctuations, switching disturbances, and parameter changes continuously affect converter performance. Therefore, proper control becomes essential to maintain stable operation. If the Bridgeless Boost PFC converter is operated in open-loop mode, the output voltage becomes highly sensitive to variations in input voltage, load power demand, switching disturbances, converter parameter variations.

Such variations may result in unstable DC bus voltage and improper operation of the subsequent Full Bridge LLC converter stage. In the proposed charging system, the Bridgeless Boost PFC converter is required to maintain a regulated 400V DC bus voltage irrespective of load variation. Since the Full Bridge LLC converter continuously draws power from the DC bus, voltage regulation becomes extremely important. Additionally, the converter must ensure that the input current waveform follows the sinusoidal input voltage waveform. This current shaping action is necessary to achieve high power factor and reduced Total Harmonic Distortion (THD). To accomplish these objectives simultaneously, a **dual loop control strategy** is employed.

7.1.2 Dual Loop Control for Bridgeless Boost PFC Converter

The dual loop control technique is one of the most widely adopted control methods in Power Factor Correction converters because it offers superior regulation capability, improved dynamic performance, and better input current shaping. In this control method, two control loops operate simultaneously in a coordinated manner one is outer voltage control loop and other is inner current control loop. The overall purpose of dual loop control is to maintain both output voltage regulation and input current shaping. The general structure of dual loop control is shown in Fig. 7.1 .

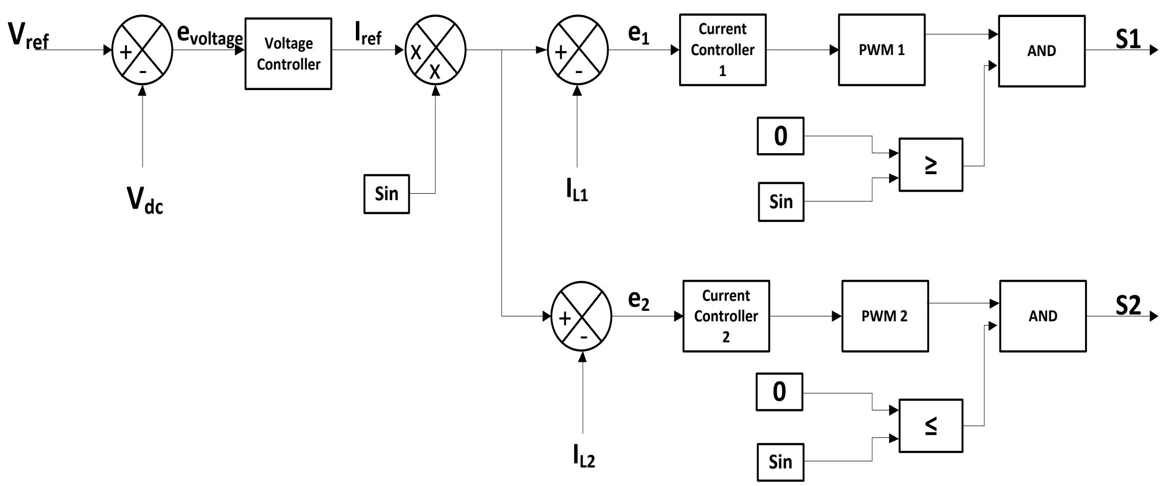


Fig. 7.1 Dual Loop Control of Bridgeless Boost Converter

The operation of both loops is coordinated in such a way that outer loop maintains voltage regulation while inner loop shapes input current and bring it close to the phase of input voltage. The outer voltage loop generally operates slower because voltage dynamics change gradually. In contrast, the inner current loop operates faster since current changes rapidly during switching action. Conventional PI controllers are being employed as voltage and current controller.

Small Signal Model of PFC circuit - Since the Bridgeless Boost PFC converter behaves similarly to a conventional boost converter during each half cycle, its mathematical modelling can be performed using the state-space averaging technique. The objective of controller design is to determine the relationship between duty cycle variation and output response. Linearized small signal equations of the PFC converter can be obtained by using averaged equations derived in chapter 5 and neglecting second order non-linear terms.

$$L\frac{d\hat{i}_L}{dt} = \hat{V}_{in} - (1-D)\hat{v}_o + V_o\hat{d} \tag{7.1}$$

$$C\frac{d\hat{v}_o}{dt} = (1-D)\hat{i}_L - I_L\hat{d} - \frac{\hat{v}_o}{R} \tag{7.2}$$

By using the eq. 7.1 and 7.2 duty to output voltage transfer function can be obtained as

$$G_{vd}(s) = \frac{\hat{V}_o(s)}{d(s)} = \frac{(1-D)V_o - LsI_L}{LCs^2 + \frac{L}{R}s + (1-D)^2} \tag{7.3}$$

Similarly duty to Inductor current transfer function can be obtained as

$$G_{id}(s) = \frac{\hat{I}_L(s)}{d(s)} = \frac{V_oCs + \left(\frac{V_o}{R} + (1-D)I_L\right)}{LCs^2 + \frac{L}{R}s + (1-D)^2} \tag{7.4}$$

Bode Plots of corresponding transfer function for suitable values of $K_p$and K_i are shown in Fig. 7.2

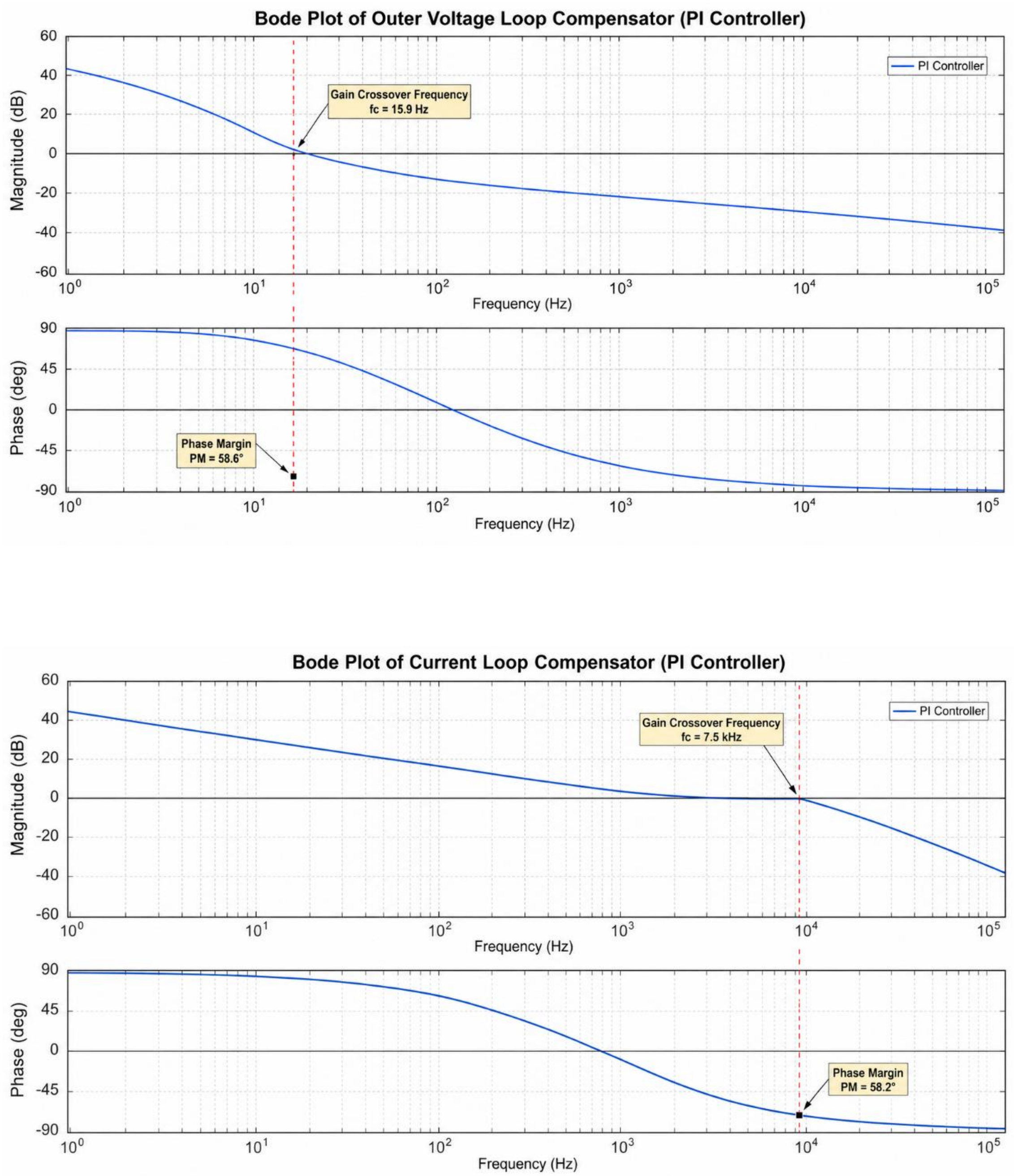


Fig. 7.2 Bode Plot of Voltage & Current loop compensator

From the Bode plot, it is clearly seen that both the compensators are meeting the required criteria of stability and good transient response for a close loop, that is crossover frequency of inner current loop compensator is much higher than outer voltage loop compensator and Phase Margin (PM) of both designed compensator lies in the desired range of (40-50) degrees, to achieve stability.

Outer Voltage control loop - The outer loop regulates the DC link voltage produced by the boost converter. The output voltage (400V) is continuously monitored and compared with a reference value. The error between the measured voltage and the reference is processed through a **PI controller.**

$$e_v(t)=V_{ref}-V_{dc}(t) \tag{7.5}$$

The PI controller generates the reference current for the inner loop

$$I_{ref}(t)=K_{pv}.e_v(t)+K_{iv}\int e_v(t)dt \tag{7.6}$$

Role of Outer Loop

- Keeps the DC link voltage stable under line variations
- Adjusts the input power drawn from the AC supply
- Ensures proper operation of the downstream LLC stage

Since the voltage loop deals with relatively slow variations (AC line frequency), it operates with a **low bandwidth**, ensuring stable and robust behavior.

Inner Current Control Loop - The inner loop forces the input current to follow the shape of the rectified line voltage. The reference for this loop is

$$i_{ref}(t)=I_{ref}(t).\frac{v_{in}(t)}{V_{peak}} \tag{7.7}$$

This means the converter draws a sinusoidal current in phase with the input voltage. The current error for currents in L_1 and L_2 are

$$e_1(t)=i_{ref}(t)-i_{L1}(t) \quad (7.8)$$

$$e_2(t)=i_{ref}(t)-i_{L2}(t) \quad (7.9)$$

These errors are fed into two separate PI controllers as shown in Fig. 7.1 to generate duty (D), which on passing through given logic circuit triggers S_1 and S_2.

$$d(t)=K_{pi}.e_i(t)+k_i\int e_i(t)dt \quad (7.10)$$

Role of Inner Loop

- Ensures power factor correction
- Reduces input current distortion
- Enables fast dynamic response to load and line changes

The current loop has a higher bandwidth than the voltage loop to ensure fast tracking of reference.

7.2 CONTROL OF FULL BRIDGE LLC RESONANT CONVERTER

7.2.1 Control Objective

The Full Bridge LLC resonant converter forms the second stage of the proposed battery charging system and performs the task of isolated DC-DC power conversion and output voltage regulation for charging the 48 V battery system. Unlike conventional PWM converters, the LLC resonant converter exhibits highly nonlinear gain characteristics that vary with switching frequency, load conditions, and resonant tank parameters. Therefore, operating the converter at a fixed switching frequency may not provide stable output voltage under varying load conditions.

The main objectives of LLC converter include stable output voltage regulation, compensation of load variations, soft switching achievement, improved converter efficiency. To achieve these objectives, Pulse Frequency Modulation is adopted in the proposed work.

7.2.2 PULSE FREQUENCY MODULATION (PFM) CONTROL

In pulse width modulation the variable is the duty ratio (D) which is varied to achieve the desired output voltage and make regulation easier for the converter. But in pulse frequency modulation (PFM) the duty ratio is kept constant but the switching frequency varies based on the load which is the drawback in the PWM as the switching frequency is constant so at the light load conditions the switching losses are high. Pulse frequency modulation is based on either on-time fixed and variable off-time or off-time fixed and variable on-time. At higher load, switching frequency increases and at light load condition it decreases as in Fig.7.2. This provides higher efficiency due to minimized switching losses across the controlled switches.

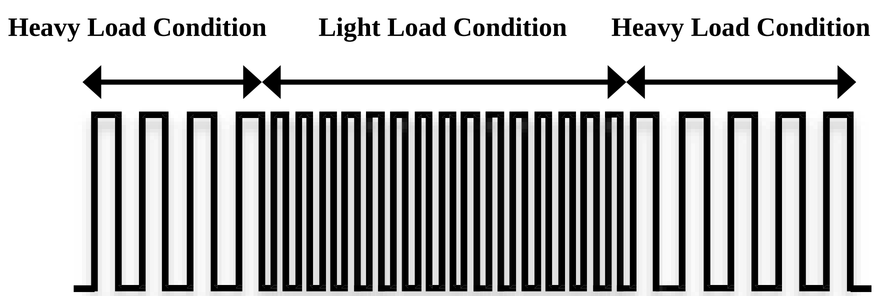


Fig. 7.3 Variation in switching frequency (f_{sw}) based on loading

PFM as operating with variable switching frequency leads to difficulty in designing filter as the frequency cannot be predicted at particular instant. If it comes within the 20 kHz audible range can leads to ringing. So, this have to be consider while controlling a switching converter using pulse frequency modulation (PFM). In PFM, the output voltage is the function of switching frequency (f_{sw}).

$$V_0 = f^n(f_{sw}) \tag{7.11}$$

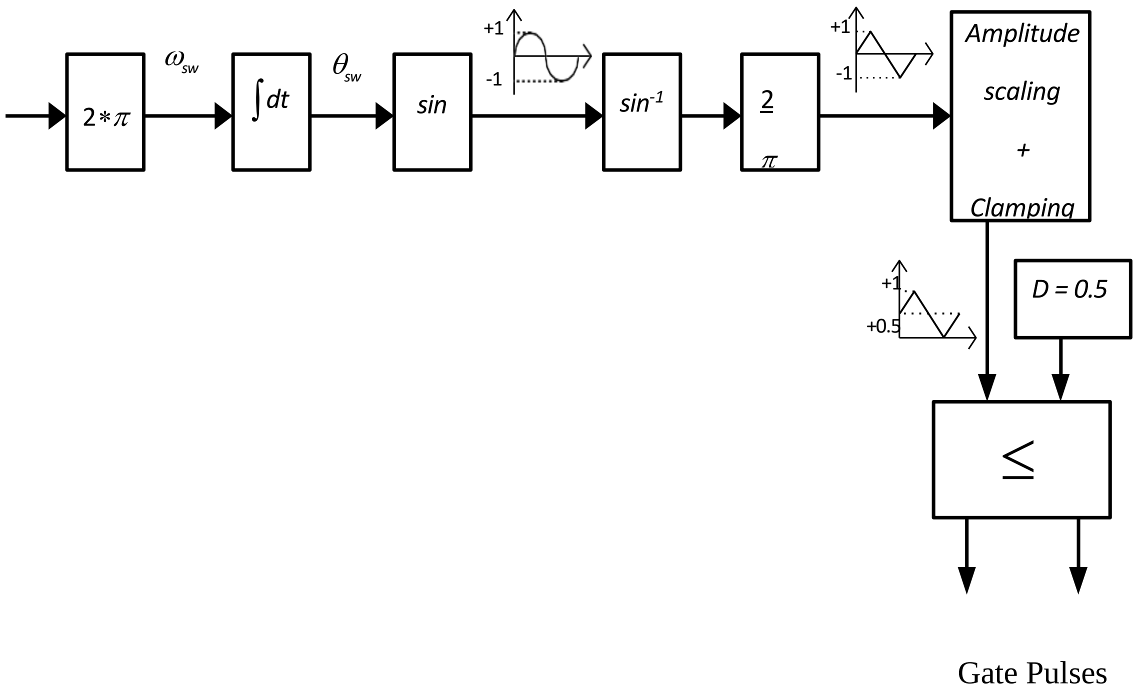


Fig. 7.4. PFM Control Block Diagram

Fig. 7.3 shows the PFM block diagram where the variable frequency f_{sw} is provided at the input of the system which is the multiplied with 2π to get angular frequency ω_{sw}. This output is then passed through an integrator to produce theta θ_{sw} and this theta is required to generate sine wave having amplitude range +1 and -1. This is utilized by forwarding it to the inverse sine to get reference theta which is multiplied by $\frac{2}{\pi}$ to get a triangular wave having amplitude ranging between +1 and -1. This wave is passed through amplitude scaling and clamping circuits to generate a triangular wave having same number of cycles but amplitude ranging between +1 and 0, zero crossing at +0.5. This generated carrier wave is compared with the duty ratio which is fixed in the case of PFM i.e. D=0.5

and amplitude of carrier wave is compared with 0.5 and wherever amplitude is less than equal to 0.5, gate pulses are generated.

$$\omega_{sw} = 2 \times \pi \times f_{sw} \tag{7.12}$$

$$\theta_{sw} = \int \omega_{sw}.dt \tag{7.13}$$

CHAPTER 8

TWO STAGE BRIDGELESS BOOST PFC FED FULL BRIDGE LLC RESONANT CONVERTER

8.1 INTRODUCTION

This chapter presents the simulation results and performance analysis of the proposed two-stage converter system developed for charging a 48 V battery. The proposed charging architecture consists of a Bridgeless Boost Power Factor Correction converter followed by a Full Bridge LLC resonant converter. MATLAB/Simulink environment has been employed to validate the theoretical design, control strategy, voltage regulation capability, and dynamic performance of the proposed system. The obtained simulation results are analyzed to verify the achievement of high power factor, stable DC bus voltage, reduced ripple, and regulated battery charging voltage. Fig. 8.1 shows the block diagram of the proposed converter and the Fig. 8.2 shows the circuit diagram of it.

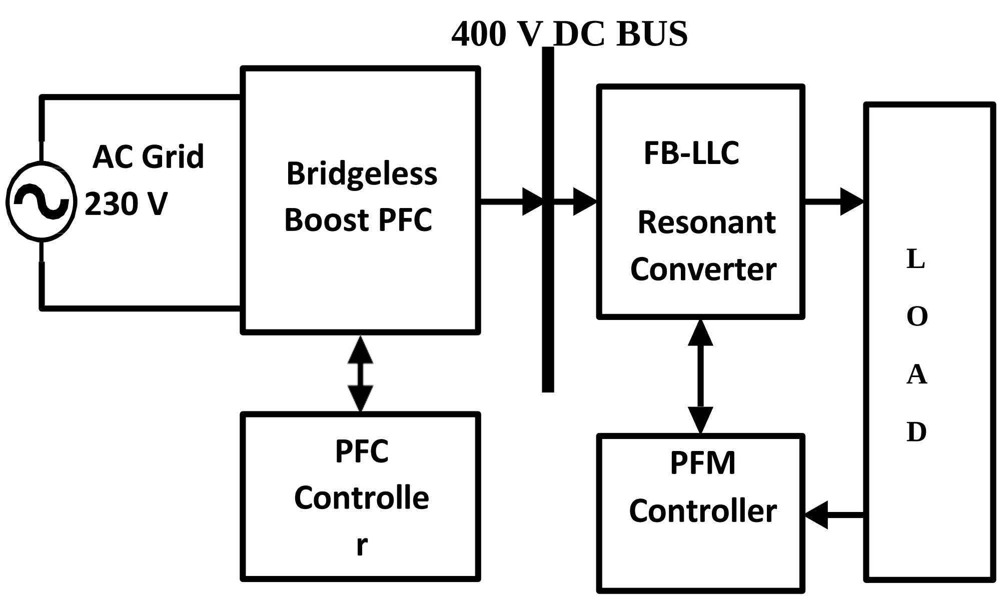


Fig. 8.1 Block Diagram of two stage converter

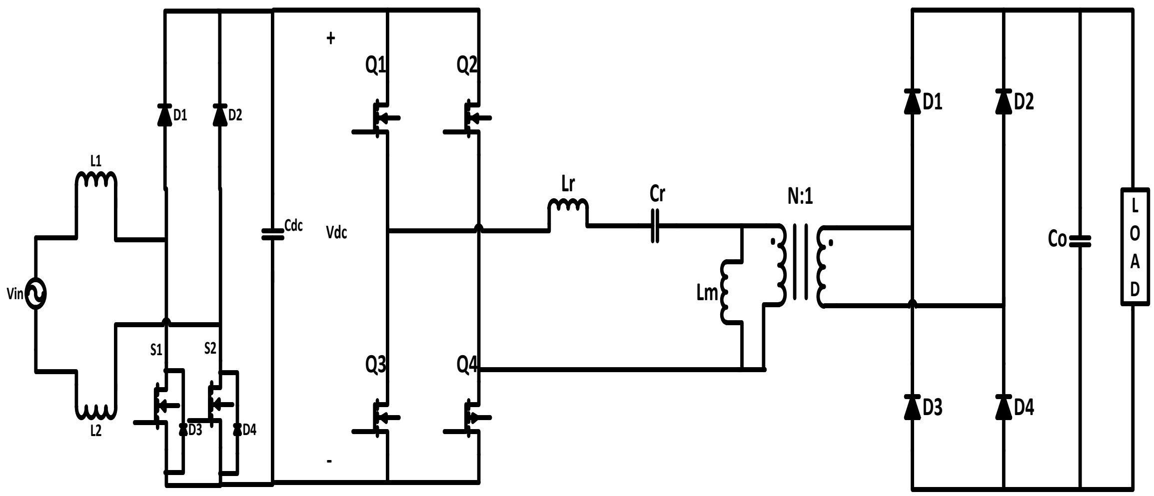


Fig. 8.2 Circuit Diagram of two stage converter

Bridgeless Boot PFC consists of two boosting source inductor L_1 & L_2 operating in one half cycle of AC input followed by a configuration consisting of two diodes D1, D2 and S1, S2 and then the output bus capacitor 'C_{dc}'. By using a optimum control scheme, power factor (p.f.) can be improved by reducing Total Harmonic Distortion (THD). It maintains a DC bus voltage of 400 V under different conditions. The output of the bridgeless boost PFC is given as an input supply to the FBLLC converter. The generated voltage is given to a circuit which is a full bridge inverter which generates a bipolar square waveform to feed & excite the LLC tank circuit. L_r, C_r starts to resonate at resonanting frequency f_o and acts as a series resonant circuit. Due to which, the LLC tank circuit generates a sinusoidal current which resonates at resonant frequency. The magnitude of this current is controlled using the turns ratio of the high frequency transformer. This resonating current is transferred to the secondary side of transformer which includes the full bridge diode rectifier for rectification purpose, followed by the output filter capacitance which gives DC at the output. This generated DC is then utilized for charging a lithium-ion battery. Fig.8.2 represents the circuit diagram of the proposed two stage converter.

The designing of Bridgeless Boost PFC and full bridge LLC resonant converter is analyzed as discussed in chapter 5 and chapter 6 respectively and specification of first stage is tabulated in Table 8.1 and specification of second stage is tabulated in Table 8.2.

Table. 8.1 Design specification for first stage Bridgeless boost PFC converter

2

Parameters	Value
L-N rms grid voltage (V_s), grid frequency (f_s)	230 V, 50 Hz
DC bus voltage (V_{dc})	400V
Power Rating (P_{ac})	1 kW
Output Current (I_o)	2.5 A
Switching Frequency (f_{sw})	100 kHz
DC Bus Capacitance(C_{bus})	1000 µF
Boost Inductance (L_s)	470 µH
Input Current THD	< 5%

Table. 8.2 Design specification for second stage FBLLC resonant converter

Parameters	Value
Bus voltage (V_{dc_min}-V_{dc_max}), Nominal bus voltage (V_{dc_nom})	380-420 V,400 V
Output voltage (V_{o_min}-V_{o_max}), Nominal output voltage (V_{o_nom})	42-52 V, 48 V
Quality factor (Q)	0.6
Transformer turns ratio (n)	25:3
Resonating Inductance (L_r)	31.4 µH
Resonating Capacitance (C_r)	80.6 nF
Magnetizing Inductance (L_m)	157 µH
Resonating Frequency (f_o)	100 kHz
Inductance ratio	5

8.2 SIMULATION RESULTS

8.2.1 Input Current (V_s) & Input Voltage (I_s)

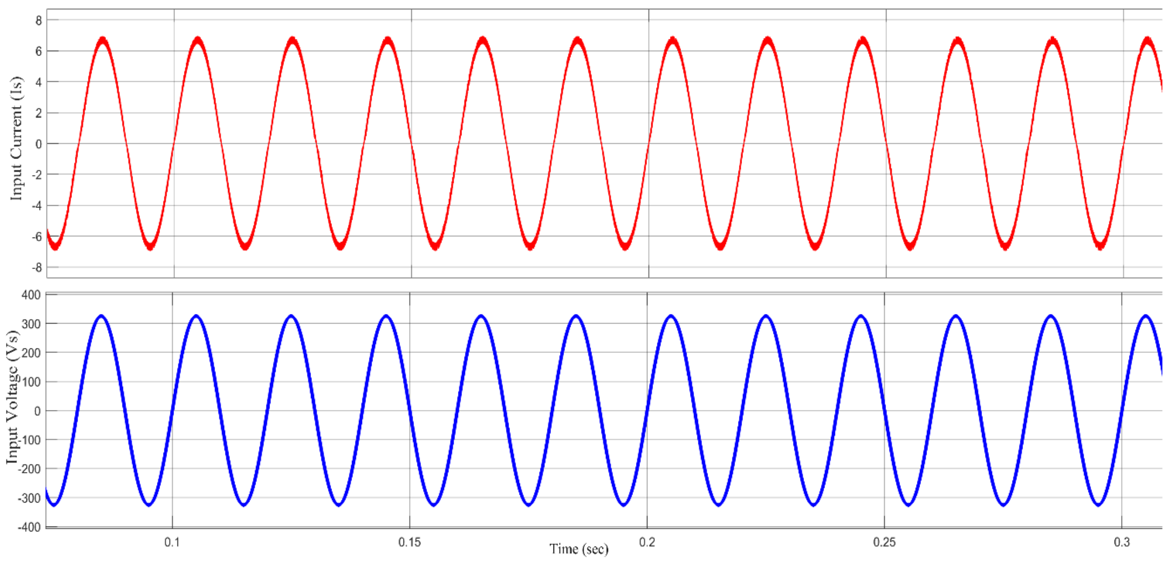


Fig 8.3 Input Current (I_s) & Input Voltage (V_s)

8.2.2 Input Current THD

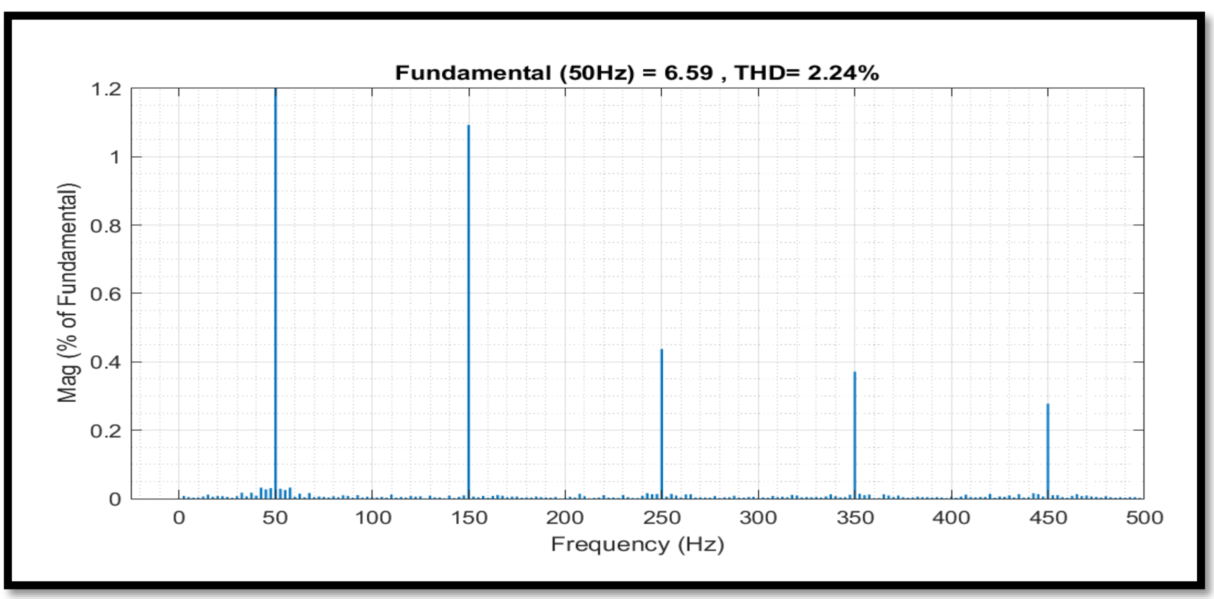


Fig 8.4 Input Current (I_s) THD

8.2.3 Gate Pulses (S1 & S2)

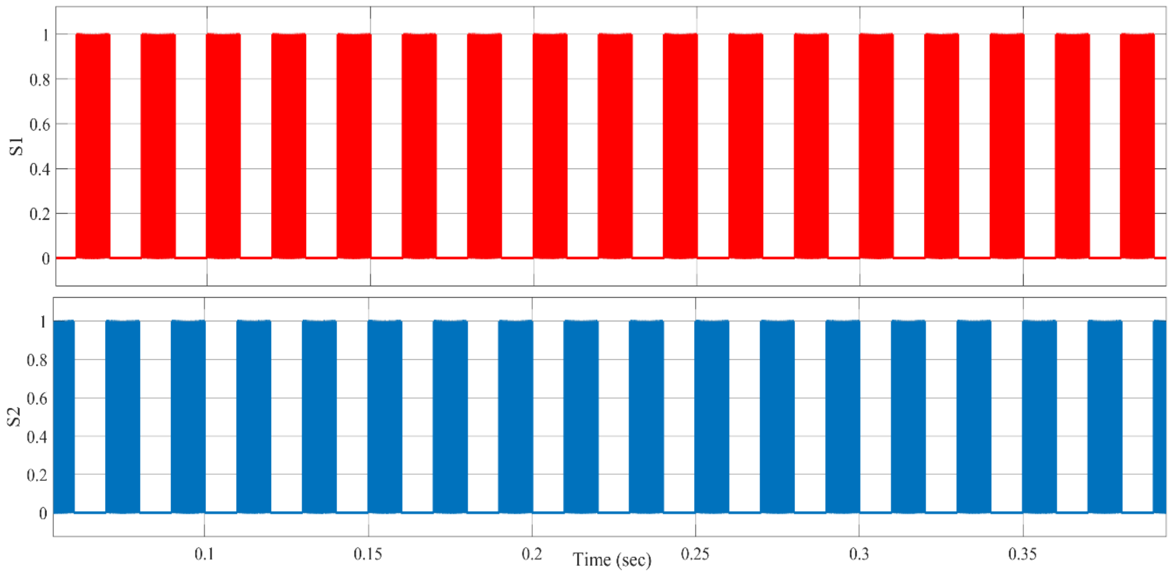


Fig 8.5 Gating Pulses of (S1 & S2)

8.2.4 Switching Pulse of S1

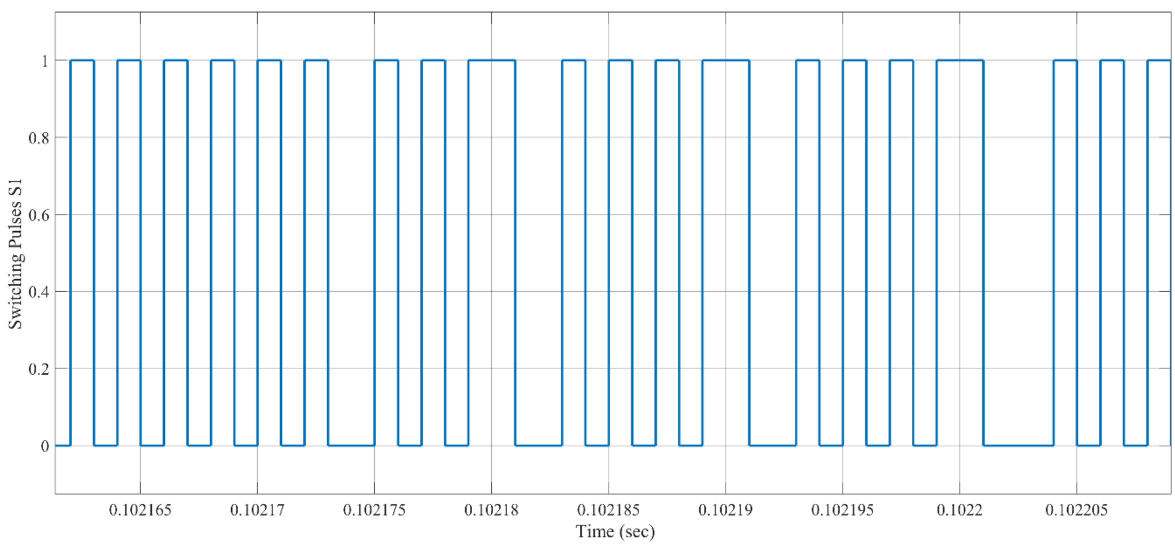


Fig 8.6 Switching Pulses of S1

8.2.5 Voltage Stress (V_{ds}) of S1 & S2

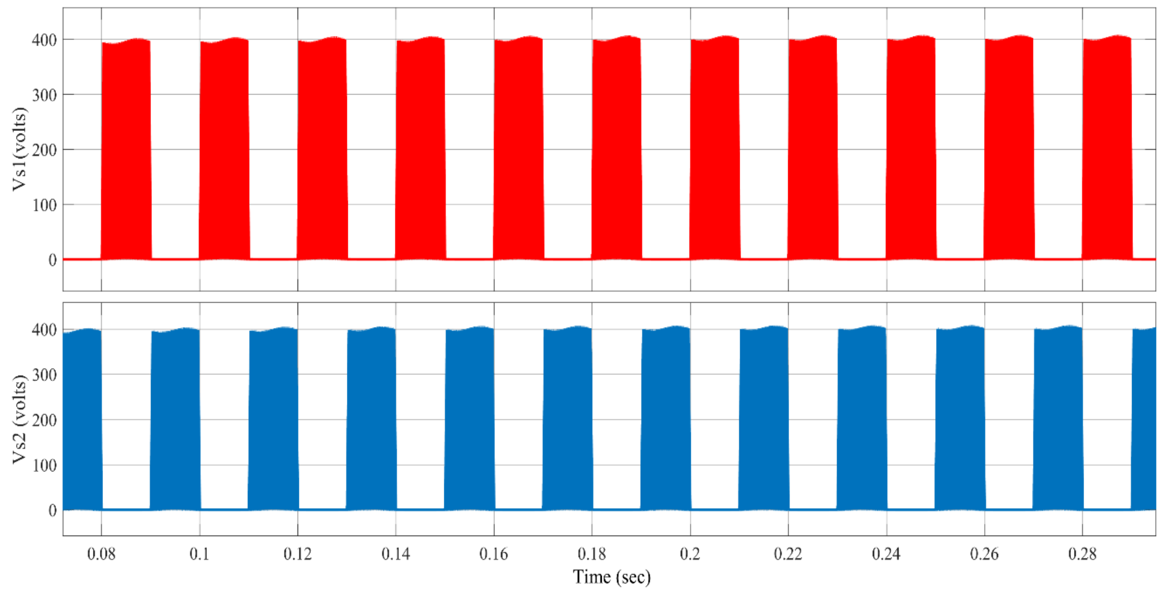


Fig 8.7 Voltage (V_{ds}) of S1 & S2

8.2.6 Switching Voltage (V_{ds}) of S1

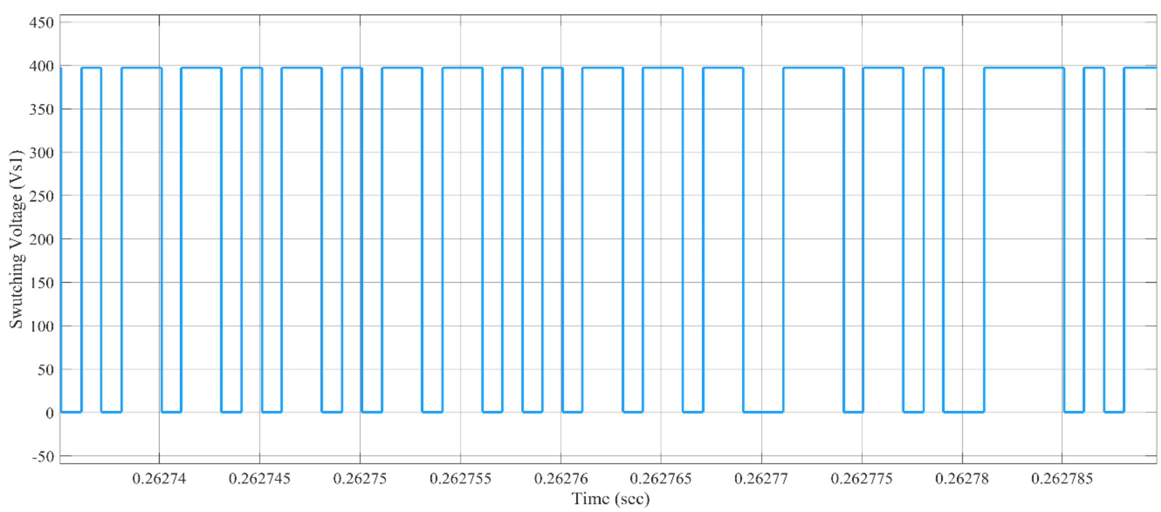


Fig 8.8 Switching Voltage (V_{ds}) of S1

8.2.7 Switch Current (I_{ds}) of S1 & S2

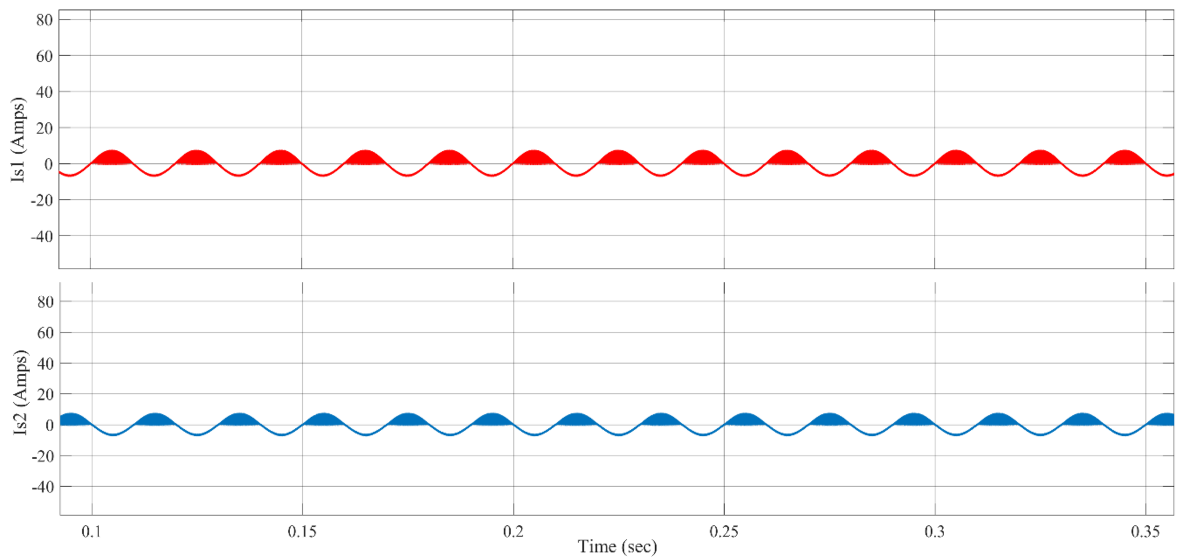


Fig 8.9 Switch Current (I_{ds}) of S1 & S2

8.2.8 DC Link Capacitor Voltage (V_{dc})

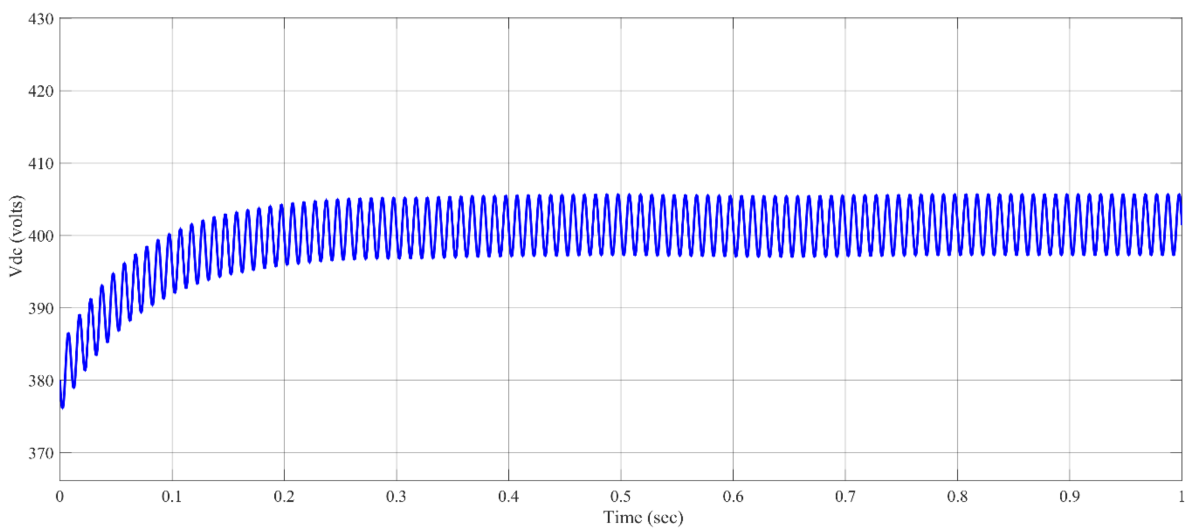


Fig 8.10 DC Bus Voltage (V_{dc})

8.2.9 Gate Pulses of Q1 Q2 Q3 Q4

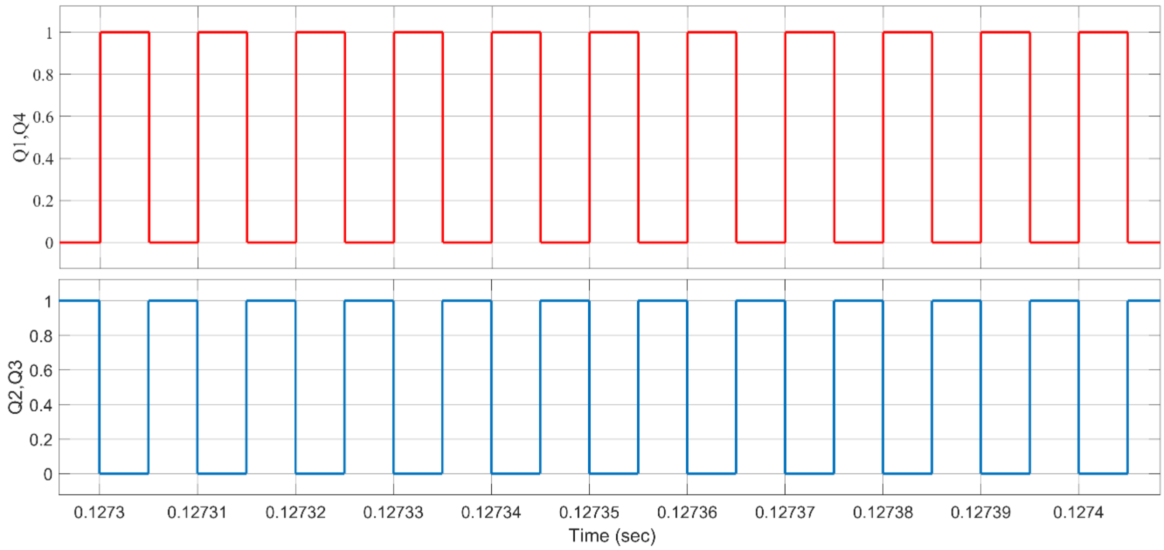


Fig 8.11 Gate Pulses of Q1 Q2 Q3 Q4

8.2.10 Voltage (V_{ds}) and Current (I_{ds}) of MosFet (Q1) - Evidence of ZVS

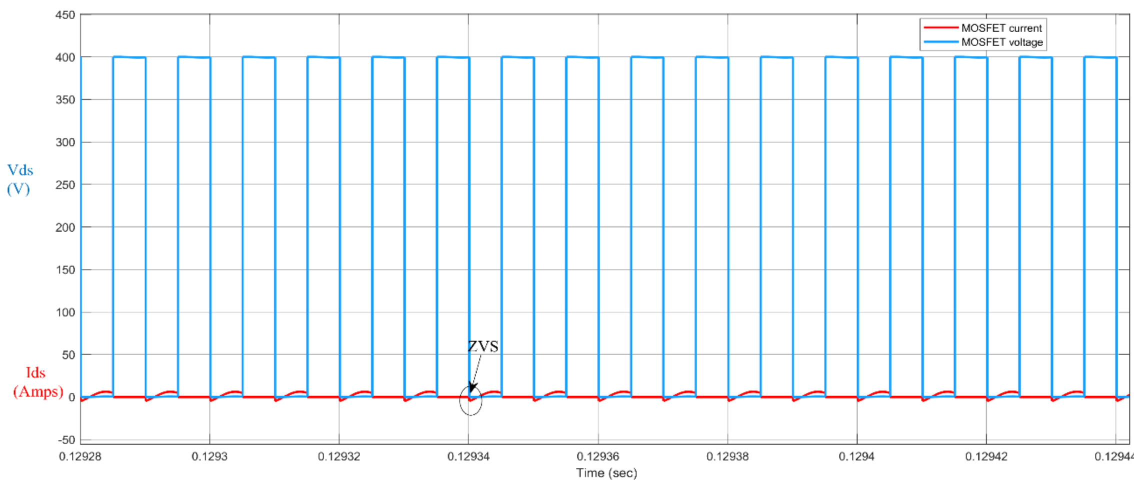


Fig 8.12 Voltage (V_{ds}) and Current (I_{ds}) of MosFet (Q1)

8.2.11 LLC Resonating Current (I_r)

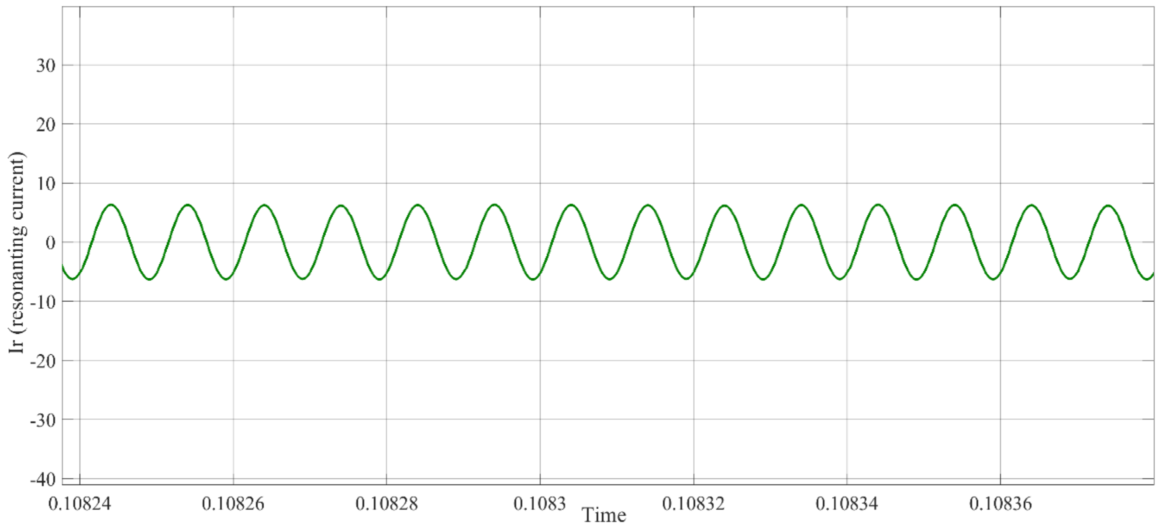


Fig 8.13 Resonating Current (I_r)

8.2.12 LLC Capacitor Voltage (V_{cr})

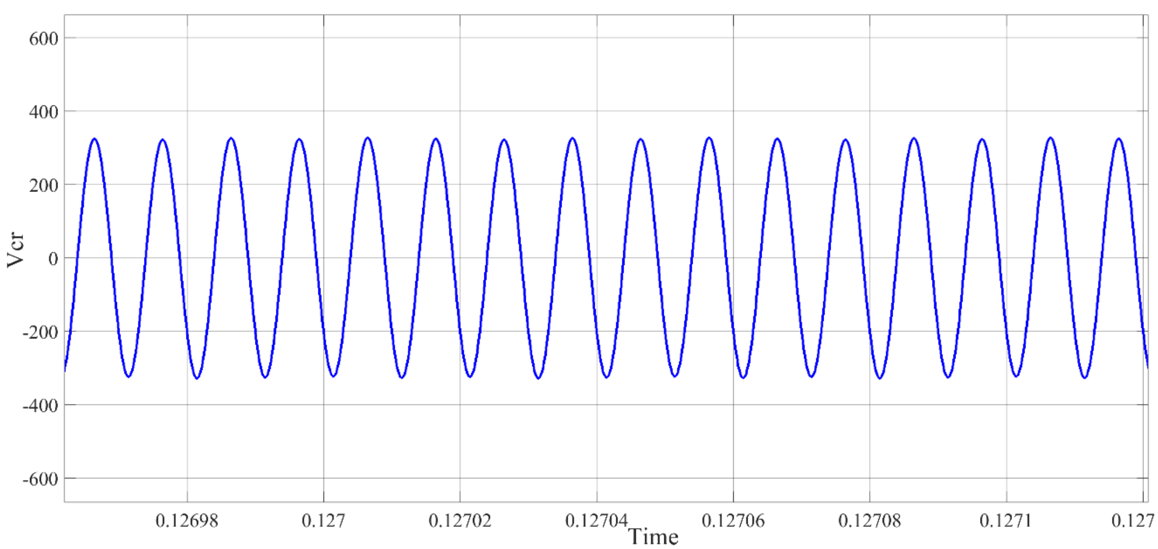


Fig 8.14 Capacitor Voltage (V_{cr})

8.2.13 LLC Magnetizing Current (I_m)

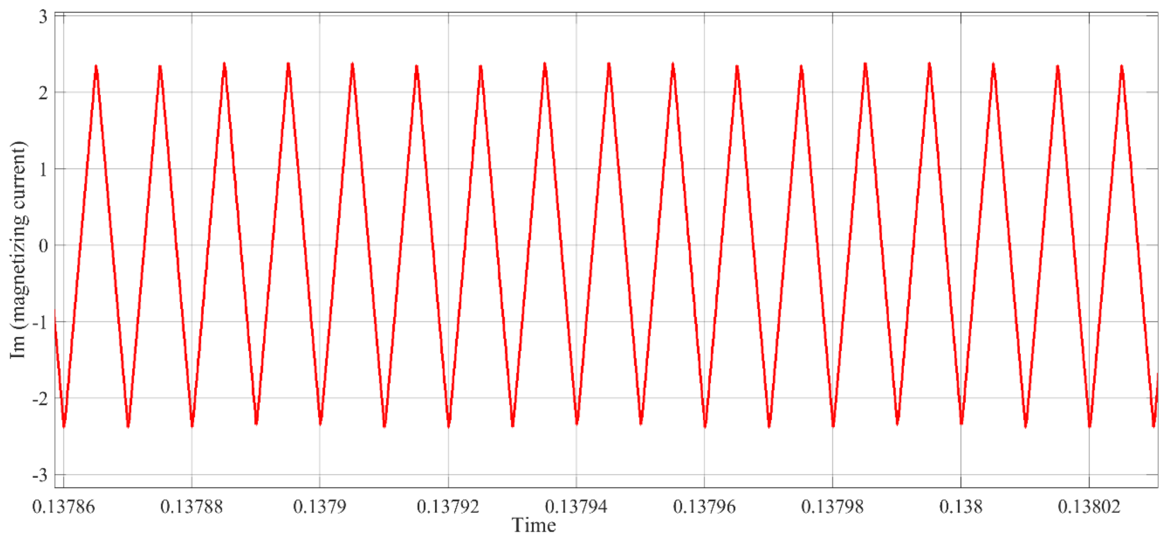


Fig 8.15 LLC Magnetizing Current (I_m)

8.2.14 LLC Transformer Primary and Secondary Voltage (V_p) & (V_s)

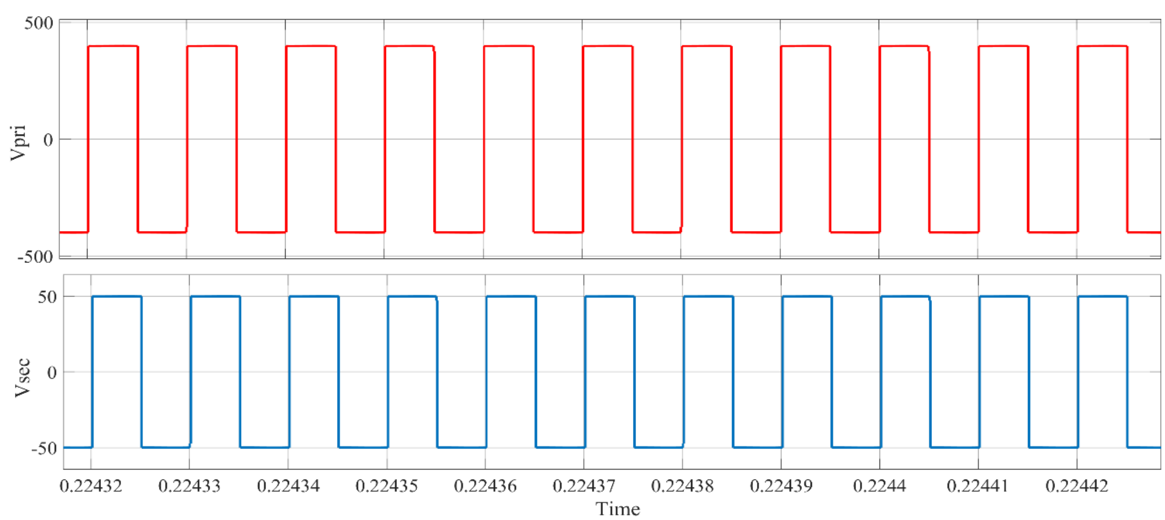


Fig 8.16 Primary and Secondary Voltage (V_p) & (V_s)

8.2.15 Secondary side diode Voltage & Current (V_d& I_d) - ZCS

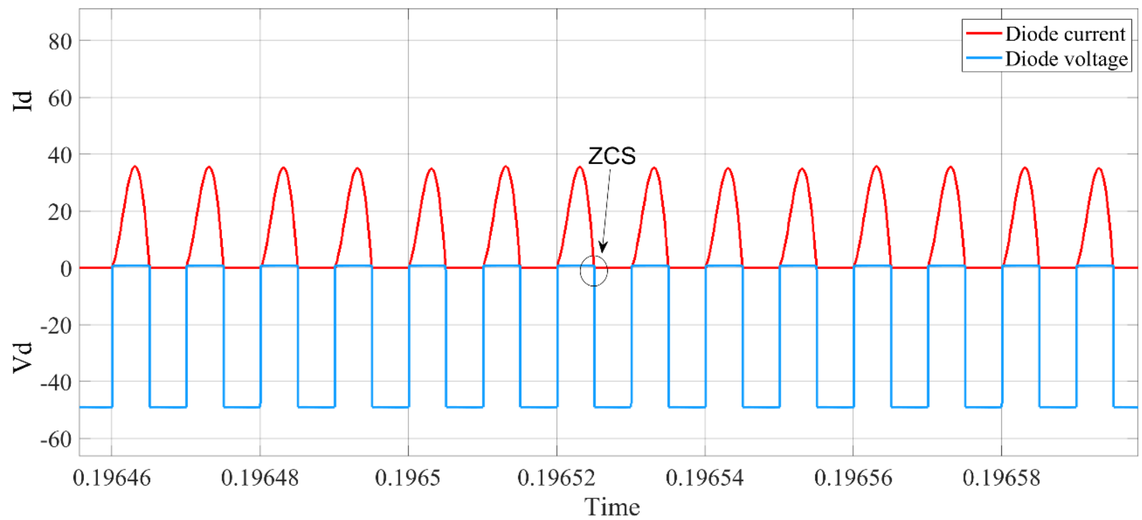


Fig 8.17 Secondary side diode Voltage & Current (V_d& I_d)

8.2.16 Output Voltage (V_0)

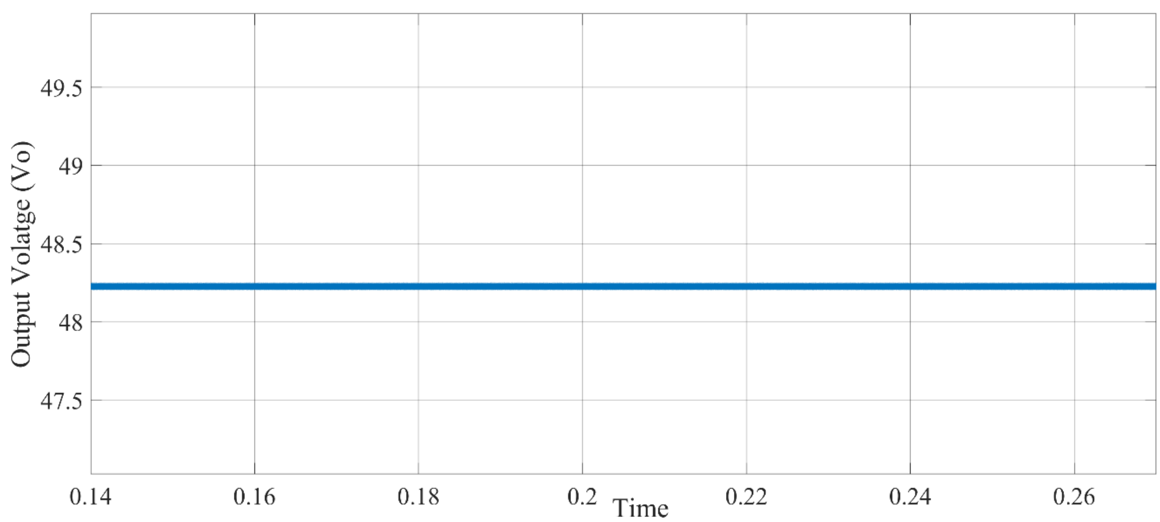


Fig 8.18 Output Voltage (V_0)

8.2.17 Output Voltage Ripple (ΔV_0)

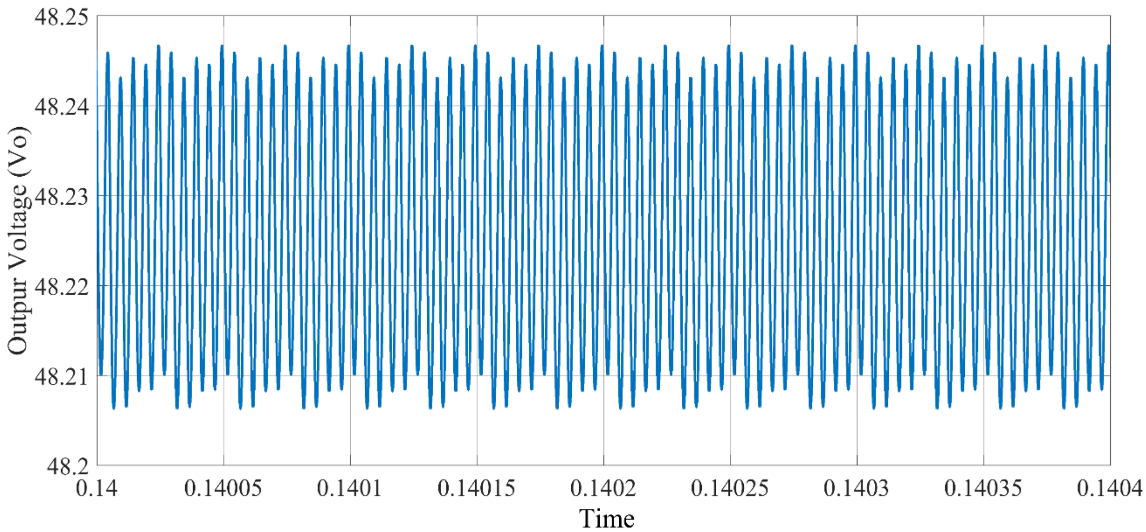


Fig 8.19 Output Voltage Ripple (ΔV_0)

CHAPTER 9

CONCLUSION AND FUTURE SCOPE

9.1 CONCLUSION

In this thesis, a two-stage cascaded battery charging system was proposed where there is use of Bridgeless Boost Power Factor Correction (BBPFC) followed by Full Bridge LLC resonant converter for charging 48 V battery system. The proposed battery charging topology was designed in view to attain better power quality, high efficiency, regulated output voltage and reliable battery charging operation.

The first stage of the system employed a Bridgeless Boost PFC converter to improve input power quality and establish a stable DC bus voltage. Unlike traditional boost PFC converters, which have diode bridges at their front ends, this type of bridgeless topology did not use any diode bridge rectifier, thus reducing conduction losses to improve the performance of the converter. The converter was designed to work in CCM mode at a frequency of 100 kHz. Thus, smoother waveforms and less ripple contents were obtained. Designing procedures based on a series of mathematical formulas were applied for designing the major parameters of the converter, including duty cycle calculation, inductance and capacitance selection, switches ratings, and diodes ratings according to the specified converter parameters. Based on the mathematical design of the converter, suitable component values were chosen for the stability of the converter and to reduce its electrical stresses. In order to achieve stable operation of the BBPFC converter, a two-loop scheme was considered, with an outer voltage loop and inner current loop. The outer loop controlled the DC bus voltage at 400 volts, whereas the inner loop controlled the input currents following input voltage waveform. As a consequence, improved power quality and power factor close to unity was achieved.

The second section in the designed charging system was the Full Bridge LLC resonant converter that was used for isolated DC-DC power conversion from input voltage to get regulated output voltage for charging 48V battery system. For controlling purposes, the LLC resonant converter uses the Pulse Frequency Modulation (PFM) method, where the variation of switching frequency occurs at resonant frequency. As a result, output voltage is regulated through achieving soft switching operation. Moreover, using PFM method made it possible to regulate output voltage regardless of converter's operation mode. LLC resonant converter operation helped achieve high efficiency.

The whole cascaded topology structure was implemented in MATLAB Simulink software in order to verify the functionality and performance of the implemented design methodology and control strategy. As can be seen from the simulation results, good performance of the converters was achieved when operating in closed loop configuration. Therefore, the design of bridgeless boost PFC stage regulated input DC bus voltage, while the Full Bridge LLC resonant converter generated regulated output voltage.

9.2 FUTURE SCOPE

Although the proposed converter demonstrated satisfactory performance through simulation analysis, several opportunities exist for further improvement and practical enhancement of the work.

Hardware Implementation of the Converter - The present work is primarily based on MATLAB Simulink modelling and simulation**.** As a future extension, the proposed cascaded converter may be implemented in hardware to experimentally validate converter performance under real operating conditions. Practical implementation would help analyze switching losses, thermal behavior, electromagnetic interference, and controller performance more accurately.

Advanced Digital Control Implementation - In the present work, conventional PI based dual loop control and Pulse Frequency Modulation techniques have been employed. In future, advanced control techniques such as fuzzy logic control, model predictive control (MPC), adaptive control, artificial intelligence based control, may be implemented to improve transient response, robustness and converter adaptability under varying operating conditons.

Interleaved or Totem pole PFC integration - In future, the Bridgeless Boost PFC converter may be replaced with more advanced front-end topologies such as Interleaved Bridgeless Boost PFC, Totem Pole PFC to achieve higher efficiency, reduced current ripple, higher power density.

Battery Management System (BMS) Integration - Future research may incorporate an intelligent Battery Management System (BMS) to monitor battery temperature, State of charge (SOC), State of Health (SOH), Charging protection.

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