Innovative Energy & Research
ISSN: 2576-1463

Case Study | Open Access

Design of Phase Shift DCDC Converter for EV

Shantanu Mundhe*

Department of Power Electronics from College of Engineering Pune, India

Abstract

The demand for robust and efficient power converters is driving the research of various DC-DC converter topologies and enhanced control strategies. In this paper, comparative analysis of full-bridge LLC (Inductor-Inductor-Capacitor) and phase-shifted full-bridge converters, center-tapped and bridge rectifiers, synchronous and passive rectifiers have been performed. Zero voltage switching (ZVS) resonant considerations for the Phase Shift Full Bridge (PSFB) have been studied. A 1kW phase-shifted full-bridge DC-DC ZVS converter has been designed and modeled. Aspects of the selection of components of an isolated DC-DC converter studied and discussed. The theoretical design of a converter is compared with and validated by simulation. Design aspects of shim inductor and effect of changing the position of shim inductor and clamping diodes is discussed. With correct position of shim inductor and clamping diodes primary current is reduced which result in reduced conduction losses of switches and increase in efficiency.

Keywords: Automotive; DC-DC converter; Electrical vehicle, Phase shifted full bridge converter (PSFB); Zero voltage switching (ZVS)

Introduction

Growing environmental impact is giving boost to the expansion of more ecofriendly technologies in all industrial area. The concern of automotive industry is greatly to reduce the exhaust gas emissions. Recently, Because of environment friendly, high-efficiency and low-noise electric vehicles (EV) are getting more attention. A typical EV power train consists of different power electronics converter subsystems. Most of the electric vehicles have the input voltage near to 350 V and some have input voltage greater than 350 V. Electric vehicles (EVs) consists a DC-DC converter to convert the high-voltage battery pack voltage to low output voltage (12 V) to power auxiliary loads. From survey input voltage range decided is 60 V to 400 V and output voltage fixed to 12 V [1]. Different converter topologies are being used in EV to convert from high voltage to low voltage. There are different DC-DC converter topologies available in the market used for battery charger application in electric vehicles. Mainly DC-DC converters classified as isolated and non-isolated converters. Most of the systems nowadays require isolation between the source and the load, which is essential for safety and noise issues. To avoid bulky magnetic components, the switching frequency of the converter is usually in the range of hundreds of kHz. Also, the transformer is used to scale the voltage up or down to achieve the optimal point of operation [2-5]. With converter topology choosing control strategy is also vital. If magnitudes of current and voltage are high during the switching transient hard switching is observed. During hard switching, instantaneous losses and stress on the semiconductor devices are high. Moreover, hard switching creates electromagnetic interference (EMI) problems. The alternative of the hard switching is called soft switching. The soft switching is observed if the current or voltage is zero or close to zero during the transient. This switching method is more challenging to implement because the switch timing must be controlled to match current and voltage waveforms. There are two soft switching methods zero current (ZCS) and zero voltage switching (ZVS). In both the cases switching losses are very low. Moreover, unlike ZCS, during turn on, the energy of the parallel capacitance is not dissipated in the device but returned to the circuit through resonant action. Since the capacitive turn on losses occurs at every cycle for ZCS circuits, they are proportional to the switching frequency. Therefore, for higher frequency (≥1MHz) applications, the ZVS topologies are preferred [6]. Mainly phase shifted full bridge (PSFB) and full bridge LLC topologies are widely used in EVs for battery charger application [7]. For these topologies ZVS is mandatory. These are generally high voltage to low voltage converters to be connected to high input voltage of 400 V or more in EV. EV has auxiliary loads like lighting loads, window cleaning, climate control, audio system etc. which consume power of 1 kW to 3.5 kW.

Considering Asian Automotive market resistive load of 1 kW is considered for designing the converter. Auxiliary loads in EV generally use 12 V power supply which is provided by a 12 V battery charged by the high voltage to low voltage isolated DC-DC converter [8]. PSFB with ZVS topology is more efficient than full bridge LLC topology for battery charger application for medium to high power application. Diode rectification selected over synchronous rectification to avoid complexity of gate driver circuit though by synchronous rectification power losses can be reduced [9]. Design aspects of PSFB are discussed in this paper. By changing position of shim inductor and clamping diodes reduces transformer primary current and reduces MOSFET conduction losses as well which will result in higher efficiency then conventional PSFB topology. PSFB with diode rectification is designed and modelled with correct position of shim inductor and its effects are discussed in this paper. Simulation results of proposed topology gives 87-94% efficiency when input voltage range is 60 V to 400 V and output power is 1 kW. PSFB with ZVS topology is suitable for load varying from 600 W to 3.3 kW in electric vehicle.

Converter Topology

Full bridge LLC converter

For medium to high voltage application phase shifted full bridge and full bridge LLC are commonly used topologies in electric vehicle battery charger application. Figure 1 shows FB LLC topology and Figure 2 shows PSFB topology. Both topologies consist of full bridge

***Corresponding author:** Shantanu Mundhe,Department of Power Electronics from College of Engineering Pune, India, E-mail: shantanu.mundhe@tatatechnologies.com

Received: 22-Dec-2023, Manuscript No: iep-23-123263, **Editor assigned:** 26-Dec-2023, PreQC No: iep-23-123263 (PQ), **Reviewed:** 09-Jan-2023, QC No: iep-23-123263, **Revised:** 13-Jan-2023, Manuscript No: iep-23-123263 (R), **Published:** 18-Jan-2024, DOI: 10.4172/2576-1463.1000372

Citation: Mundhe S (2024) Design of Phase Shift DCDC Converter for EV. Innov Ener Res, 13: 372.

Copyright: © 2024 Mundhe S. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

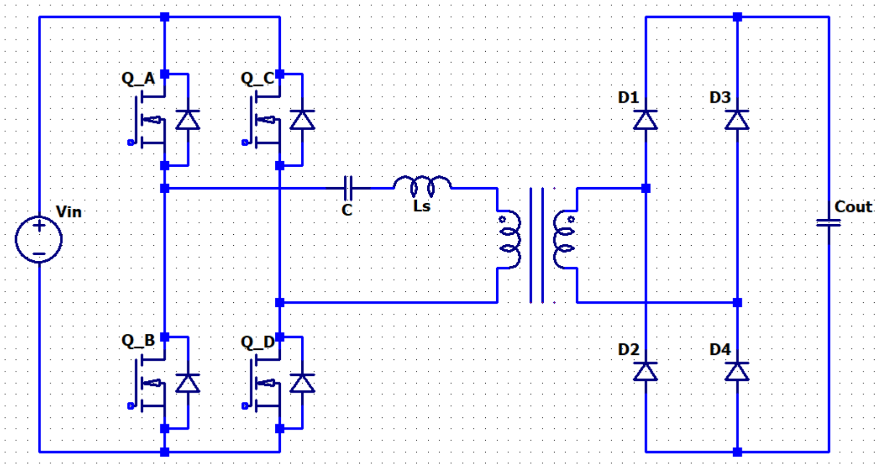

Figure 1: Full Bridge LLC converter.

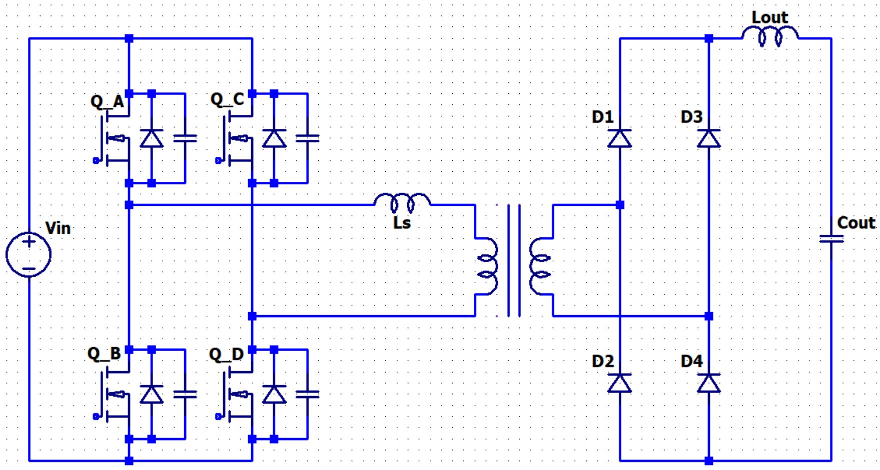

Figure 2: Phase Shifted Full Bridge converter.

that consists of four semiconductor switching devices. FB LLC topology has resonant tank that consists of a capacitor, series inductance and parallel inductance that is usually the magnetizing inductance of the transformer.

Both topologies have high-frequency transformer which can be standard or center-tap based rectification, full wave rectifier which can be full bridge rectifier or center-tap rectifier, output capacitor and output inductor. The output voltage of the FB LLC converter is controlled by changing the switching frequency, and the gain varies with frequency.

Phase shifted full bridge converter

In PSFB body diode and the parasitic capacitance of each semiconductor device as shown in Figure 2 and shim inductance is used for ZVS instead of LLC resonance tank. In some cases, leakage inductance of the transformer can be utilized instead of a separate inductor. Leakage inductance shown in Figure 2 is internally adjusted in transformer. In hard switched full bridge DC-DC converter transformer with zero leakage inductance is required.

FB LLC converter topology is the best choice for the point-of-load converters, where it would operate near the resonance frequency most of the time since FB-LLC demonstrates the highest efficiency and the lowest EMI when it is at the resonance frequency. Although FB-LLC has higher efficiency and lower EMI at the resonance point compared with the PSFB, it has variable frequency operation therefore it's difficult to synchronize with other converters and parallel current sharing.

Therefore, PSFB topology has been selected for battery charger application. ZVS is possible for all primary and even secondary side active and passive switches. However, difficult at light loads, and varies for leading and lagging legs in case of PSFB and for FB LLC ZVS difficult at higher frequencies. The control of the PSFB converter is different from FB-LLC converters. For PSFB, two sets of gate signals are used, so Qand Q are not in phase as in FB-LLC, but have cycle as, a specific phase shift. This phase shift is the main control parameter that changes the output voltage.

Rectifier Topology

For rectification both center-tapped and full-bridge rectifiers can be used. Both topologies are full-wave rectifiers. However, one uses center-tapped transformer and two semiconductor devices, whereas the, voltage applied to diodes will be two times higher, compared to the bridge rectifier. Also, transformer utilization factor (TUF) is higher for the bridge rectifier.

Diode rectification

The diode rectifier the most common and simple rectification technique used in medium and high-power applications as shown in

Figure 3. The main advantages of using diode rectifier are robustness and simple implementation. However, the lower limit of voltage drop across a diode is 0.3V, and that affects the efficiency of the system.

Synchronous rectification: In synchronous rectification MOSFETs are utilized instead of diodes as shown in Figure 4. The voltage drop across MOSFETs can be decreased by lowering VRdson (drain to source resistance during ON). So, for certain current levels, synchronous rectification can be more efficient. However, there is an addition of two gate drive circuits and more complex control. Therefor full wave diode rectification is chosen for easy control.

Design of PSFB Converter

A phase-shift full bridge converter with diode rectification has specifications given in Table 1. It is designed and simulated in MATLAB/Simulink software. PSFB with conventional position of shim inductor is as shown in Figure 2 where shim inductor is connected to transformer lead leg. PSFB with preferred position of shim inductor and clamping diodes where shim inductor is connected to transformer lag leg is as shown in Figure 5.

Transformer turns ratio selected based on 70% duty.

$$N = \frac{Ns}{Np} = \frac{\text{VINmin} - 2\text{VRdson}}{\text{Vo} + \text{Vd}} \quad (1)$$

In the equation above, the V_{Rdson} is a voltage drop over the MOSFET

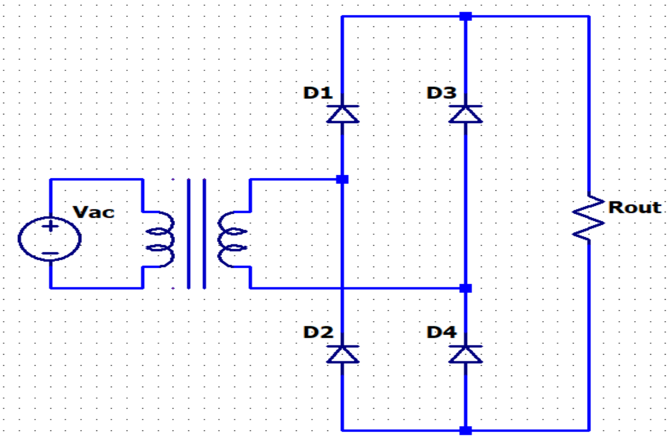

Figure 3: Diode rectification.

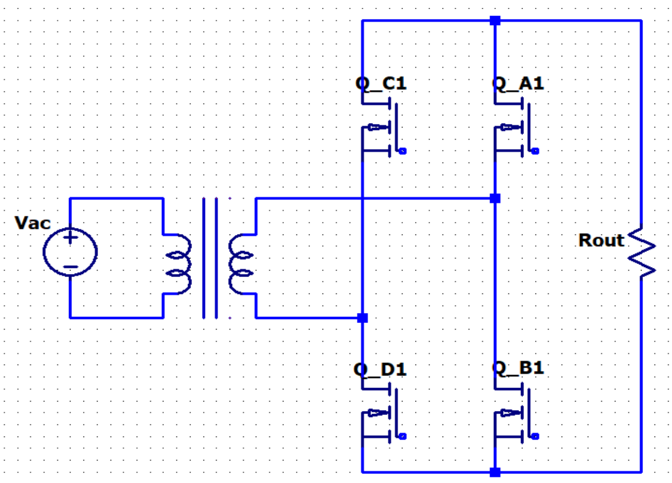

Figure 4: Synchronous rectification.

Table I: Design specifications of the PSFB converter.

Parameter	Units	Value
Rated Power	kW	1
Min. Input Voltage	V	60
Nominal Input Voltage	V	200
Max. Input Voltage	V	400
Output Voltage	V	12
Max. Output Voltage Ripple	V	1
Efficiency	%	94
Switching Frequency	kHz	200
Max. Duty Cycle D_{max}	-	0.7
Output Current (max)	A	83.3
Output Current Ripple	A	1.5

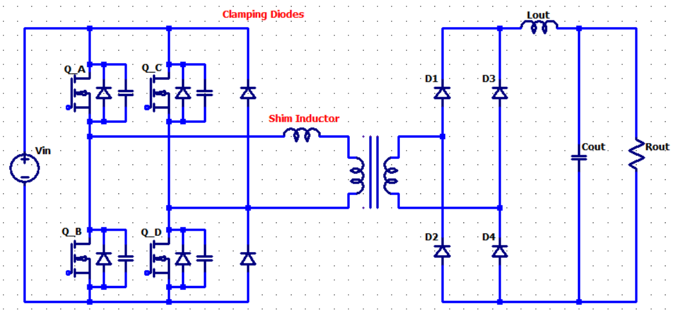

Figure 5: PSFB with transformer lag configuration.

and considered to be 0.3 V, and V_d is a voltage drop across the rectifier diode and considered to be 0.3 V.

$$D_{typ} = \frac{(V_{out} + V_{Rdson}) * N}{V_{in} - 2V_{Rdson}} \quad (2)$$

Output inductor ripple current is limited to 20% of the output current.

$$\Delta I_{Lout}(P_{out}) = \frac{P_{out}}{V_s} * 0.2 \quad (3)$$

Magnetizing inductance of primary transformer is calculated as

$$L_{mag}(P_{out}) = \frac{V_{in}(1 - D_{typ})}{\left(\frac{\Delta I_{Lout} * P_{out} * 0.5}{N}\right)} \quad (4)$$

The shim inductor value can be calculated to allow ZVS between 30% and 100% load as

$$Ls = \left[(2C_{oss_{eff}} + C_{xformer} + 2C_{ext})\frac{(V_{in_{max}})^2}{\left(I_{pp}(1000W) - \frac{\Delta I_{Lout}(1000W)}{N}\right)^2}\right] \quad (5)$$

Where, I_{pp} is the peak value of the primary current that can be calculated from circuit parameters assuming the efficiency of 94%. Inductor Lo is designed for 20% output inductor current ripple. The output inductor is calculated as

$$L_{out}(1000W) = \frac{V_{Lout\_max}\, t_{on}}{\Delta I_{Lout}(P_{out})} \quad (6)$$

Based on the values of average output capacitance of selected MOSFETs and the sum of shim inductance and transformer leakage inductance, the resonant tank frequency can be calculated as

$$Ls = \left[\frac{1}{2\pi\sqrt{(L_s + L_{xformer})(2C_{oss_{eff}} + C_{xformer} + 2C_{ext})}}\right] \quad (7)$$

The dead time between complementary MOSFETs of the same leg, when both are turned off, is calculated based on the empirical data as

$$t_{tr} = \frac{1}{4f_r} \quad (8)$$

Conduction Loss in single MOSFET:

$$P_{conduction\_Q\_A} = \left(\frac{I_{prms}(P_{out})}{2}\right) Rdson_{Q\_A} = 18.073\ W \quad (9)$$

Switching Loss in single MOSFET

$$t_{on}(P_{out}) = Crss * Rg_{totalon}\left(\frac{V_{ds}(P_{out}) - V_{pl}}{V_g - V_{pl}}\right) + Ciss * Rg_{totalon} * \ln\left(\frac{V_g - V_{th}}{V_g - V_{pl}}\right) \quad (10)$$

$P_{switching\_Q\_A\_off\,(1000W)} = 0\ W$

To achieve ZVS the energy stored in parasitic capacitances should be less than energy stored in combined inductances of magnetizing inductance of transformer, leakage inductance and external inductances called shim inductance. Table 2 while transitioning from one leg to another voltage across drain to source of MOSFET becomes zero when output power will be greater than 300 W. Therefore, switching losses will be zero when load will be greater than 300W as there will sufficient inductive energy to discharge parasitic capacitive energy while transitioning from one switch to another of same leg. To give extra window to dissipate capacitive energy transition time or dead time is provided which is calculated as one fourth of resonance frequency as given in Equation (8).

Simulation Results

A PSFB with ZVS DC-DC converter operating at 200 kHz switching frequency has been simulated in PSIM environment. Gate pulses, full bridge output voltage and shim inductor voltage responses are as shown in figure. As shown in Figures 6-9 the duty cycle loss describes the reduced time for each half switching cycle to reverse current polarity in the primary side and commute the current between the secondary side rectifiers. It reduces the time available for power

Table 2: Comparison of ZVS and hard switching losses.

Parameter	Unit	ZVS switching	Hard Switching
Conduction Losses	Watts	18.073	18.073
Switching Losses	Watts	0	0.42

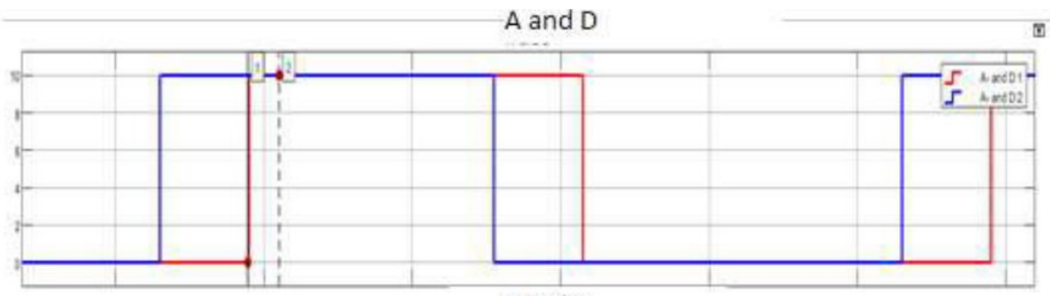

Figure 6: Gate Pulses.

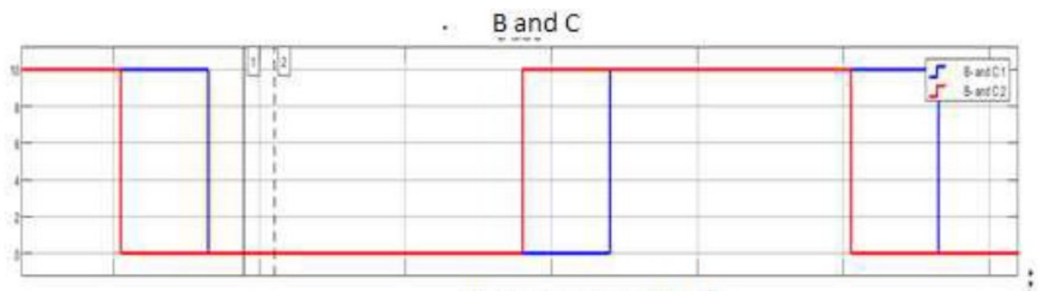

Figure 7: Full Bridge Output Voltage.

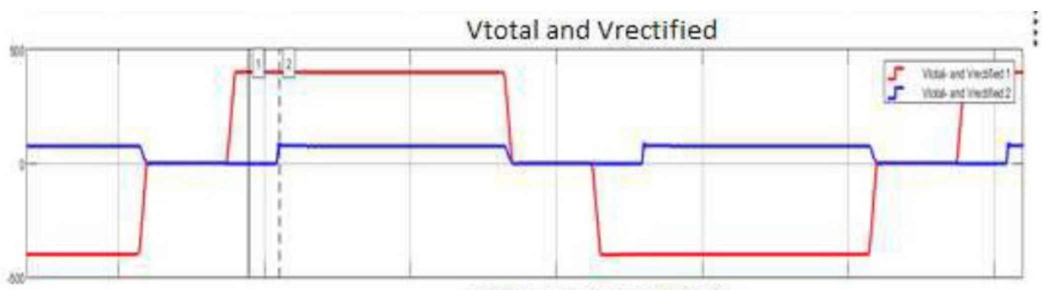

Figure 8: Shim Inductor Voltage Responses.

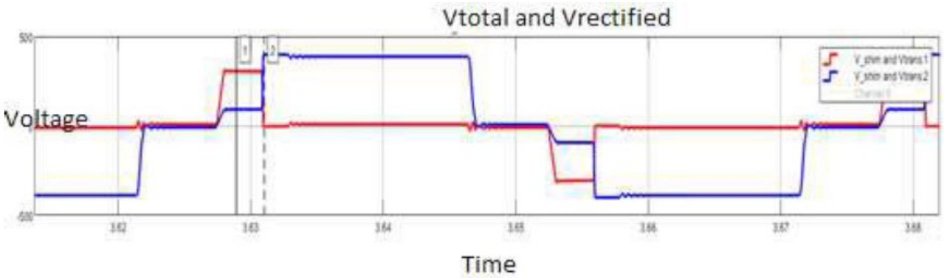

Figure 9: Duty Cycle Loss.

delivery, therefore, duty cycle loss must be considered while calculating the turn's ratio, and otherwise the converter might lose regulation at heavy load conditions especially at higher leakage inductance values.

As the current of resonant inductance is smaller in the converter in which the transformer is connected to lagging leg of full bridge, the conduction loss and duty cycle loss is reduced. Duty cycle loss can also be reduced by reducing dead time i.e., turn on and turn off delay set between the MOSFETS of same leg in phase shifted full bridge.

By reducing the inductance in the primary current path duty cycle loss can be reduced. This can be achieved by reducing the number of primary turns of the main transformer, but this will cause increase in peak voltage on secondary rectification MOSFETS and increase in magnetization current. For this reason, diode rectification is chosen.

The position of shim inductor and the transformer has effect on performance and behaviour of converter. As per simulation transformer lag has advantages over transformer lead type converter like

1) **Easy to achieve ZVS:** The transformer lead type has enough energy to charge/discharge output capacitors of the leading MOSFETs. This energy is provided only by the filter inductance. In transformer lag type converter, the energy is provided by the filter inductance and the resonant inductance. So, it is slightly easier to achieve ZVS for the transformer lag type converter than the transformer lead type converter.

2) **Current in clamping diode:** The clamping diodes only conduct once in a switching cycle in transformer lag type converter, so the current rating of the clamping diodes can be reduced.

3) The resonant inductance current is smaller in transformer lag type converter than transformer lead type converter, so the conduction loss of the resonant inductance and the primary side is reduced, leading to a higher efficiency.

4) **Duty cycle loss:** The duty cycle loss is reduced by the reduced resonant inductance current, which is potentially benefited for the efficiency increase.

The output current at 400 V input and at full load condition is 83.33 A. Output

Efficiency is calculated for different load conditions like 300 W, 600 W, 1kW. With load varying from 30% to 100% of full load the converter has attained efficiency 87% to 93%.

Conclusion

A design and simulation of 1 kW high voltage to low voltage isolated DC-DC converter has been done using MATLAB software. The converter has been clearly defined from the customer requirements. Two of the isolated DC-DC converter topologies with high power density and efficiency, namely, full bridge LLC and phase-shifted full-bridge have been studied. After the comparative analysis of the topologies, PSFB is selected due to its robustness, relatively straightforward control, and ability to work in ZVS over the wide load range. Diode rectification is chosen because of simple control. PSFB with ZVS has reduced overall losses. The position of shim inductor and the transformer has effect on performance and behaviour of converter. As per simulation transformer lag has more advantages over transformer lead type converter. The transformer lag is preferred because of less primary current, reduced conduction losses and increase in efficiency. The full power open loop simulation showed 87% to 93% efficiency.

References

1. Chakraborty, Sajib (2019) DC-DC Converter Topologies for Electric Vehicles, Plug-in Hybrid Electric Vehicles and Fast Charging Stations: State of the Art and Future Trends. Energies.
2. S. Inoue and H. Akagi (2007) A Bidirectional Isolated DC-DC Converter as a Core Circuit of the Next-Generation Medium-Voltage Power Conversion System. in IEEE Transactions on Power Electronics.
3. Tsukiyama, Daisuke (2011) A new 98% soft-switching full bridge DC-DC converter based on secondary-side LC resonant principle for PV generation systems. IEEE Ninth International Conference on Power Electronics and Drive Systems.
4. Texas Instruments, Phase-Shifted Full-Bridge, Zero-Voltage Transition Design Considerations-Application report.
5. Yang B, Duarte J L, Li W, Yin K, He X at al. (2010) Phase-shifted full bridge converter featuring over the full load range. In Proc. 36th Annual Conference of the IEEE Industrial Electronics Society.
6. S. Telrandhe, J. Sabnis and M. Rajne (2020) Design Considerations for an On-Board Charger Based on PSFB converter with ZVS. IEEE First International Conference on Smart Technologies for Power, Energy and Control (STPEC),
7. Texas Instruments UCC28950 600-W, Phase-Shifted, Full-Bridge Application Report.
8. Watanabe, Toshiyuki and Fujio Kurokawa (2015) Efficiency comparison between phase shift and LLC converters as power supply for information and communication equipment's. IEEE International Telecommunications Energy Conference (INTELEC).
9. Texas Instruments; Phase-Shifted Full-Bridge Controller with Synchronous Rectification (2012).