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Simulation and Analysis of Bridgeless Dual Boost PFC with LLC Resonant Converter for Battery Charging Applications

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Abstract : This paper proposes an analysis and simulation of high power factor, high efficiency two-stage AC - DC power converter for charging application. The first stage comprised of active power factor correction (PFC) circuit namely, bridgeless dual boost PFC to provide a DC supply from a single phase 50Hz, 220V AC. The latter stage is half bridge LLC resonant converter for dc/dc conversion. The conventional or bridge PFC boost rectifiers are nonlinear in nature and consequently generate harmonic currents in AC line power resulting in low power factor and high percentage total harmonic distortion (THD). The harmonic distortions have numerous harmful effects, including low percentage efficiency and interfere with the communication, control circuits nearby. To improve the quality of the line current and to get power factor closer to unity bridgeless dual boost PFC is analyzed in this paper and LLC resonant converter with improved efficiency. The circuit is simulated using PSIM. Simulation results shows that the first-stage bridgeless dual boost PFC achieves reduced ITHD of 1.2 % and a power factor of above 0.99 compared to bridge PFC and the second stage LLC converter operates with 94.23% peak efficiency.
Keywords: Bridgeless dual boost PFC, Half bridge LLC Resonant Converter, Current Total Harmonic Distortion (ITHD), Power Factor (PF).

Introduction

Power architecture of a battery charging application includes two stages[1]. First stage is the PFC stage with AC/DC converter as shown in Fig.1 and the second stage is a DC/ DC converter. Due to large filter capacitor at the output of conventional rectifier diode in AC/DC converter, the line input current is distorted and is not sinusoidal. During each cycle, the filter capacitor remains charged at or near the peak of AC voltage resulting in line input current with positive and negative pulses containing harmonic distortion[2]. The objective of PFC stage is to take care of total harmonic distortion (THD) of the line input current keeping input current and voltage in phase to have the power factor closer to unity and it regulates the desired voltage at DC-link capacitor. Typically passive power factor correction circuit and active power factor correction circuits are mainly used to shape the input current waveform. In passive approach, the passive elements are introduced to improve the quality of the supply line current. The level of voltage at the power supply increases means the size of PFC components also increases. Due to presence and interaction of inductors and capacitors the system

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resonance may occur at different frequencies. To control the amount of power drawn by a load and to obtain a power factor as close as to unity active PFC circuits are introduced next[3]. In this, to obtain a controllable output voltage a combination of the reactive elements and some active switches increase the effectiveness of the line current shaping. By this approach automatic correction of the AC input voltage can be obtained[4]. In the second stage zero voltage switching (ZVS) resonant converter topologies are preferred to enhance the efficiency of the charger. A topological analysis in[5] shows that among various isolated resonant converter topologies, LLC resonant converter outperforms for plug in electric vehicle battery charging application because it has desired features like ZVS operation, wide output voltage range, soft commutation of secondary rectifier diodes, short circuit protection capability, and good voltage regulation over light load.[6-7]

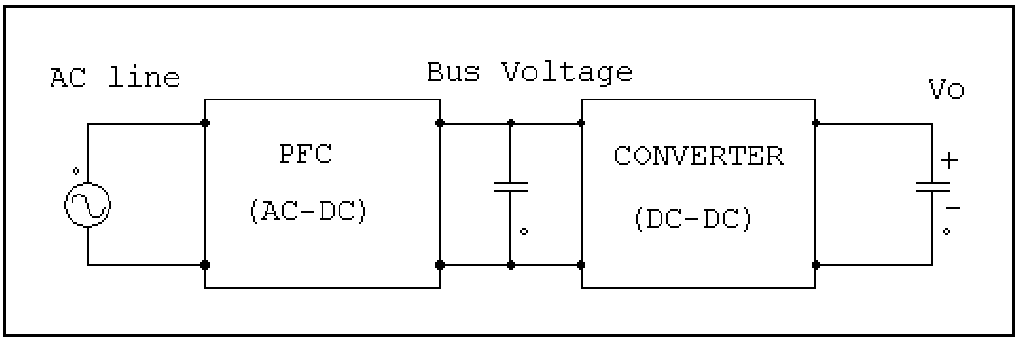


Fig.1 Power architecture of a battery charger

To improve the quality of the line input current at the first stage and to enhance the converter efficiency at the second stage this paper has developed a high power factor and high efficiency AC - DC power converter[8]. The first stage achieves high power factor purpose by power factor correction architecture. The latter stage achieves soft switching of power switches by the use of LLC resonant DC-DC converter.

Section II describes the operating principle of bridged PFC and bridgeless dual boost PFC rectifier configuration. In Section III, LLC converter gain and the design procedure is given. Simulation results are presented in section IV and conclusion is given in Section V.

Active PFC Topologies

In most of the applications active PFC controls the input current because of that current waveform is proportional to the nature of the supply voltage, a pure sinusoidal wave. Different topologies of active PFC are discussed in the literature[9-11].This paper discusses on the analysis and simulation of bridged PFC boost rectifier and Bridgeless dual boost PFC rectifier for shaping the supply current waveform and to improve the power factor.

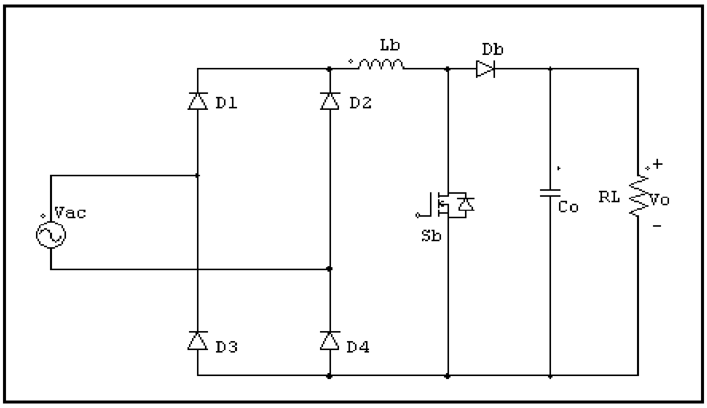


Fig.2 Conventional/Bridge PFC boost rectifier

A.Conventional/Bridge PFC boost rectifier

It is the most popular topology because of its simple power circuitry, control and single-switch construction[12-14]. It consists of a full-bridge diodes (D_{1-} D_4) used to rectify the AC signals followed by the boost converter section as shown in Fig.2. When, Switch S_b is in ON condition, inductor (L_b) energized by the DC source. Capacitor C_o maintains the output voltage by using the previously stored power. When, Switch S_b is in open condition, both the DC source and energy stored in the inductor will supply power to the load, hence boosting the output voltage. Desired value of output voltage higher than the input voltage can be obtained by calculating the duty ratio suitably. In this design, every moment (i.e switch ON and OFF) inductor current goes through three semiconductor devices, it creates degradation of efficiency. Main disadvantage of this topology is high input current ripple.

The design equations of the bridge PFC boost rectifier are as follows:

The duty ratio (D) of a boost converter is given by

$$\frac{Vo}{Vi} = \frac{1}{(1-D)} \qquad (1)$$

The inductor can be designed using equation (2)

$$L = \frac{R * D * (1-D)^2}{2f} \qquad (2)$$

Where f = switching frequency and R= Load resistance.

The value of capacitance is given by the equation (3)

$$c = \frac{Vo * D}{f * \Delta V * R} \qquad (3)$$

Where ΔV = Output voltage ripple

B. Bridgeless dual boost PFC rectifier

To reduce the high common-mode noise problem associated with the bridgeless network[15] that circuit is modified by adding two slow diodes (D_3 & D_4). To supply a LF path between the output ground and ac source additional inductor is added in the circuit. The modified design forms the two dc/dc dual boost circuit as shown in Fig.3.

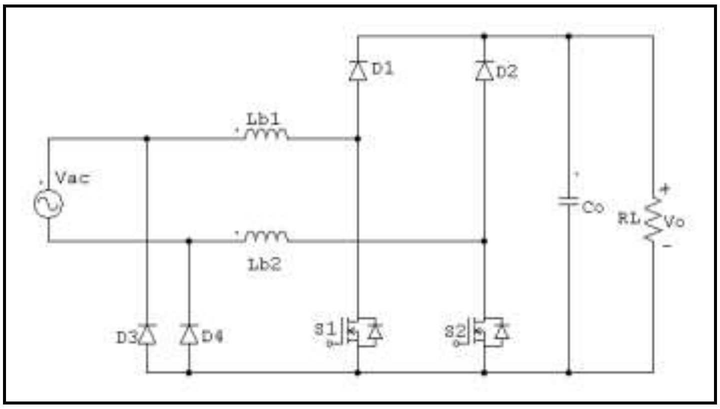


Fig.3 Bridgeless dual boost PFC rectifier

During positive and negative half cycle operation, the output ground is connected to the ac source through the slow diode D_3 and D_4. Inductors are expected as a common-mode filter to reduce the common-mode problem. Switches S_1 & S_2 are driven with the same PWM signal, which simplifies the control circuitry also. Positive half cycle operation is divided into two modes. In first mode, S_1 turns ON, inductor L_{b1} stores energy through the path V_{ac}-L_{b1}-S_1-D_4. In second mode, S_1 turns OFF, the stored energy in the inductor L_{b1} gets released and the current flows through diode D_1, load R_L, and returns back to the mains through diode D_4. Again negative half cycle operation is divided into two modes. In first mode, the switch S_2 turns ON, inductor L_{b2} stores energy through the path V_{ac}-L_{b2}-S_2-D_3. In second mode, switch S_2 is turns OFF the energy stored in the second inductor L_{b2} gets released and the current flows through diode D_2, load R_L, and returns to the mains through diode D_3. It is noted that the two inductors compared to a single inductor have better thermal performance.

Half Bridge LLC Resonant DC-DC Converter

LLC resonant converter is a popular topology because of its simple structure and desirable features. High power density, low electromagnetic interference (EMI) and Zero Current Switching (ZCS) of the output rectification diodes[16-17] are the important features of LLC. The size of their reactive components (L_r, C_r &L_m) can be reduced by high switching frequency operation. The two inductors in resonant tank can be integrated into transformer which decreases components count[18] and suitable for high power applications.

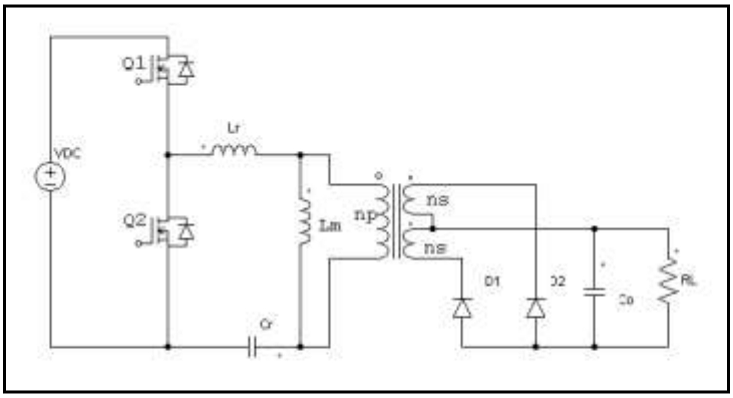


Fig.4 Half bridge LLC resonant DC-DC converter

Fig.4 shows the half bridge LLC resonant converter topology. It has two resonant frequencies, the first involves the combination of L_r and Cr and the second involves Lm. Two resonant frequencies of LLC are described in equation (4) & (5) and it is denoted as f_{r1}& f_{r2}. Equation (4) is always true regardless of load (R_L) but Equation (5) is true only at no load condition. In this topology second resonant frequency is always less than first resonant frequency. i.e. $f_{r2} < f_{r1}$. Separation between f_{r1}& f_{r2} depends upon the inductance ratio m = Lm / L_r and increases with increase in m. The switching frequency f_{sw} controls the power flow from input to the load which increases with the decrease in f_{sw} and vice versa. The range of f_{sw} is $f_{min} \le f_{sw} \le f_{max}$. f_{min} is the frequency at required maximum gain with $f_{min} > f_{r2}$ to maintain soft switching and f_{max} is the frequency at required minimum gain with $f_{max} \ge f_{r1}$.

$$f_{r1}=\frac{1}{2\pi\sqrt{L_r C_r}} \quad (4)$$

$$f_{r2}=\frac{1}{2\pi\sqrt{(L_r+L_m)C_r}} \quad (5)$$

The design procedure for the resonant tank elements using First Harmonic Approximation (FHA) is summarized in the following steps[18].

Step 1: Initially the terminal voltages V_{in_min}, V_{in_max}& V_{in_nom} must be taken from the LLC converter specifications mentioned in section IV.

Step 2: Transformer turns ratio (n) can be obtained from Equation (6)

$$\frac{Np}{Ns}=\frac{V_{in\_min}}{V_{out}} * M_{nom} \quad (6)$$

Here $M_{nom} = 1$

Step 3: M_{g_min} and M_{g_max} calculated using Equation (7) & (8)

$$M_{g\_max} = \frac{V_{in\_nom}}{V_{in\_min}} * M_{nom} \quad (7)$$

$$M_{g\_min} = \frac{V_{in\_nom}}{V_{in\_max}} * M_{nom} \quad (8)$$

Step 4: By selecting proper values for inductance (m) and Quality factor (Q_e) the corresponding attainable peak gain K_{max} value can be calculated from the gain graph.

Step 5: If it satisfies the desired condition that is $K_{max} > M_{g\_max}$ then the designed converter should operate in the inductive region.

Step 6: Finally the resonant tank values such as Cr, Lr, and L_m can be calculated based on Equation (9), (10) & (11)

$$Q_{max} = \frac{\sqrt{L_r / C_r}}{R_{ac\_min}} \quad (9)$$

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (10)$$

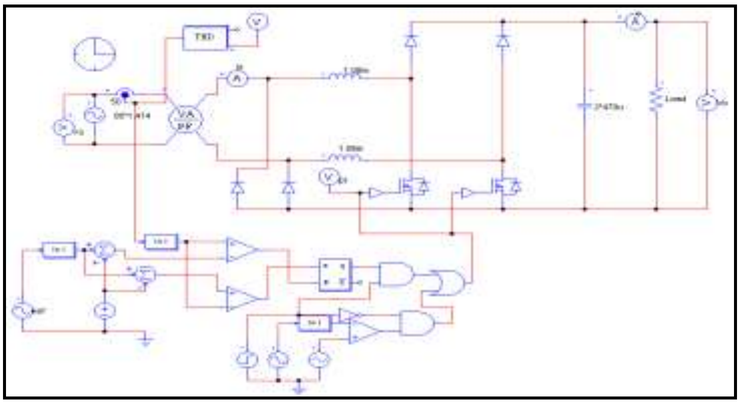
$$m = \frac{L_m}{L_r} \quad (11)$$

Simulation Results

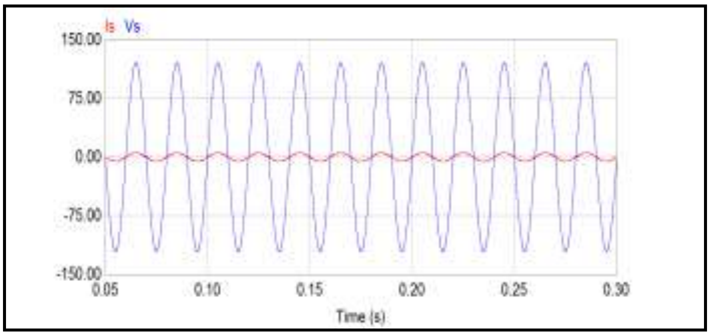
In this section, bridgeless dual boost PFC with LLC resonant converter has been simulated using PSIM. Simulation parameters of bridgeless dual boost PFC is shown in Table.1.Simulink model and corresponding supply voltage and supply current waveforms are shown in Fig. 5 (a) & (b). To improve the quality of the line current Continuous Conduction Mode (CCM) gating pulses are given to the PFC circuit. Simulation has been designed for $220V_{ac}$ and output voltage of PFC normally regulated to $390V_{dc}$.

Table. I Simulation parameters of PFC

Parameter	Designator	Value
Input voltage	V_{in}	85-264 V_{ac}
Output Voltage	V_o	390 V_{dc}
Output Current	I_o	0.88A
Boost Inductor	L_{b1}&L_{b2}	1.08mH
Capacitor	C_o	470µF



(a)



(b)

Fig. 5 (a) Bridgeless dual boost PFC (b) Supply voltage and supply current

Fig.6. shows the supply voltage and supply current waveform bridge PFC rectifier. Compared to bridge PFC, line current waveform is proportional to the nature of the supply voltage in the proposed bridgeless dual boost PFC as shown in Fig.5 (b)

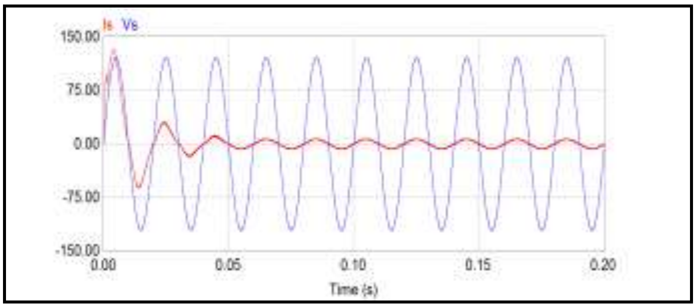
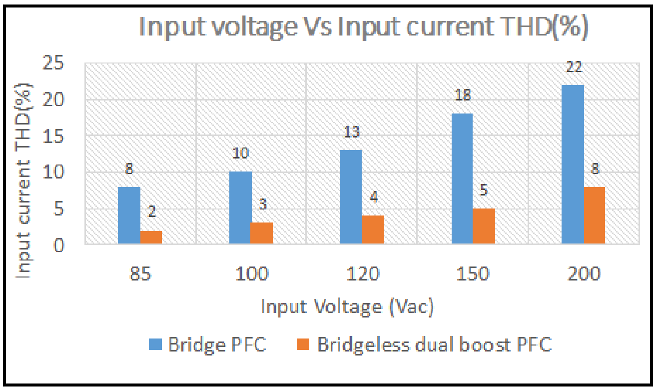
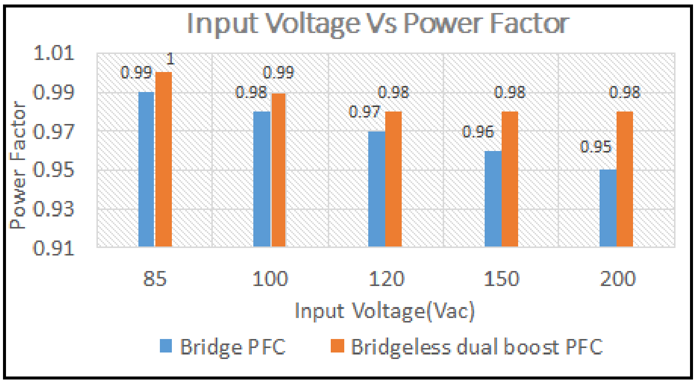


Fig. 6 Supply voltage and supply current of bridge PFC

The Input current THD (ITHD) and power factor (PF) with respect to supply voltage (V_{ac}) of bridge and bridgeless dual boost PFC are analyzed and depicted in Fig. 7(a) & (b). From this analysis it was observed that by varying the supply voltage from $85V_{ac}$ to $200V_{ac}$ the percentage of ITHD is smaller and power factor closer to unity in bridgeless dual boost PFC compared to bridge PFC.



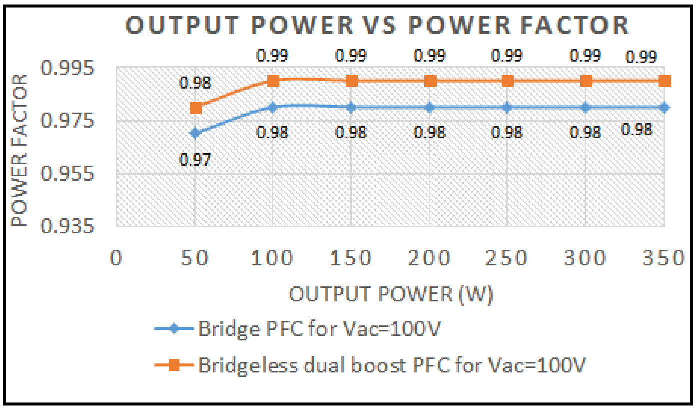
(a)



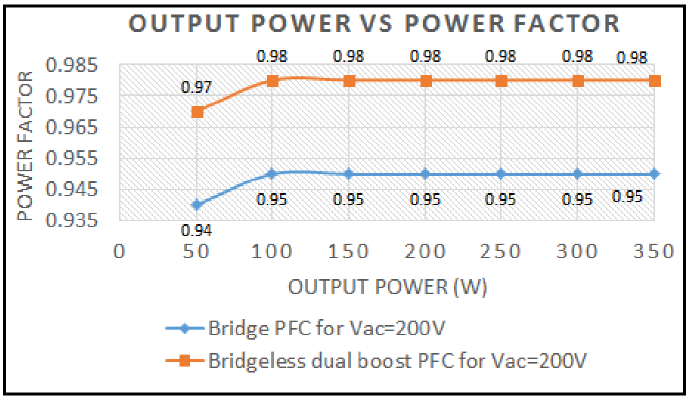
(b)

Fig.7 (a) Input Voltage (Vs) ITHD (%) (b) Input Voltage (Vs) PF

Similarly power factor (PF) with respect to output power of bridge and bridgeless dual boost PFC are analyzed for V_{ac}=100V & V_{ac}=200V and it is depicted in Fig. 8 (a) & (b). From this analysis it was observed that improved power factor of 0.99 was obtained in dual boost PFC for V_{ac}=100V



(a)



(b)

Fig. 8 (a) Output power (Vs) PF for bridge PFC (b) Output power (Vs) PF for bridgeless dual boost PFC

From the above analysis the quality of the line current and power factor improvement was obtained in bridgeless dual boost PFC. Similarly the percentage of ITHD was smaller in this case. Compared to bridge PFC, bridgeless dual boost PFC is selected as a best front end rectifier topology for AC-DC power converter. Simulation parameters of PFC stage already mentioned in Table I. Table II and III describes the LLC converter specification and design values.

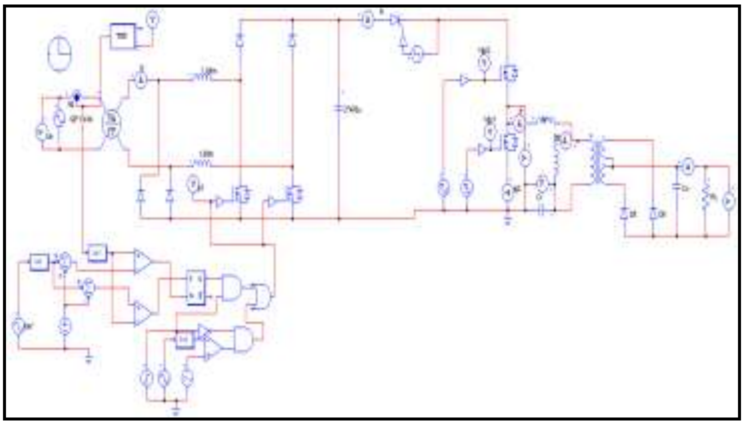
Table. II Half bridge LLC specification

Parameter	**Designator**	**Value**
Nominal input voltage	V_{dc}	$390V_{dc}$
Output current	I_{in}	5A
Output voltage	V_o	12V
Rated output power	P_o	60W

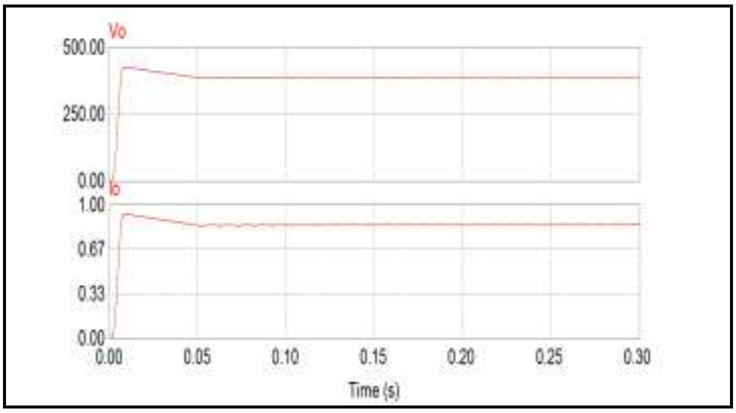
Table. II Half bridge LLC design values

Parameter	Designator	Value
Turns ratio	n	16.25
Min gain	M_{g_min}	1.0095
Max gain	M_{g_max}	1.2015
Quality factor	Q_e	0.45
Normalized inductance	L_n	3.5
Resonant frequency	f_o	94KHZ
Resonant inductor	L_r	481µH
Resonant capacitor	C_r	5.26nF
Magnetizing inductance	L_m	1924µH

Simulink diagram of front end bridgeless dual boost PFC with half bridge LLC resonant converter as shown in Fig.9(a). Fig.(b),(c),(d) shows the corresponding PFC output voltage, gating pulse pattern of Vgs_1 and Vgs_2 and output voltage of LLC. Input is from the single phase 50Hz, 220V AC supply. Output of PFC nearly achieves 390Vdc. Next, dc-dc section receives the PFC output. Resonant tank elements (L_r,C_r &L_m) process the signal in sinusoidal form. Finally the output stage of LLC delivers 12V, 5A and 60W output power.



(a)


Vo
500.00
250.00
0.00
Io
1.00
0.67
0.33
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0.10
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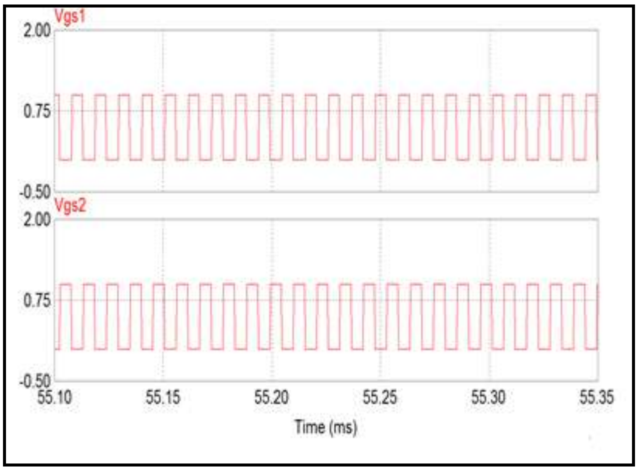
0.20
0.25
0.30
Time (s)

(b)


Vgs1
2.00
0.75
-0.50
Vgs2
2.00
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55.10
55.15
55.20
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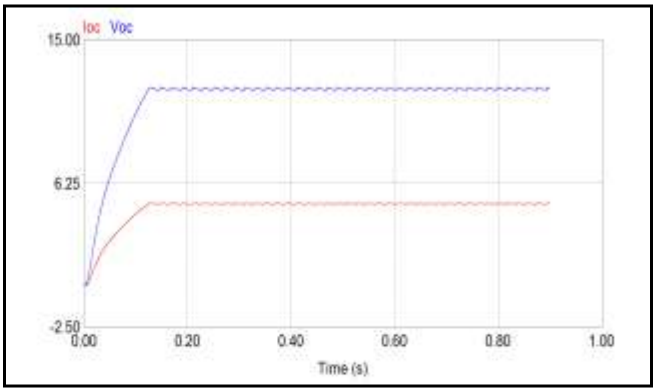
55.30
55.35
Time (ms)

(c)



(d)

Fig. 9 (a) Front end dual boost PFC with LLC (b) Output Voltage of PFC (c) Gating Pulses of Vgs1,Vgs2 (d) output voltage and current of LLC

Fig.10 shows the ripple measurement of LLC output voltage. Comparison between bridge PFC and bridgeless dual boost PFC with half bridge LLC resonant converter shown in Table IV. From the analysis it was observed that the proposed bridgeless dual boost PFC with half bridge LLC resonant converter achieves power factor higher than 0.99 and high peak efficiency 94.23% at full load (5A) compared to conventional one. Overall output ripple reduction of this power architecture is 190mV from 357mV.

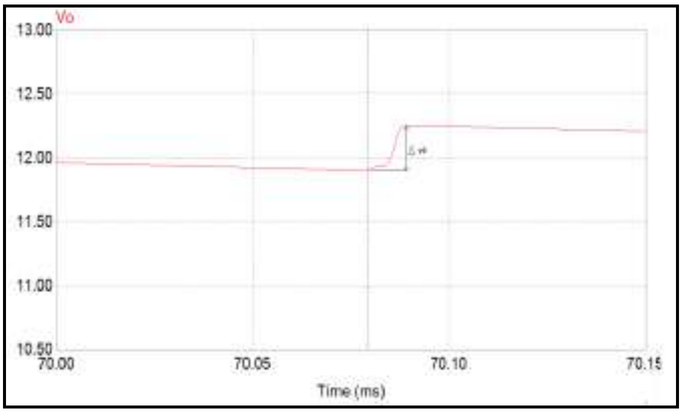


Fig.10 Output Ripple Voltage of LLC

Table. IV Comparative results

Topology	**PF**	**ITHD (%)**	**Output ripple voltage of LLC**	**Efficiency at full load (5A)**
Bridge PFC with LLC resonant converter	0.971	1.83	357mV	88.84%
Bridgeless dual boost PFC with LLC resonant converter	0.999	1.2	190mV	94.23%

Conclusion

This paper proposes high efficiency, high power factor AC-DC power converter for battery charging application. The first stage AC/DC conversion achieved by bridgeless dual boost PFC rectifier and the second stage DC/DC conversion achieved by half bridge LLC resonant converter. The proposed topology achieves high power factor of above 0.99 and reduced ITHD of 1.2% compared to the conventional bridge PFC topology. Hence, the bridgeless PFC with LLC is a promising candidature for battery charging applications.

References

1. Deng J, Li S, Hu S, Mi C C, and Ma R. Design Methodology of LLC Resonant Converters for Electric Vehicle Battery Chargers. Vehicular Technology, IEEE Transactions., May 2014, 63; 1581-1592.
2. Marian K, Kazimierczuk. Pulse-width Modulated DC-DC Power Converters. Ohio, USA: John Wiley & Sons Ltd., 2008, 129-134.
3. Jovanovic M M, Jang. State-of the-Art, Single-Phase, Active Power-Factor-Correction Techniques for High-Power Applications-An Overview. IEEE Trans. On Ind. Electron ., 2005, 52; 701-708.
4. Maswood A. I, LiuF. A unity power factor front end rectifier with hysteresis current control. IEEE transactions on Energy Conversion., 2011, 21; 153-160.
5. Wang H, Khaligh A. Comprehensive Topological Analyses of Isolated Resonant Converters in PEV Battery Charging Applications. Transportation Electrification Conference and Expo (ITEC); 16-19 june 2013, 1-7.
6. Bai H, Mi C. Comparison and evaluation of different DC/DC topologies for plug–in hybrid electric vehicle chargers. Int. J. Power Electron., Feb 2012, 4; 119–133.
7. Bai H, Zhang Y, Semanson C, Luo C, Mi C C. Modeling, design and optimization of a battery charger for plug-in hybrid electric vehicles. IET Elect. Syst. Transp., May 2012, 1; 3–10.
8. Huang W C. Analysis and Implementation of a Half-Bridge LLC Resonant Converter with Front-End Power Factor Correction. M.S. thesis, Dept. Electric. Eng., Tatung Univ., Taipei, Taiwan, 2009.
9. Yang Xi-jun, Wang Han. Theoretic Analysis and Experimental Study of a Novel Bridgeless Partial Active PFC. IEEE Electrical Machines and Systems Conf., Oct 2008, 1179-1184.
10. Sahid M R, Yatim A H M. An isolated bridgeless AC-DC converter with high power factor. IEEE International Conference on Power and Energy, Kuala Lumpur, Malaysia.,Nov 2010, 791-796.
11. Tollik D, Pietkiewicz A. Comparative analysis of 1-phase active power factor correction topologies. Proc. Int. Telecommunication Energy Conf., Oct. 1992, 517–523.
12. Enjeti P N, Martinez R. A high performance single phase AC to DC rectifier with input power factor correction. in Proc. IEEE Applied Power Electronics Conf., Mar 1993, 190–195.
13. Crbone, Scappatura A. A high efficiency power factor corrector for single phase bridge diode rectifier .IEEE Conf. ESC., June 2004.
14. Wang C M. A novel zero-voltage switching PWM boost rectifier with high power factor and low conduction losses. International Telecommunication Energy Conf. (INTELEC) Proc., Oct 2003,224-229.
15. Choi W Y, Kwon J M. Bridgeless dual-boost rectifier with reduced diode reverse-recovery problems for power-factor correction. IET Power Electron., 2008, 1; 194-202.
16. De Simone, Adragna C, Spini C, Gattavari G. Design-oriented steady state analysis of LLC resonant converters based on FHA. in Proc. Int. SPEEDAM., 2006, 200–207.
17. Beiranvand R, Rashidian B, Zolghadri M R, and Alavi S M H. A design procedure for optimizing the LLC resonant converter as a wide output range voltage source. Power Electronics, IEEE Transactions., Aug 2012, 27; 3749–3763.
18. Iqbal S, and Shahzad M. I. LLC resonant DC–DC converter with series connected primary windings of transformer. IEEJ Trans Elec Electron Eng., Dec 2014, 10; 229–236.

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