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Investigation and Comparison of Performance Parameters Between Bridged and Bridgeless Interleaved Boost Converter

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Abstract: Switched mode power supplies have high efficiency but low power factor. They are used to power the DC loads. Efforts are taken to improve the power factor of these supplies using power factor correction circuitry. Just like the conventional Interleaved Boost Converter topology, the Bridgeless Interleaved Boost Converter (IBC) topology is used for active Power Factor Correction (PFC). IBC consists of a number of boost converters operating in parallel with the only difference being the elimination of the input diode bridge rectifier stage. This paper deals with the investigation and comparative study of bridged and bridgeless interleaved boost PFC converter topology along with the loss analysis and efficiency evaluation. Simulation of the proposed circuits is executed in MATLAB/Simulink and the results verify that the efficiency and the power factor of bridgeless converter is slightly higher than that of conventional IBC PFC Converter.

Key words: Bridgeless · Efficiency · MATLAB · Power factor · THD

INTRODUCTION

An AC-DC converter is used to convert an AC source of fixed magnitude to a DC source of variable magnitude. The commonly used method employed for this purpose is by varying the duty ratio of the switching element. An AC-DC conventional boost rectifier has an output DC voltage whose magnitude is greater than the input voltage. These converters are commonly employed for shaping the input current waveform, which in turn improves the supply power factor. The supply from the mains consists of harmonics, which distorts the waveform. Hence, by employing an AC-DC converter, this waveform can be shaped. The benefits of improved power factor are as follows:

- Reduced electricity bills
- Improved load carrying capability of the system
- Reduced power system losses
- Reduced THD of the supply current [1,2].

An interleaved boost converter is a parallel connection of two or more conventional boost converters. The output voltage of the boost converter is greater than the input voltage. This is done by decreasing the input current. A bridged interleaved boost converter has a bridge rectifier which converts the supply AC voltage to a DC voltage. A bridgeless interleaved boost converter eliminates the bridge rectifier circuit. It has better performance characteristics like reduced Total Harmonic Distortion (THD), improved power factor and better efficiency [3,4].

In this paper, a detailed analysis and comparison is done between the bridged and the bridgeless interleaved boost converter. The various performance parameters like THD, power factor, RMS value of output voltage and the efficiency of both the converters are analysed. The output voltage ripple, current ripple are obtained for both the topologies for different duty ratios. The simulation is performed in Matlab.

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Bridged interleaved boost converter

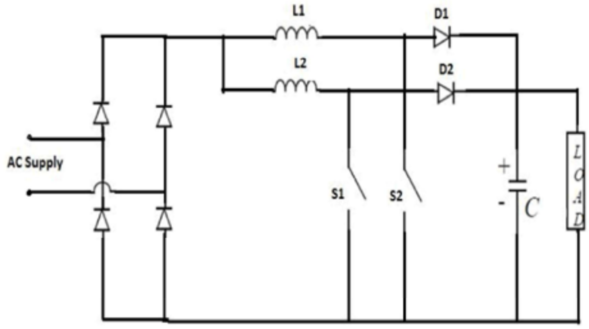


Fig. 1: Circuit diagram of a two -phase interleaved boost converter

A bridged interleaved boost converter is a parallel connection of two or more conventional boost converters. It consists of an AC source, which is converted to DC by a bridge rectifier. The DC voltage is then increased at the output side by reducing the input current. The number of parallel connections is given by the number of phases of the interleaved boost converter. The switches are switched at a phase difference of 360°/n, where n is the number of phases. The switching frequency is the same for both the switches. The advantages of the bridged IBC compared to the conventional boost converters are:

- Reduced output voltage and current ripple.
- Improved power factor.
- Reduced conduction and switching losses.
- Higher power capability.
- Improved efficiency and reduced power inductor volume.

Figure 1, Shows the circuit diagram of a two phase interleaved boost converter.

Working Principle: The working principle of the bridged boost converter can be explained by two mode.

Mode 1: S_1 is closed and S_2 is open

Current flows through the inductor L_2 and so it stores some energy in it. The energy which was stored in the inductor L_1, during the previous cycle will be transferred to the load through the diode D_1.

Mode 2: S_1 is open and S_2 is closed

Current flows through the inductor L_1 and so it stores some energy in it. The energy which was stored in the inductor L_2, during the previous cycle will be transferred to the load through the diode D_2.

Since the output voltage in both the modes is the sum of the supply voltage and the inductor voltage, the value is larger than the input voltage. In the two phase bridged interleaved boost converter, the phase difference between the switches are 180°. The ripples in both the cases cancel each other and so the output ripple is minimum [5].

Design Aspects of IBC

Duty Ratio: The duty ratio D of the converter is given by

$$D = \frac{V_{out} - V_{in}}{V_{out}} \tag{1}$$

where,V_{out} is the output voltage of the converter, V_{in} is the input voltage of the converter

Inductance

$$L = \frac{V_{in} * D}{f * \Delta I} \tag{2}$$

where, f is the frequency of switching, ΔI is the inductor current ripple

Capacitance

$$C = \frac{V_{out} * D}{R * f * \Delta V} \tag{3}$$

where, ΔV is the output voltage ripple

Selection of the Device: The device which is chosen for the interleaved boost converter is power MOSFET because of its high commutation speed and high efficiency at low voltages.

Selection of Duty Ratio: For a two-phase bridged interleaved boost converter, the ripple reduction is maximum at a duty ratio of 0.5. Hence, the duty ratio chosen is 0.5 [6,7].

Table 1 shows the design parameters, which were calculated based on the design equations for the bridged interleaved boost converter.

Table 1: Design parameters for Bridged interleaved boost converter

Parameter	Value
Input voltage	26 V
Switching frequency	50kHz
Duty ratio (D)	0.5
Inductance (L1, L2)	150µH
Capacitance (C)	850µF
Load Resistance (R)	50Ω

Bridgeless interleaved boost converter

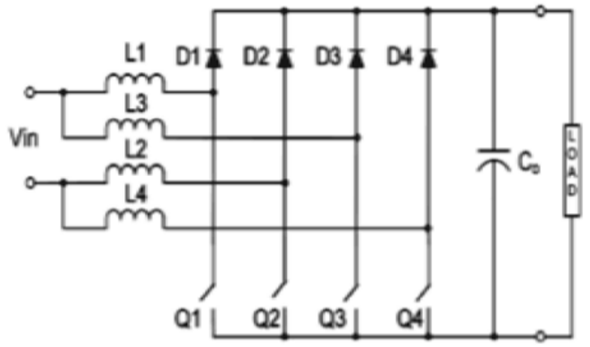


Fig. 2: Circuit diagram of a two phase bridgeless IBC

A bridgeless interleaved boost converter eliminates the bridge rectifier employed in the conventional topology. This reduces the losses due to the presence of the diodes in the bridge rectifier. Although it introduces some new losses due to the presence of additional switches and inductors, the efficiency of the bridgeless topology is better, as the losses due to the bridge rectifier is very large. Also, the THD of the current is reduced and the power factor is improved. A two-phase bridgeless IBC has two additional switches and inductors compared to the bridged converter topology [8].

Working Principle: The working principle of the circuit can be divided into two modes. The switches Q_1 and Q_2 are operated at the same time. The switched Q_3 and Q_4 are operated at a phase difference of 180°.

During mode 1, the switches Q_1 and Q_2 are closed. Q_3 and Q_4 are in the open position. Current flows through the inductor L_1 and Q_1 and returns to the supply through L_2 and Q_2, storing energy in L_1 and L_2.Now, Q_1, Q_2 are opened and Q_3, Q_4 are closed. Current flows through the inductor L_3 through Q_3 and returns to the supply through L_4 and Q_4. The energy which was stored in the inductors L_1 and L_2 will be released to the load through the diode. Again, when Q_1, Q_2 are closed and Q_3, Q_4 are opened the energy which was stored in L_3 and L_4 will be released to the load.

During mode 2, the switches Q_1 and Q_2 are closed. Q_3 and Q_4 are in the open position. Current flows through the inductor L_2 and Q_2 and returns to the supply through L_1 and Q_1, storing energy in L_1 and L_2. Now, Q_1, Q_2 are opened and Q_3, Q_4 are closed. Current flows through the inductor L_4 through Q_4 and returns to the supply through L_3 and Q_3. The energy which was stored in the inductors L_1 and L_2 will be released to the load through the diode. Again, when Q_1, Q_2 are closed and Q_3, Q_4 are opened the energy which was stored in L_3 and L_4 will be released to the load. The same simulation parameters are considered for the bridgeless topology [9].

Design Equations:
Inductance

$$L = \frac{V_{in} * D}{f * \Delta I} \tag{4}$$

where,
f is the frequency of switching
ΔI is the inductor current ripple
D is the duty ratio

Capacitance

$$C = \frac{Vout * D}{R * f * \Delta V} \tag{5}$$

where,
ΔV is the output voltage ripple

Selection of the Device: The device which is chosen for the interleaved boost converter is power MOSFET because of its high commutation speed and high efficiency at low voltages.

Selection of Duty Ratio: For a two phase bridged interleaved boost converter, the ripple reduction is maximum at a duty ratio of 0.5. Hence the duty ratio chosen is 0.5 [10].

Design Parameters for Bridgeless Interleaved Boost Converter: Table 2 shows the design parameters for Bridgeless interleaved boost converter.

Table 2 Design parameters for Bridgeless interleaved boost converter

Parameter	Value
Input voltage	26 V
Switching frequency	50kHz
Duty ratio (D)	0.5
Inductance (L1, L2)	150µH
Capacitance (C)	850µF
Load Resistance (R)	50Ω

Performance Parameters: The various performance parameters which are considered for the comparison between the bridged and bridgeless interleaved boost converter topology are listed below.

Total Harmonic Distortion (THD): The Total Harmonic Distortion (THD) is an indicator of the distortion of a signal. It is defined as the ratio of the square root of the sum of the squares of all harmonic components to the fundamental frequency component. Mathematically, it is represented as:

$$THD_V = \frac{\sqrt{\sum_{n=2} V_n^2}}{V_1}$$
$$THD_I = \frac{\sqrt{\sum_{n=2} I_n^2}}{I_1} \quad (6)$$

Distortion Factor or Purity Factor (K_p): The distortion factor (K_p) describes how the harmonic distortion of a load current decreases the average power transferred to the load. Mathematically, it is represented as

$$K_p = \frac{1}{\sqrt{1+THD^2}} \quad (7)$$

Displacement factor (Kd): The cosine of the angle between the voltage and current is known as the displacement factor.

$$K_d = \cos\theta \quad (8)$$

Power Factor (PF): Power factor is the product of the Distortion Factor K_p and the Displacement Factor K_d. [11]-[12]

$$PF = K_p * K_d \quad (9)$$

Efficiency: The efficiency is defined as the ratio of output power to the input power.

$$\eta = \frac{P_{out}}{P_{in}} \quad (10)$$

where,
P_{out} is the output power
P_{in} is the input power

The output power can also be written as the difference of input power and the losses. In other words, the efficiency can be written as

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \quad (11)$$

where,
P_{loss} is the power loss in the converter

The power loss in the converter is the sum of inductor loss, MOSFET loss and diode loss.

Inductor Loss: Power loss due to inductor is given by

$$P_{inductor} = R_L * \left(\frac{I_{out}}{1-D}\right)^2 \quad (12)$$

where,
R_L is the equivalent resistance of the inductor
I_{out} is the output current
D is the duty ratio

MOSFET loss: Loss in MOSFET is due to the sum of conduction loss and switching loss

$$P_{MOSFET} = P_{conduction} + P_{switching} \quad (13)$$

$$P_{conduction} = R_{on} * D * \left(\frac{I_{out}}{1-D}\right)^2 \quad (14)$$

$$P_{switching} = \frac{1}{2} * C_{oss} * V_{DS}{}^2 * f_{sw} \quad (15)$$

where,
R_{on} is the ON state Drain-Source resistance
I_{out} is the RMS value of output current
D is the duty cycle
C_{oss} is the output capacitance of the MOSFET
V_{DS} is the voltage across Drain and Source
f_{sw} is the switching frequency

Diode Loss: The power loss in the diode is given by

$$P_{diode} = R_D * I_{out}^2 + V_F * I_{out} \quad (16)$$

where,

R_D is the diode resistance
V_F is the forward voltage drop of the diode [13]-[15]

Simulation Results

Bridged Interleaved Boost Converter:

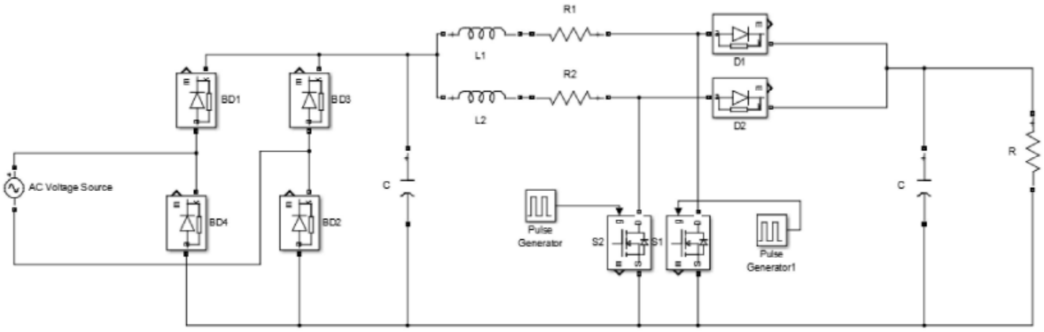


Fig. 3: MATLAB implementation of Bridged interleaved boost converter

Fig. 3 shows the circuit diagram of MATLAB implementation of the bridged Interleaved Boost converter.

Table 3: Ripple and gain value of Bridged interleaved boost converter

Duty Ratio	RMS value of output voltage (V)	Output Voltage Ripple (X10^{-3})	Output Current Ripple (X10^{-3})	Gain
0.2	29.59	1.688	1.687	1.128
0.3	33.93	3.831	5.891	1.305
0.4	39.61	3.778	3.776	1.527
0.5	47.57	1.527	1.525	1.836
0.6	59.38	8.382	7.541	2.294
0.7	78.65	11.40	9.50	3.044
0.8	115.2	22.30	12.50	4.488
0.85	148.4	19.80	16.79	5.827

Table 3 shows the values of the RMS value of the output voltage, output voltage ripple, output current ripple and the gain of the Bridged Interleaved Boost converter for different values of duty ratios ranging from 0.2 to 0.85.

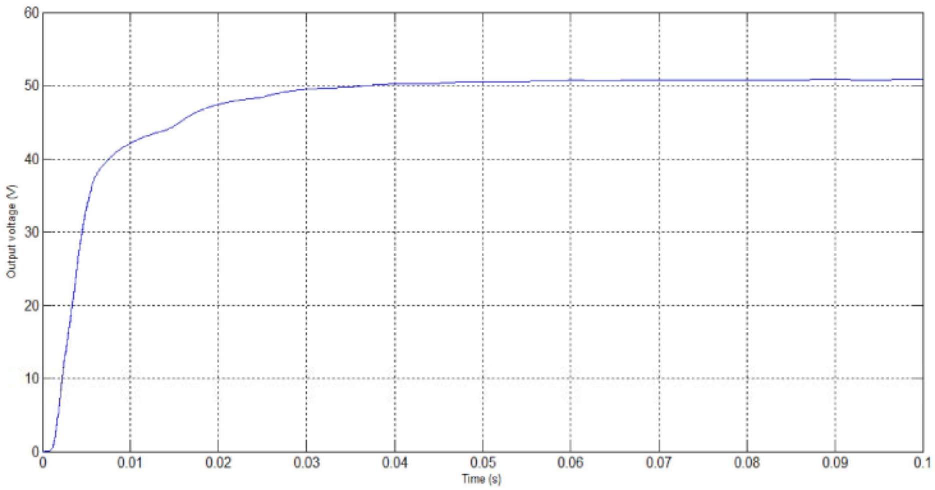


Fig. 4: Output voltage waveform of bridged interleaved boost converter

Figure 4 shows the output voltage waveform for bridged interleaved boost converter. The output voltage obtained is 50V for the duty ratio of 0.5.

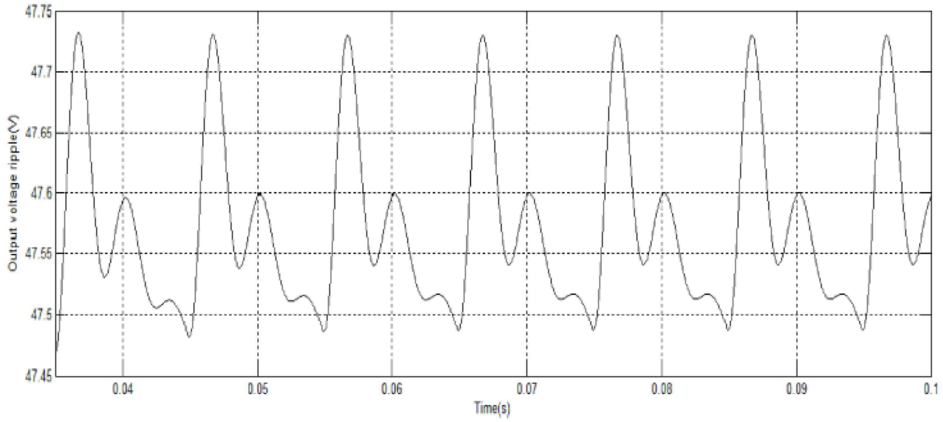


Fig. 5: Output voltage ripple waveform of bridged interleaved boost converter

Figure 5 shows the output voltage ripple waveform of Bridged interleaved boost converter for a duty ratio of 0.5. The ripple value obtained is 1.527.

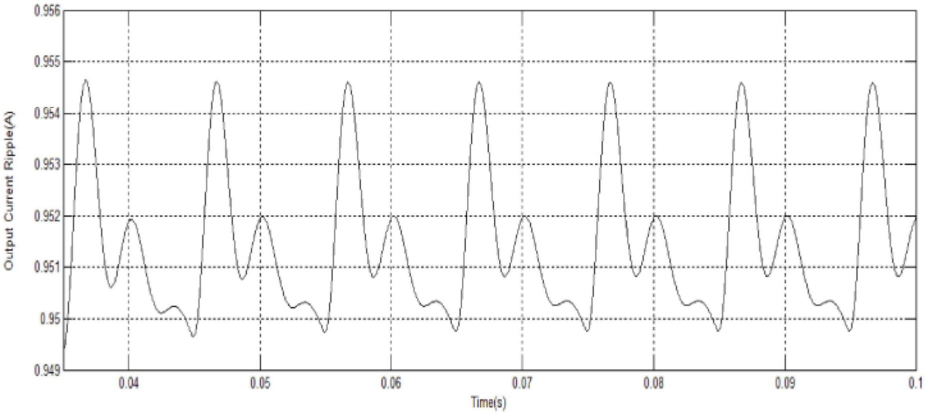


Fig. 6: Output current ripple waveform of Bridged interleaved boost converter

Figure 6 shows the output current ripple waveform of Bridged interleaved boost converter for a duty ratio of 0.5. The ripple value obtained is 1.525.

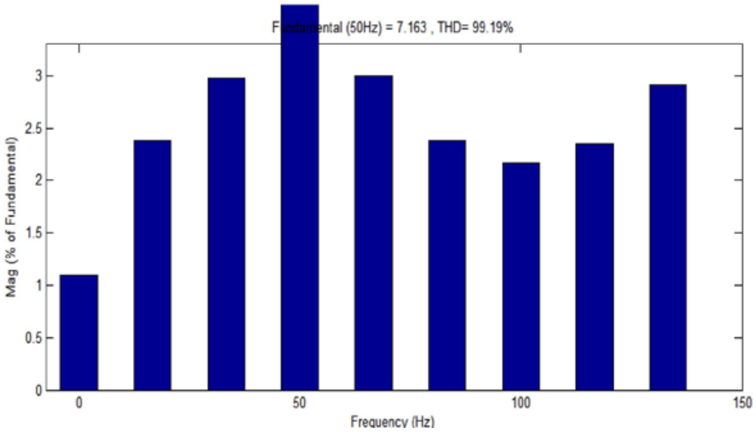


Fig. 7: FFT analysis of Bridged interleaved boost converter

Figure 7 shows the FFT analysis done for obtaining the THD of the input current. The value of THD obtained is 99.19%.

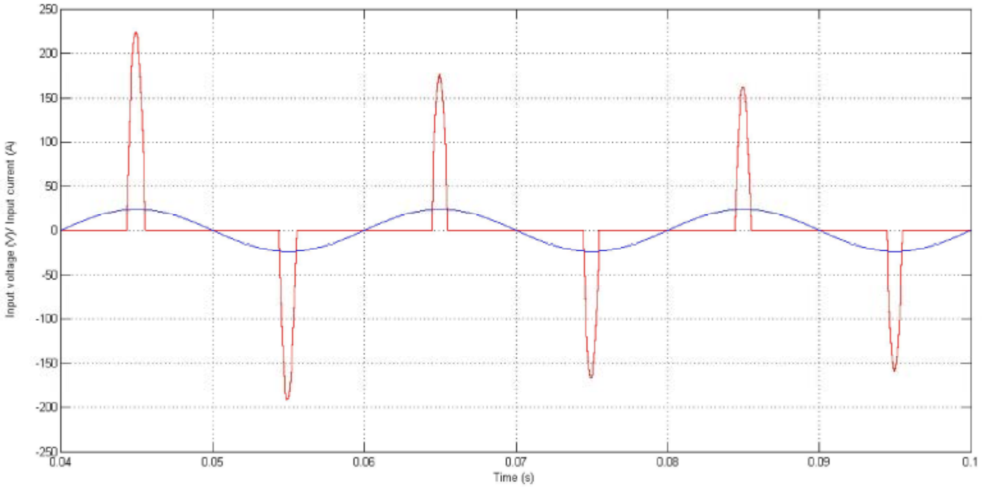


Fig. 8: Input voltage and input current waveform

Figure 8 shows the input current and input voltage waveform of Bridged interleaved boost converter.

Table 4: Loss and efficiency of Bridged interleaved boost converter

% Load	Inductor loss (W)	MOSFET loss (conduction+ switching) (W)	Fast diode loss (W)	Bridge Rectifier loss (W)	Total loss (W)	Output power (W)	Input power (W)	% Efficiency
100	0.362	0.7432	0.76	3.047	4.912	45.097	50.009	90.178
80	0.560	1.1352	0.948	3.797	6.44	56.074	62.514	89.70
60	0.989	2.0001	1.259	5.054	9.302	74.230	83.532	88.86
40	1.098	4.4129	1.880	7.5415	14.933	109.79	124.723	88.03
20	4.217	16.889	3.693	14.863	39.66	210.865	250.53	84.17

Table 4 shows the calculation of the losses in the Bridged Interleaved Boost converter and the efficiency obtained for the load varying from 20 to 100 percent

From the results in Table 4, it can be inferred that as the % load increases, the total power loss decreases and the efficiency increases.

Table 5: RMS value of current for MOSFET, inductor and fast diode for Bridged interleaved boost converter

% Load	RMS value of MOSFET current (A)	RMS value of inductor current (A)	RMS value of Fast diode current (A)
20	3.358	4.702	3.324
40	1.744	2.419	1.711
60	1.197	1.646	1.164
80	0.9227	1.258	0.8894
100	0.7583	1.025	0.7253

Table 5 shows the RMS value of the MOSFET current, inductor current and the fast diode current for different values of the load varying from 20 to 100 percent for Bridged interleaved boost converter.

From Table 5, it can be seen that as the % load increases, the RMS value of MOSFET current, inductor current and fast diode current decreases.

Bridgeless interleaved boost converter

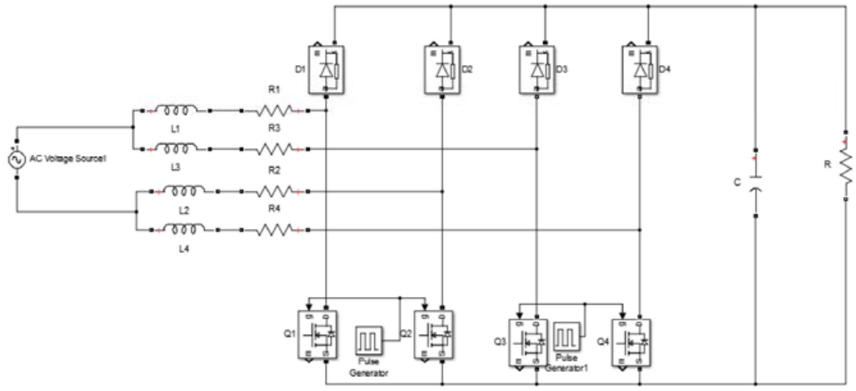


Fig. 9: MATLAB implementation of Bridgeless interleaved boost converter

Figure 9 shows the circuit diagram of the Bridgeless Interleaved Boost converter, which was implemented in MATLAB.

Table 6: RMS value of output voltage, output voltage and current ripple, gain of Bridgeless interleaved boost converter

Duty Ratio	RMS value of output voltage (V)	Output Voltage Ripple	Output Current Ripple	Gain
0.2	30.85	0.1045	0.1053	1.288
0.3	35.20	0.0940	0.0940	1.433
0.4	40.86	0.0919	0.0919	1.673
0.5	48.46	0.0769	0.0952	2.004
0.6	61.57	0.1085	0.1094	2.481
0.7	80.10	0.1333	0.1212	3.173
0.8	116.6	0.1017	0.1066	4.538
0.85	151.5	0.0902	0.0927	7.250

Table 6 shows the RMS value of the output voltage, the output voltage /current ripple and the gain for different values of duty ratios varying from 0.2 to 0.85 for the Bridgeless Interleaved Boost converter.

From Table 6, it is observed that the output voltage ripple, output current ripple is minimum at a duty ratio of 0.5. This is because, the ripple cancellation is effective at this duty ratio.

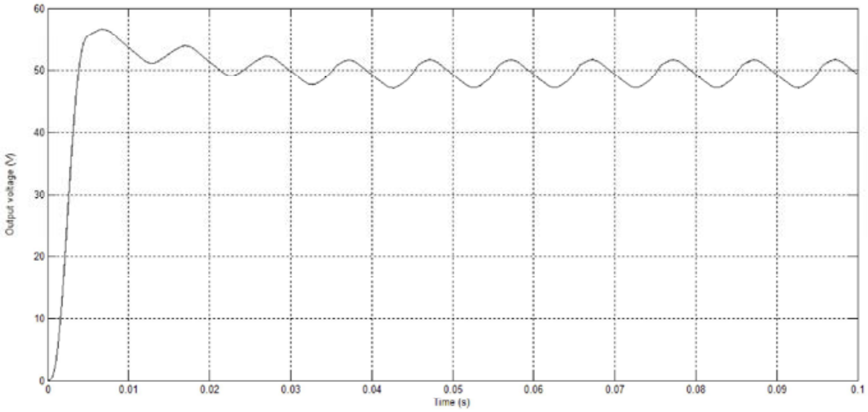


Fig. 10: Output voltage waveform of Bridgeless interleaved boost converter

Figure 10 shows the output voltage waveform of Bridgeless interleaved boost converter. The RMS value of the output voltage obtained for a duty ratio of 0.5 is 50V.

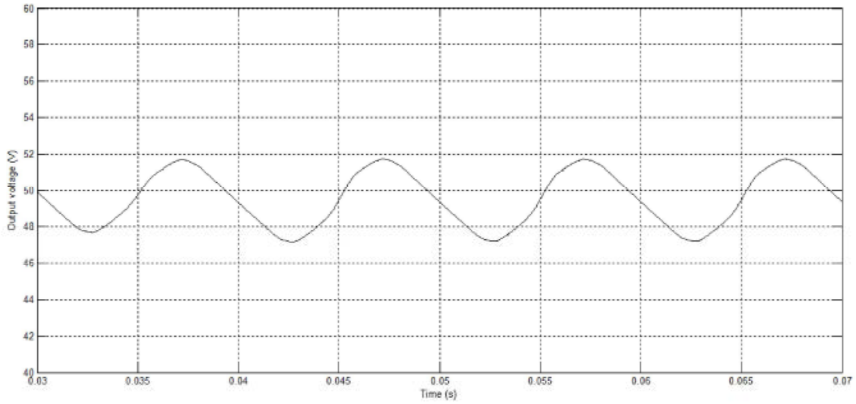


Fig. 11: Output voltage ripple waveform of Bridgeless interleaved boost converter

Figure 11 shows the output voltage ripple waveform of Bridgeless interleaved boost converter. The ripple value obtained for a duty ratio of 0.5 is 0.076.

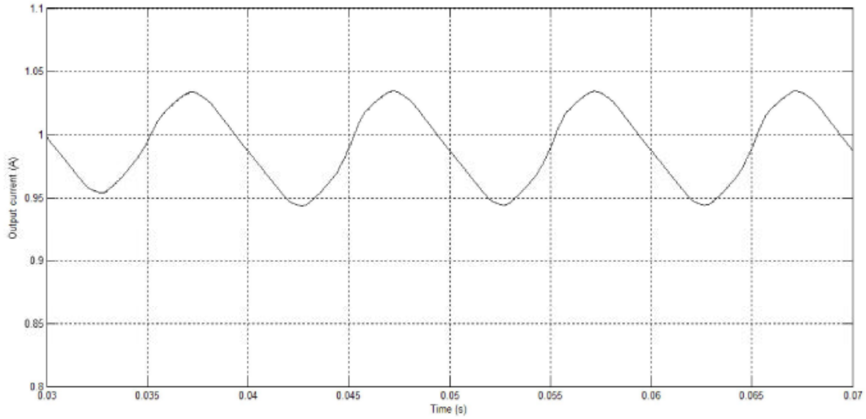


Fig. 12: Output current ripple waveform of Bridgeless interleaved boost converter

Figure 12 shows the output current ripple waveform of Bridgeless interleaved boost converter. The ripple value obtained for a duty ratio of 0.5 is 0.0952.

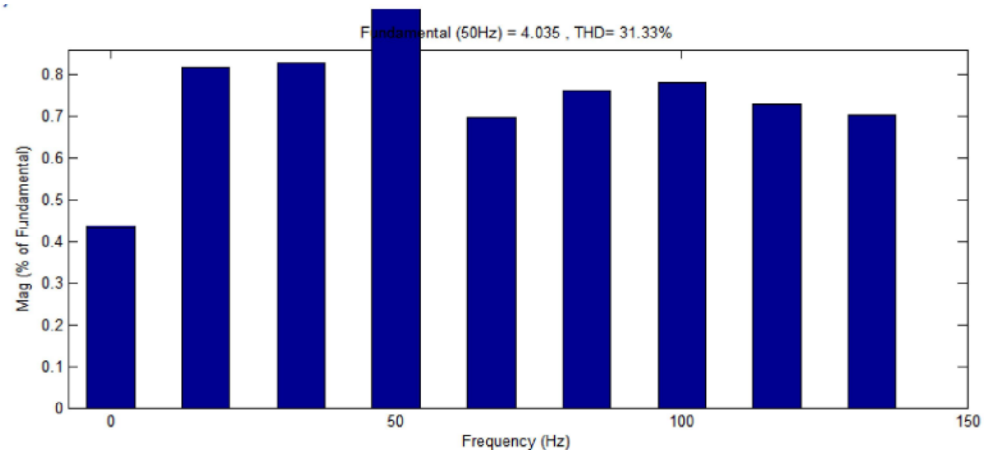


Fig. 13: FFT analysis of Bridgeless interleaved boost converter

Figure 13 shows the FFT analysis done for obtaining the THD of the input current. The value of THD obtained is 31.33%.

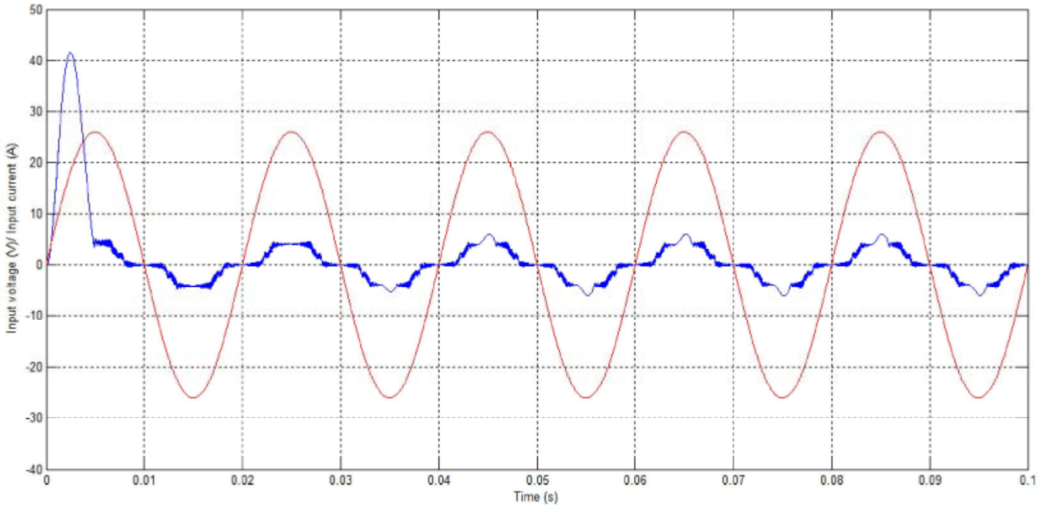


Fig. 14: Input current and input voltage waveforms of Bridgeless interleaved boost converter

Figure 14 shows the input current and input voltage waveform of Bridged interleaved boost converter.

Table 7: Loss and Efficiency calculation of Bridgeless interleaved boost converter

% Load	Inductor loss (W)	MOSFET loss (conduction+ switching) (W)	Fast diode loss (W)	Total loss (W)	Output power (W)	Input power (W)	% Efficiency
100	0.7834	1.6170	1.5853	3.9857	48.965	52.951	92.47
80	1.1888	2.4226	1.9534	5.5648	59.450	65.015	91.44
60	2.043	4.1284	2.5620	8.7330	76.592	85.325	89.76
40	3.321	6.6835	3.7290	13.734	110.02	123.75	88.90
20	7.211	24.883	6.8300	38.913	212.285	251.20	84.51

Table 7 shows the calculation of the losses in the Bridged Interleaved Boost converter and the efficiency obtained for the load varying from 20 to 100 percent.

From Table 7, it can be observed that as the % load increases, the efficiency increases. Also the % efficiency in bridgeless interleaved boost converter is greater than that obtained for conventional interleaved boost converter for the same % load.

Table 8: RMS value of MOSFET current, inductor current and fast diode current

% Load	RMS value of MOSFET current (A)	RMS value of inductor current (A)	RMS value of Fast diode current (A)
20	6.005	6.928	3.467
40	3.426	3.948	1.975
60	2.333	2.687	1.347
80	1.765	2.030	1.018
100	1.431	1.646	0.8296

Table 8 shows the RMS value of the MOSFET current, inductor current and the fast diode current for different values of the load varying from 20 to 100 percent.

Table 8 shows that the RMS value of MOSFET current, inductor current and fast diode current decreases as the % load increases. But the values are slightly higher than that of conventional boost converter.

Comparison between the Bridged and Bridgeless interleaved boost converter

Table 9: Power factor and THD comparison between Bridged and Bridgeless interleaved boost converter

Topology	THD(%)	Distortion factor	Displacement factor	Power factor
Bridged interleaved boost converter	99.19	0.7100	0.9900	0.7029
Bridgeless interleaved boost converter	31.33	0.9542	0.9998	0.9541

Table 9 shows the comparison between the performance parameters of the Bridged and Bridgeless interleaved boost converter.

From Table 9, it is observed that the power factor is improved and the THD is reduced in the case of Bridgeless interleaved boost converter.

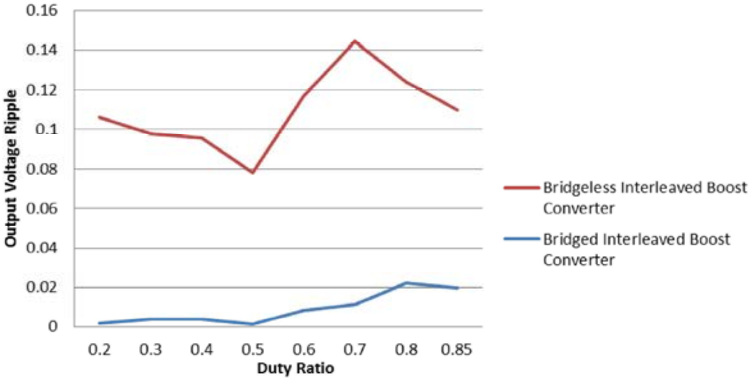


Fig. 15 Output voltage ripple comparison between Bridged and Bridgeless interleaved boost converter

Figure 15 shows the comparison graph between Bridged and Bridgeless interleaved boost converter for output voltage ripple.

From Figure 15, it is observed that the output voltage ripple value is minimum at a duty ratio of 0.5 for both Bridgeless and bridged interleaved boost converter. It is also observed that the ripple value is higher in the case of Bridgeless interleaved boost converter.

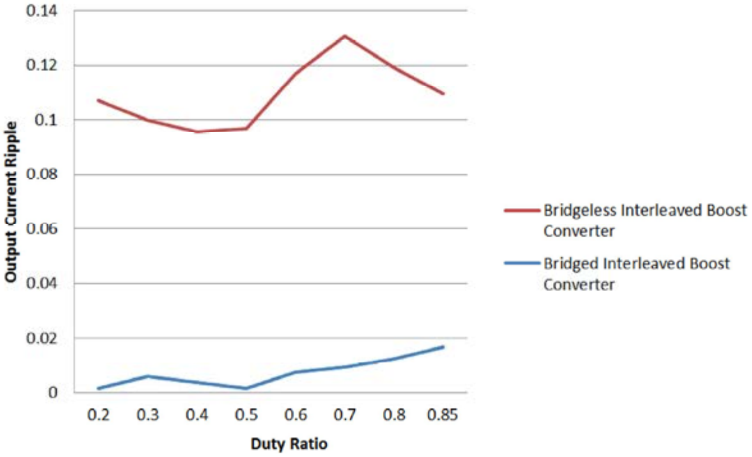


Fig. 16: Output current ripple comparison between Bridged and Bridgeless interleaved boost converter

Figure 16 shows the comparison graph between Bridged and Bridgeless interleaved boost converter for output current ripple.

From Figure 16 it can be observed that the output current ripple value is minimum at a duty ratio of 0.5, because ripple cancellation is effective at this duty ratio.

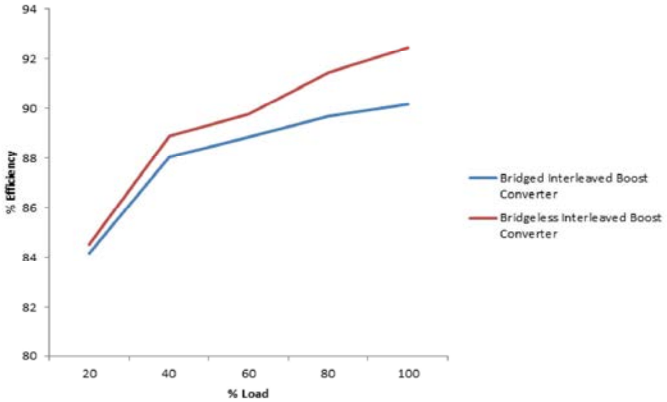


Fig. 17: Graph showing the comparison between Bridged and Bridgeless interleaved boost converter for % efficiency

Figure 17 shows the graph between the % efficiency and the % load for Bridgeless and Bridged interleaved boost converter.

It can be observed that the efficiency in the case of Bridgeless Interleaved Boost converter is higher than the Bridged interleaved boost converter. As the % load increases, the efficiency increases.

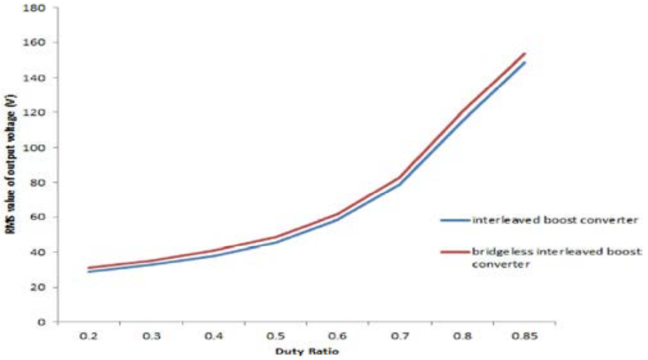


Fig. 18: Comparison of RMS value of output voltage between Bridged and Bridgeless interleaved boost converter

Figure 18 shows the graph between the RMS value of the output voltage and duty ratio.

It is observed that the RMS value of output voltage increases as the duty ratio increases. The RMS value is higher for the Bridgeless interleaved boost converter.

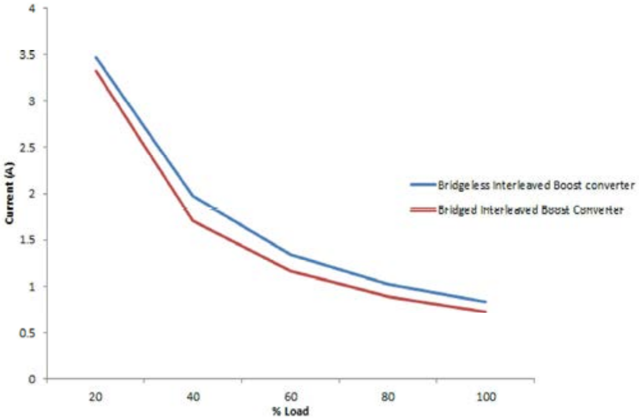


Fig. 19: Graph showing comparison of RMS value of current in fast diode between Bridged and Bridgeless interleaved boost converter

Figure 19 shows the graph between the RMS value of the current in fast diode and the % load.

It is observed that the Bridgeless interleaved boost converter has a better RMS current value. As the % load increases, the RMS value of the current decreases.

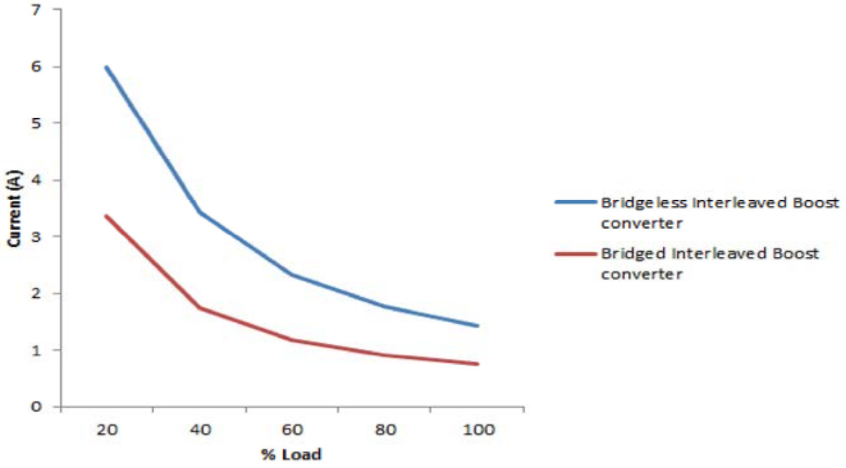


Fig. 20: Graph showing comparison of RMS value of current in MOSFET between Bridged and Bridgeless interleaved boost converter

Figure 20 shows the graph between the RMS value of the current of the switch and the % load. The RMS value of the Bridgeless interleaved boost converter is greater than the bridged interleaved boost converter. As the % load increases the RMS value of current decreases.

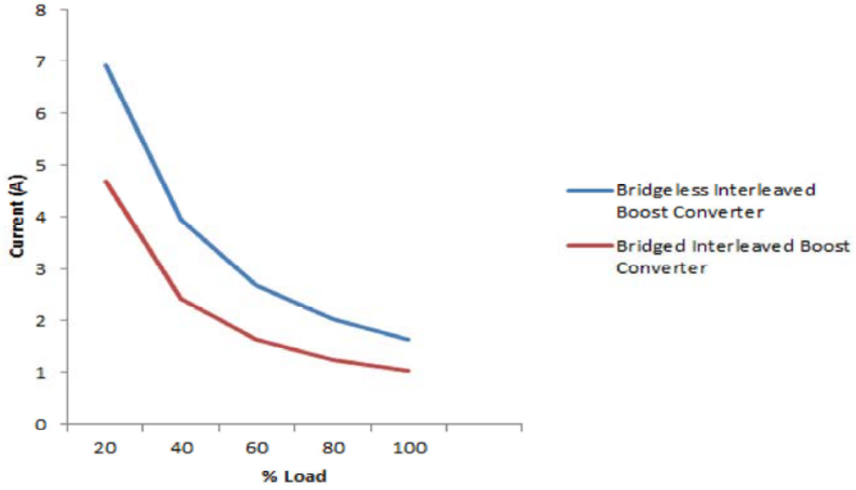


Fig. 21: Graph showing comparison of RMS value of current in inductor between Bridged and Bridgeless interleaved boost converter

Figure 21 shows the graph between the RMS value of the inductor current and the % Load.

It is observed that the RMS value of inductor current is higher in the case of Bridgeless interleaved boost converter and the value decreases as the % load increases.

Hardware Implementation: The prototype of two-phase bridgeless IBC is built with power MOSFETS and fast recovery diodes alongwith optocoupler circuit. Arduino is employed for generating the phase shifted pulses to the switches. The entire hardware setup is shown in Fig.22.

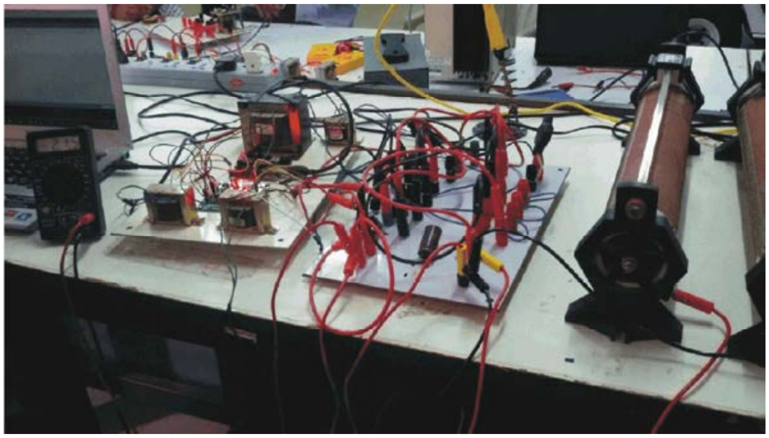


Fig. 22: Hardware implementation of Bridgeless Interleaved Boost converter

```
Vmax= 9.80V   |Vavg=48.0mV   |Rise<300ns
Vmin=-9.80V   |Vrms= 9.21V   |Fall<200ns
Vpp= 19.6V    |Vovr=0.2%     |+Wid=9.850us
Vtop= 9.57V   |Vpre=1.3%     |-Wid=10.45us
Vbase=-8.89V  |Prd=20.30us   |+Duty=48.5%
Vamp= 18.5V   |Freq=49.26kHz -Duty=51.5%
5.00V                Time 5.000us   T→0.0000s
```

Fig. 23: Pulse generated using Arduino for a duty ratio of 0.5

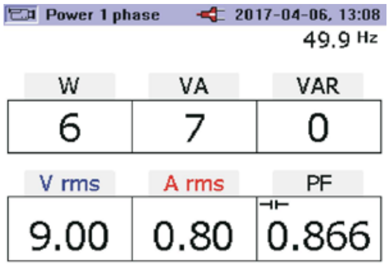
Figure 23 shows the pulse generated using Arduino for a frequency of nearly 50kHz with 0.5 s duty ratio.

Volts 2017-04-06, 12:45

0.0 Hz

V ac	V avg	V pk
0.30	22.79	-23.07
V/Hz	%RPL	CF
OL	1.3	1.03

Fig. 24: Output voltage ripple



Power 1 phase 2017-04-06, 13:08

49.9 Hz

W	VA	VAR
6	7	0
V rms	A rms	PF
9.00	0.80	0.866

Fig. 25: Input power factor

Figures 24 & 25 show the output voltage ripple obtained as 1.3% and power factor of 0.866 which verified the simulation results. Hence, bridgeless IBC results in better performance compared to the bridged type IBC.The experimental results are shown below:

For an Input voltage = 11.1V, Switching frequency= 50kHz, Duty ratio= 0.5, the obtained

Output voltage= 21.5V, Output voltage ripple= 1.3% and Power factor= 0.866.

CONCLUSION

The two topologies, namely, the bridged interleaved boost converter and bridgeless interleaved boost converter were simulated using Matlab. Various performance parameters of both the topologies such as output voltage and current ripple, THD, input current power factor, efficiency, RMS value of current for inductor, MOSFET switch and fast diode were analysed and compared. Comparison graphs were plotted for these parameters. It was observed that the Bridgeless interleaved boost converter offered better performance in terms of higher power factor, lower THD, better efficiency, improved RMS value of current for inductor, MOSFET and the fast diode. The efficiency was found to be increasing with load. Also the RMS value of current for inductor, MOSFET and the fast diode was found to be decreasing with increase in load. The Bridgeless interleaved boost converter was implemented in hardware.

Hence, the bridgeless interleaved boost converter is widely preferred for applications which require higher power factor and increased efficiency.

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