International Journal For Advanced Research In Science & Technology
A peer reviewed international journal www.ijarst.in
ISSN: 2457-0362

Power Factor Correction Converter of a Wide Input and Output Voltage Range Battery Charger Using Buck-Boost Converter with BLDC Motor Drive

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Abstract—This Paper deal among Power Factor Correction (PFC) in Brushless motor drives Buck-Boost DC-DC converter topology. To improve the Power quality (PQ) power factor corrected converter is essential. This paper mainly focuses on analysis and operating modes for a interleaved boost cascaded-by buck (IBCBB) converter suitable for a power factor correction (PFC) converter. The designed control structure provides a wide degree of control freedom to operate even if the VDC/Vmax (output voltage to peak of Input) less than 0.5. Moreover, the proposed converter is validated on the experimental setup and the results are presented in the paper. In addition, a two-stage universal battery charger with wide input and output voltage is been simulated and presented in the paper.

Keywords— Power Quality (PQ), Power Factor Correction (PFC), Bridgeless converters, cuk Converter, Bridgeless isolated cuk converter, Brushless dc motor(BLDC).

1.Introduction

Rectification is a process in which electric power is converted from AC to DC. It is widely used in many applications as most of electronics appliances nowadays require DC power. Conventional AC-DC converters, such as Bridge rectifiers, have been developed for this purpose but there are few factors to be controlled in this regard. The Non sinusoidal current drawn at the input side results in lower distortion as well displacement factors. Commanding the line current to follow the line voltage in a sinusoidal manner can gives higher efficiency with improved power factor and lower THD. AC side power factor (PF) is needed to be improved along with lowering of Total Harmonic Distortion of input line current. Tight regulation of the output voltage even in the case of dynamic loads is also a stringent requirement of DC-DC converters. A controller that simultaneously controls both the input as well as the output parameters is the choice.

To gain a high-power factor, different power factor correction (PFC) techniques have been introduced which can be divided into two parts, passive and active. Passive techniques consist of passive components such as inductors and capacitors that are used as input filter to reduce line current harmonics. However, improvements are not significant and another drawback is the relatively large size of these passive elements. Moreover, these techniques may not be able to handle dynamic loads. On the other hand, active PFC technique is more efficient solution, having a combination of switches and passive elements. Due to presence of switches, controllers can be implemented on active techniques of PFC. At the cost of complexity, the controlled active techniques can increase Power factor and reduce THD in the input AC current. Along with-it active techniques can also bring precise DC regulation for variable loads.

The active PFC technique uses a diode bridge rectifier followed by a dc–dc converter and the bulk capacitor. By controlling the dc–dc converter, the input line current is commanded to follow the input line voltage and in this way Power Factor approaches to unity. For medium and high-power applications boost dc-dc converter works better for power factor correction than other dc-dc converters such as buck boost and buck converters because of lower electromagnetic interference. Moreover, in case of boost PFC converter there is low requirement of filtering because of continuous line current, whereas other dc-dc converters such as buck, buck-boost, and Flyback have higher requirement of filtering because of pulsating line current.

As boost converter is capable of handling much higher power levels as compared to its other counterparts, much research has been carried out on many different PFC techniques of this topology

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ISSN: 2457-0362

[1]-[6]. Among all these techniques of improvement of robustness, power efficiency and cost the bridgeless topology has outperformed almost all the techniques. A brief performance evaluation of bridgeless boost PFC is presented in [7], [8]. Different new topologies of bridgeless boost DC-DC converter topology have also been discussed in some recent research [9]-[11].

In this paper a new topology of bridgeless boost PFC converter has been analysed. Its performance has been analysed by applying a simple controller on it. To avoid complexity and get maximum advantage of the controller we have applied Proportional Integral (PI) controller by using double stage Pulse Width Modulation (PWM). This controller works for both ac and dc side. The control technique is capable of improving Power Factor and reducing THD at ac side along with regulating DC voltage at the output tightly. To get best performance for variable loads, a resistor observer has been applied. Moreover, a comparison has been made between bridgeless boost PFC and conventionally used diode bridge boost PFC. The comparison clearly shows that the proposed topology and controller is giving a simple and easily implementable solution to all the discussed issues.

2 ANALYSIS AND OPERATION OF THE PROPOSED PFC CONVERTER

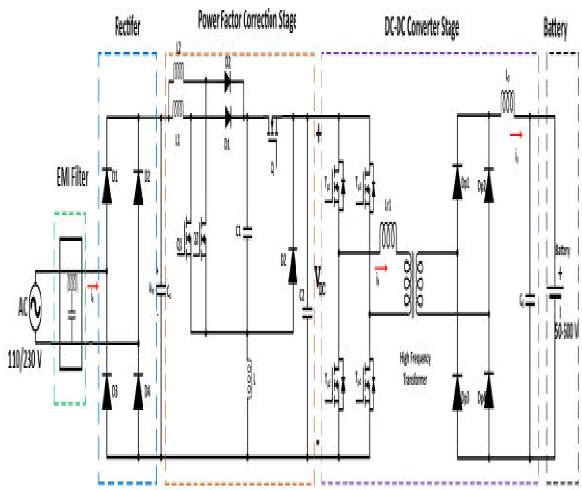


Fig.1: Proposed Interleaved boost cascaded-by buck PFC converter based on-board battery charger

The above circuit shown in Fig.1 is schematic of two stage on-board battery charger. It consists of a power factor correction converter in two-switch topology configuration and an isolated DC-DC converter. The proposed PFC converter consists of a cascaded combination of the interleaved boost with a buck converter. The inductors L1, L2 at the input provides a non-pulsating current which can be easily controlled to maintain the power quality. Interleaved combination at input also provides the reduced ripple content in the input current. The converter is operated in the continuous conduction mode (CCM) with a boost configuration formed with the switches Q1, Q2 and diode D1 D2. An LC filter is paired either at the input or the output side of the converter based on operating mode which provides non-pulsating currents to source and load. The converter controls the buck switch Q and diode D based on the input and output voltages. The output voltage of the converter is represented as VDC which can be controlled to a value either above or below of the peak value of input voltage Vmax. Fig.3 shows the rectified universal input voltage applied to converter whose output voltage (VDC) selected is greater than the peak of input voltage Vmax enabling the boost operation with controlling switches Q1 and Q2 with a duty ratio of d1 and d2 turning the buck switch Q on continuously.

If the output voltage at the converter is selected lesser than the peak of the input voltage Vmax the converter operates in both boost and buck modes. In interval [0,t1] the converter operates in boost mode controlling Q1 and Q2 as shown in switching states and from [t1, T4s] in buck mode of operation with duty ratio of dB u and it repeats for next quarter cycle.

The switching pattern of the converter during buck and boot modes of operation is showed in Fig.3. The overall gain of the converter is given as

$$M = \frac{d_{Bu}}{1 - d_{Bo}} \tag{1}$$

The duty ratio for the boost mode of operation is defined as dBo with the duty ratio of the boost switches d1 and d2 are maintained 1800 phase shift between them. The phase shift in the PWM signals generates the ripple current in the inductor in phase opposition which cancels the ripple when they are added up resulting in the reduction of ripple current at the PFC output. In the boost mode of operation, the duty ratio of the buck switch is made high dBu = 1, (turned on continuously) and the inductor at input and output provides a continuous current. The overall gain of the converter in boost mode of operation with the duty ratio dBo is given as M1 = 1−1dBo .

The detailed operating modes of the converter in boost mode are as shown in Fig.3. In mode-(a) the inductors share input current equally and the output capacitor supplies to load. A part of the input

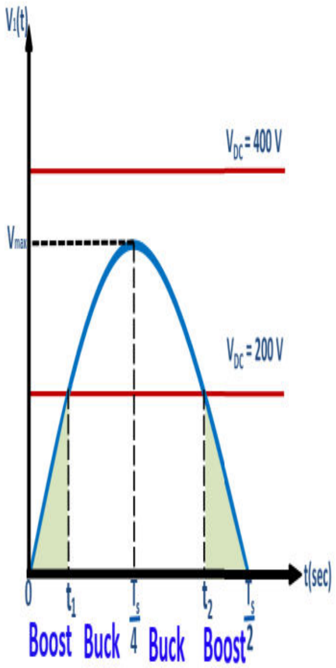
current flows to the load through the capacitor C1 providing a direct path from source to load. In mode-(b) and (c) one of the boost switch is turned off which provides a path for the input current to charge the inductor as well as to supply to load. In mode-(d) the switches are turned off and the input current flows directly to output. Similarly, in the buck mode of operation the converter is operated with a duty ratio of d2 and the boost switch is turned off making the duty ratio dBo = 0. The overall gain of the converter is given as M2 = dBu. The cascaded combination of the boost mode and the buck mode implies the product of the gains of converter.
The overall gain of converter is given as:

$$M = M_1 \times M_2 = \frac{d_{Bu}}{1 - d_{Bo}} \tag{2}$$

For analysis as shown in Fig.4 the forward voltage drop of the diodes is neglected and the rectified voltage is assumed to be same as the input voltage which is given as

$$V_1(t) = V_{max}|sin\omega t| \tag{3}$$

where Vmax is the maximum value of rectified input voltage and is given as Vmax = $\sqrt{2}$ Vac; rms.Fora ideal PFC rectifier (neglecting losses) the power at input and output is assumed to be constant. For a particular value of the output voltage VDC.



Switching States

Q1	Q2	Q	Operation
0	1	1	Boost
1	1	1	
0	0	1	
0	1	1	
0	0	0	Buck
0	0	1	

Fig. 2: Rectified input voltage waveform with different possible operating modes and switching states

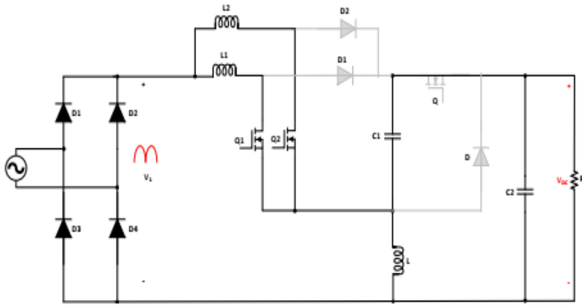


Fig 3 (a)

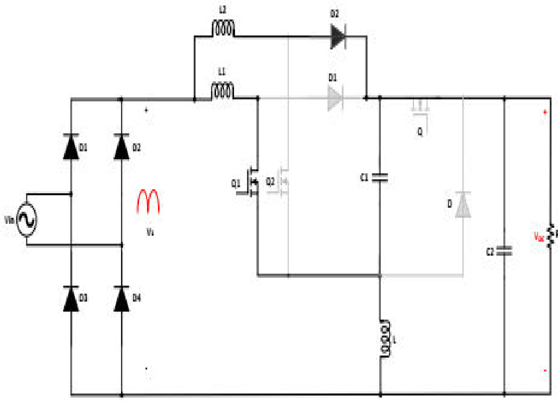


Fig 3(b)

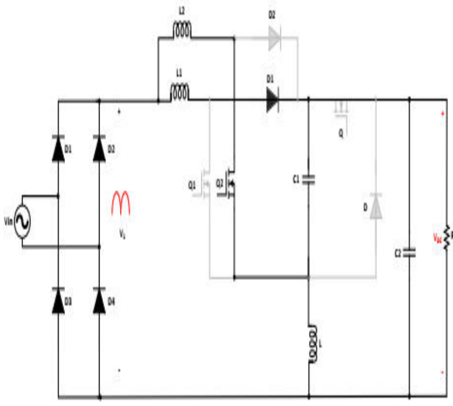


Fig 3(c)

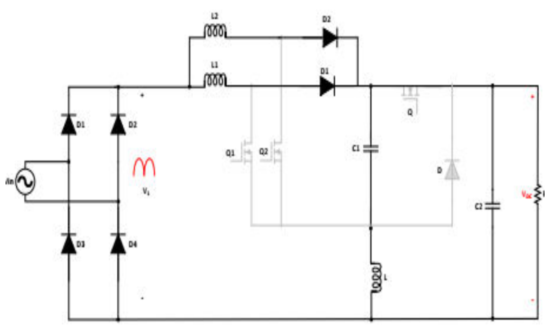


Fig 3(d)

Fig. 3: Operation of the proposed converter in boost mode

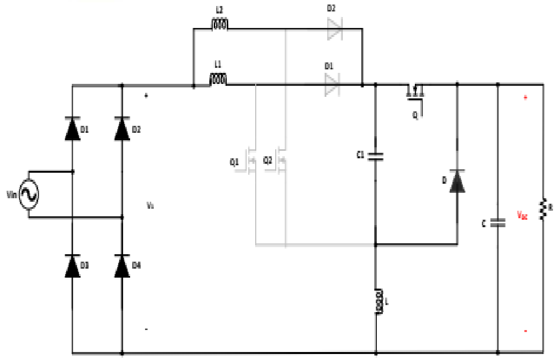


Fig. 4: Operation of the proposed converter in buck mode

The input current iin(t) is proportional to the input voltage V1(t).

$$\begin{cases} i_{in}(t) = \dfrac{\sqrt{2}V_{ac,rms}}{R_{em}}|sin\omega t| \\ i_{in}(t) = \dfrac{V_1(t)}{R_{em}} \end{cases}$$

(4)

Where Rem is the emulated resistance related to active power P0 demanded by load. The expression for the input current is given as :

$$I_{in}(t) = \frac{\sqrt{2}P_0}{V_{ac.rms}}sin(\omega t)$$

(5)

$$I_{in}(t) = \frac{4P_0}{\pi V_0(1 - d_{Bo})}sin(\omega t)$$

(6)

3.Design Parameters of PFC converter

The selection of the inductors is assumed under the condition of continuous conduction mode with less effects on current ripple. Let I1 is the average input current flowing through the inductor L1 with an peak inductor ripple of ΔI1 and I2 is the average input current flowing through the inductor L2 with an peak inductor ripple of ΔI2 .

$$I_{in} = I_{L1} + I_{L2} > \Delta I_{L1} + \Delta I_{L2}$$

(7)

The input current and the peak inductor current ripple is defined as :

$$I_{in} = \frac{V_1}{R_e} > \frac{V_1 \times d_1 T_s}{2L_{in}}$$
$$where L_{in} = L_1 = L_2$$

(8)

Where Re is the input resistance of the power converter which can be determined for a given output power.

$$L_{in} > \frac{T_s \times R_e}{2}(1 - \frac{V_{max}sin(\omega t)}{V_{DC}})$$

(9)

Similarly in the buck mode the inductance L2 can be determined from the below equations. For the selection of the capacitance C1 so that input variations will not affect much on the output voltage. The converter forms a low pass LC filter at input during mode whose frequency is more than the input line frequency.

$$L_p > \frac{(V_{max}sin(\omega t) - V_{DC}) \times V_{DC}^2 \times R_e T_s}{2 \times (V_{max}sin(\omega t))^3}$$

(10)

$$L_p = \frac{L_{in}L}{L + L_{in}}$$

(11)

The value of inductance L2 can be determined using the equations (10) and (11). For a given power rating the parameters used in the converter are detailed in Table.I. For the phase shifted ZVS DC-DC converter the standard design guidelines are followed and the parameters derived.

To have a proper ZVS for the different loads the condition shown in (12) must be satisfied.

$$\frac{1}{2}L_{lk}I_{cri}^2 > \frac{4}{3}C_{mos}V_1^2 + \frac{1}{2}C_{Tr}V_1^2$$

(12)

Here Cmos is referred as the drain to source capacitance of the switch and CT r is the transformer winding capacitance.

4. BLDC MOTOR

High efficiency, high power density and wide range speed controllability of BLDC motors make them suitable in various drive applications. In particular the spindle motors used in computer hard disk drives are to possess high speed characteristics for fast data access.

Brushless Direct Current (BLDC) motors are one of the motor types rapidly gaining popularity. BLDC motors are used in industries such as

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Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation equipment and Instrumentation. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically com- mutated. BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

- Better speed versus torque characteristics
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors. In this application note, we will discuss in detail the construction, working principle, characteristics and typical applications of BLDC motors.

A) Main Characteristics BLDC Motor

Brushless DC motors consist of two coaxial magnetic armatures separated by an air gap. In certain types of motor,

- The external armature, the stator, is fixed.
- The internal armature, the rotor, is mobile (the rotor can also be external in certain cases).
- The stator is the induced part of the machine.
- The rotor is the inductor of the machine.
- In brushless DC motors, the internal armature, the rotor, is a permanent magnet. This armature is supplied by a constant current (DC).
- The external armature (stator) is poly phased (3 phases in our case) and is covered by poly- phased currents.

In a Brushless DC motor, the rotor is a permanent magnet, this type of motor has almost the same properties and physical laws as a DC current machine.

An electric motor transforms electrical energy into mechanical energy. Two main characteristics of a brushless DC motor are:

- It has an electromotive force proportional to its speed
- The stator flux is synchronized with the permanent magnet rotor flux.

5. MATLAB/ SIMULATION RESULTS

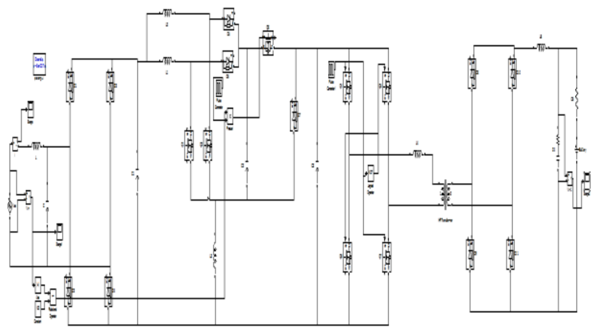
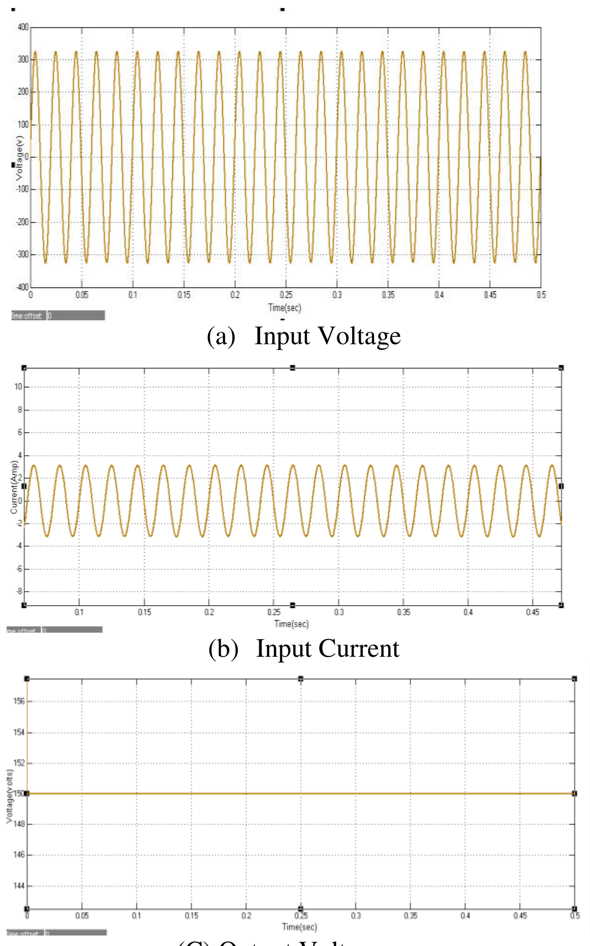


Fig 5 Simulink Diagram of Proposed PFC Converter



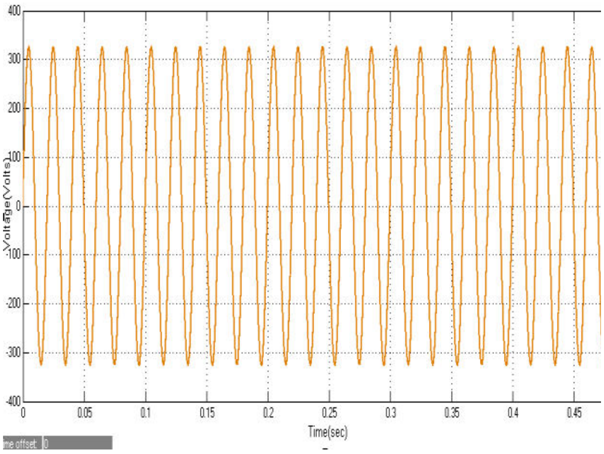
(a) Input Voltage

(b) Input Current

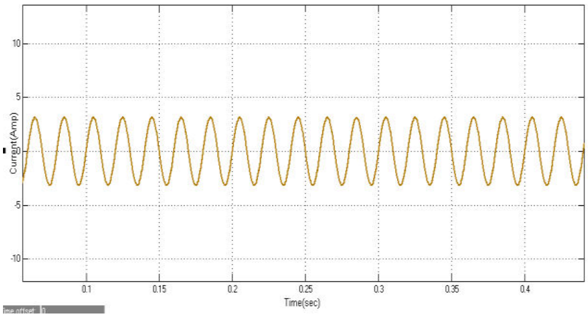
(C) Output Voltage

Fig. 6: Simulation results of converter with 150 V output voltage

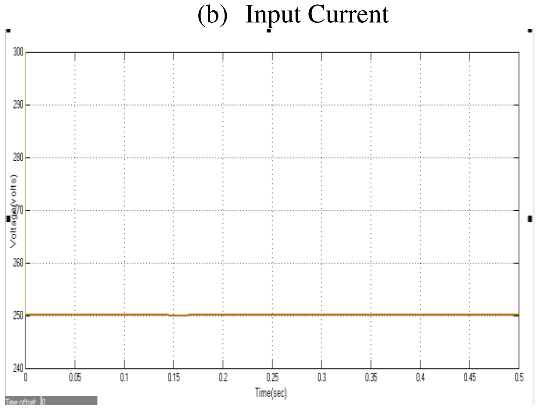
The simulations of the proposed interleaved boost cascaded by buck PFC converter were performed in PSIM 11.0.3 with the power ratings of 1 kW. Fig.6 shows the simulation result of the proposed converter configuration with an input voltage of 230 V. The output of converter is at 150 V which is less than the peak of the input voltage and the captured input current is in-phase with input voltage which maintains high power quality.



(a) Input Voltage



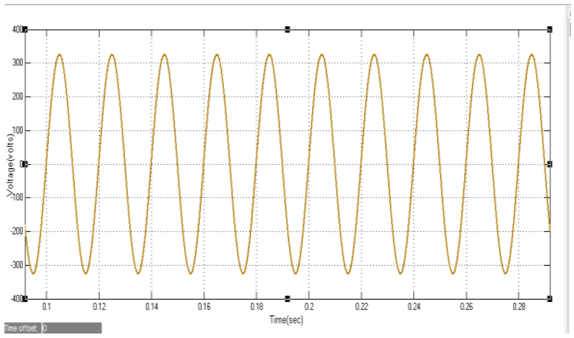
(b) Input Current



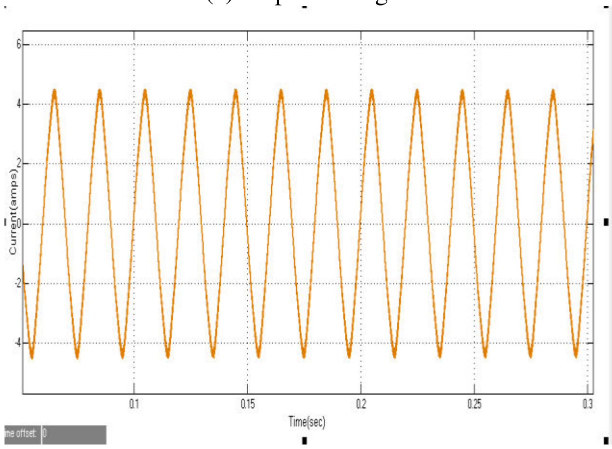
(c) Output Voltage

Fig. 7: Simulation results of converter with 250 V output voltages

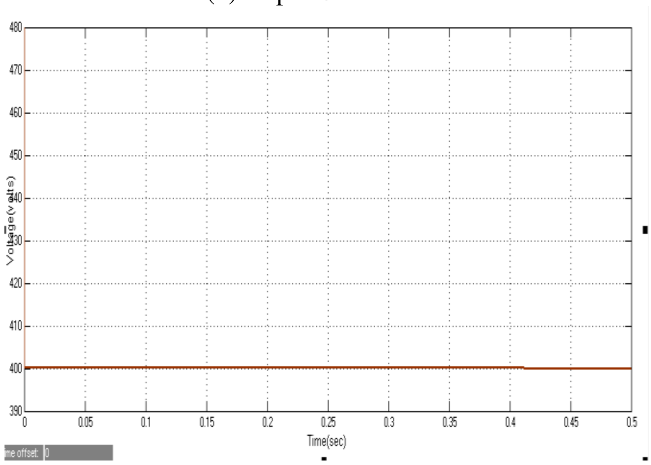
Similarly, Fig.7 shows the simulation result of the proposed converter configuration with an output voltage of 250V which reaches almost near to the peak of input voltage. The role for operation of the buck converter reduces near the peak voltages giving more operation time for the boost mode.



(a) Input Voltage



(b) Input Current



(c) Output Current

Fig. 8: Simulation results of converter with 400 V output voltage

Fig.8 shows the simulation results of converter with output voltage of 400, which is greater than peak of input voltage. The input current observed from the above waveforms Fig.6.2 to 6.4 shows the smooth operation providing a high power factor.

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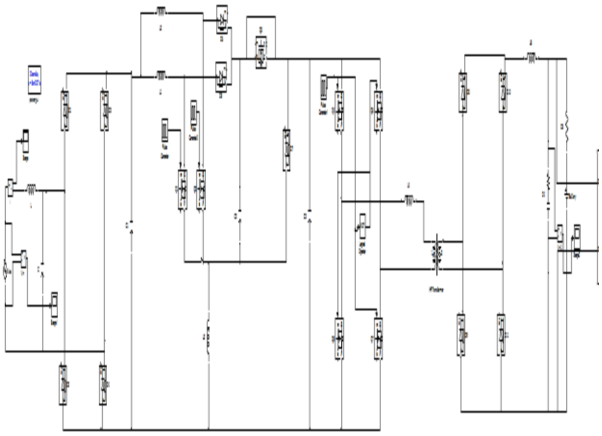

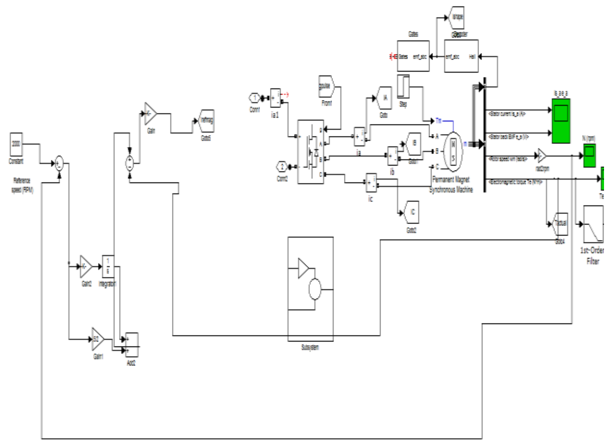

Fig 9 Simulink Diagram of BLDC Motor connected proposed converter

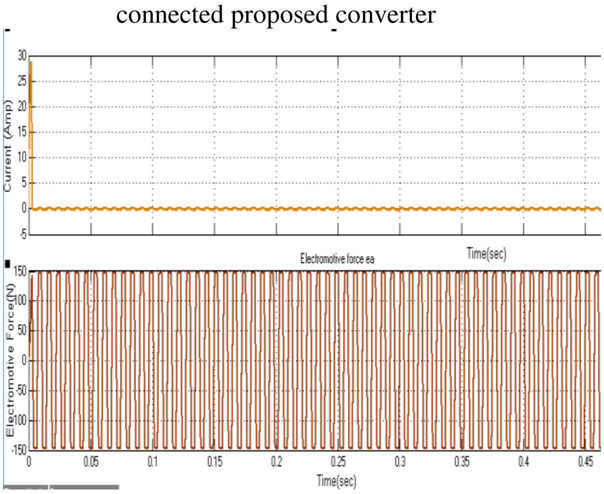

Fig.10 BLDC Motor Drive Stator Current Characteristics of Proposed Converter

Fig.10 shows the simulation results of converter with BLDC Motor Drive Stator Current Characteristics.

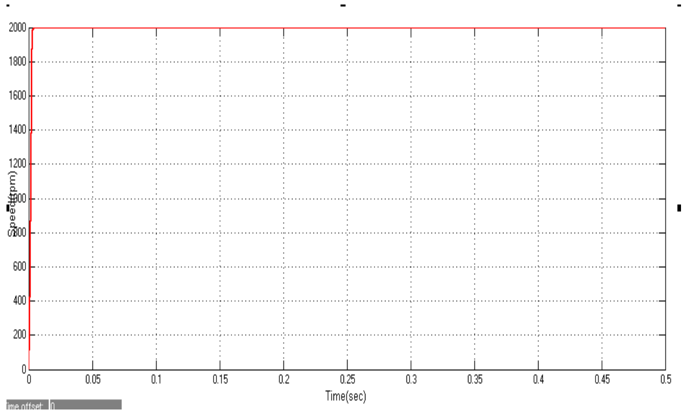

Fig.11 BLDC Motor Drive Speed Characteristics of Proposed Converter

Fig.11shows the simulation results of converter with BLDC Motor Drive Speed Characteristics.

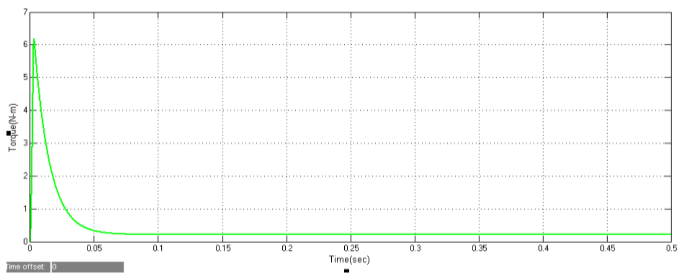

Fig.12 BLDC Motor Drive Torque Characteristics of Proposed Converter

Fig.12 shows the simulation results of converter with BLDC Motor Drive Torque Characteristics.

6.CONCLUSION

This paper proposes a new interleaved boost cascaded by-buck PFC converter for on-board battery chargers. The proposed PFC converters operates with wide output voltages for universal input voltages. The various modes of operation of the converter are detailed in the paper. Moreover, the converter is operated above and below the peak of the input voltage to provide a wide DC link voltage with smooth input current. The design considerations and the control loop to achieve the wide output voltages is also discussed in the paper. The prototype build of the proposed converter achieves high input power factor of 0.99 and able to operate with both buck and boost modes of operation. The proposed PFC converter is cascaded to a phase shifted DC-DC converter to form a two-stage layout of the battery charger which is simulated and the results are presented to validate the concept of achieving wide output battery voltages with reduced voltage and current ripple.

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