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Research Article

Design and Implementation of Three Level Interleaved Boost Converter for High Voltage Applications

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Abstract

In this paper presents implementation of high-efficiency non-isolated three-stage interleaved soft switching boost converter on-board battery charger (OBC) for high voltage applications. A suitable circuit structure is determined to charge a battery in a wide spectrum of input and output conditions. The input voltage is rectified from AC to DC then DC voltage is boosted using three phases interleaved cascade boost converter. Reviewing the comparing circuit topologies, the two phases interleaved cascade buck-boost converter having buck unit and boost unit. The buck converter switches are connected in series and the boost converter switches are connected in parallel on the circuit. In this paper we have use only boost converter, so not having isolation problems. A detailed theoretical analysis, operating strategy, simulation and hardware results are presented in order to evaluate the performance of the system.

Keywords: Interleaved Cascade boost converter; Electric vehicles; Nonisolation; On-board battery charger.

Introduction

Some of major cities in the world such as Paris, London, Seoul and California, formulates a policy and encourages popularizing an eco-friendly for high voltage application [1,2]. In order to speed up its commercial launching in the market, it is necessary to obtain a high-efficiency battery and its charger technology, which is the key power source of the vehicles. Among of various batteries, like Nickel Metal Hydride (Ni-MH), Lithium-Ion (Li-Ion) and Li-Polymer batteries, Li-Ion is mostly being used to have better energy density, efficiency, safety and cost, and the batteries performances are improving. For the battery charger [3], two different types of charger are considered, that is, a high speed battery charger with large-capacity (>50 kW) and a on-board battery charger (3.3 kW) that can be used in house electricity, which charges a battery using residential power source (from 3.3 to 6.6 kW). The OBC has to be small and light since it is implemented in vehicles. In addition, the OBC is also required for variable voltage control in a wide range of the battery voltage, i.e., from about 200–450 V [3,4].

Rechargeable batteries are extensively applied in various applications such as cellular phones, laptop computers, uninterruptible power supplies, electrical vehicles, renewable energy storage systems and others. Such equipment continuously consumes electrical energy and they require a charging circuit in a rechargeable battery. For several years, most battery chargers available on the market were of linear-mode converters, in which an active power element regulates the output voltage. A linear-mode converter with an active power element is generally used as a variable resistance to dissipate unwanted or excess voltage [4,13]. Such an arrangement results in the dissipation of large amounts of power in the active power element, potentially reducing the charging efficiency to as low as 50%. The basic requirements of battery charger circuits are smallness and high efficiency. Their low efficiency has therefore prevented linear-mode converters from being applied to battery chargers, and since the early 1970s, the uptake of

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switch-mode power converters have been increasing.

Unlike linear-mode converters, switch mode power converters use active power switches to operate in either the saturation region or the cut off region. Since either region will lead to a low switching voltage or a low switching current, power can be converted with higher efficiency using a switch-mode power converter as a battery charger circuit [8,12]. “Implementation and analysis of improved series-loaded Resonant DC-DC converter operating above Resonance for battery chargers” The switching frequency of the improved series-loaded resonant battery charger was at continuous conduction mode switching elements of the converter are ideal such that the decline in forward voltage in the on-state resistance of the switch is negligible. “An Integrated On-board Charger with Direct Grid Connection for Battery Electrical Vehicle” The electrical machine and the filter capacity can be performed to discuss the packaging issues of the concept introduced. In this case the traction voltage source inverter with the maximal blocking voltage of 600 V is not applicable, but IGBTs with a blocking voltage of 1200 V. Implementation of high-efficiency non-isolated three-stage interleaved soft switching boost converter on-board battery charger (OBC) for high voltage applications.

A suitable circuit structure is determined to charge a battery in a wide spectrum of input and output conditions. The input voltage is rectified from AC to DC then DC voltage is boosted using three phases interleaved cascade boost converter. Reviewing the comparing circuit topologies, the two phases interleaved cascade buck-boost converter having buck unit and boost unit. The buck converter switches are connected in series and the boost converter switches are connected in parallel on the circuit. In this paper we have use only boost converter, so not having isolation problems. A detailed theoretical analysis, operating strategy, simulation and hardware results are presented in order to evaluate the performance of the system.

There are many types of charging circuit in dc–dc converters, which are applied to various industrial applications. In order to charge a battery, the output voltage also varies widely. Moreover, the input of the OBC is supplied from a residential line, so the unity power factor (PF) regulations have to be satisfied [9,13]. Based on these requirements, a comparison of the circuit isolation and topologies are reviewed for application to the OBC with the specifications in Table 1. Nevertheless, a single-stage structure with transformer has been a common rule in OBC design. Furthermore, there is no electrical reason that the battery should be isolated from ac input power, because its ground is generally floating with the body ground of the vehicle.

Table 2. System Specifications and Parameter of OBC

Parameter	Value [unit]
Maximum Input	120[v_{rms}]
Minimum Input	80[V_{rms}]
Input voltage	50[H_Z]
Output Power Range	8000-
Input Current Range	9 – 12 [A_{rms}]
Output Voltage Range	370 –
Output Current Range	0 – 20 [A_{dc}]
Charging method	CC-CV
Inductance	1.44Ω
Capacitance	4.6mH

Moreover, other power conversion units connected to the high voltage battery are deactivated when the OBC transmits power to the battery. In terms of safety, a relay added on the output can be substituted for the roles of transformers in isolated topologies. Hence, a high-efficiency nonisolated three-stage OBC is reasonable. This type of OBC features strong points of decreasing losses and volume, since the transformer that affects the efficiency and power density can be removed. The nonisolation type is very desirable for the OBC when considering efficiency, volume, and cost. However, till now, few studies have been conducted to apply nonisolation topologies to the OBC because there are some difficulties in implementing wide-range input and output conditions, and with power capacity. In the charging circuits, five methods compared that is buck, boost, buck-boost, cuk, and sepic converter, but most suitable in this project is boost converter, so in this paper, we choosen boost converter for this work.The design of a highly efficient nonisolated three-stage OBC for EVs is presented, and the verification of the charging performance is provided. A discussion is also presented for the selection of topology by reviewing the efficiency and power density of circuit. Based on the results of the review, the structure and the operational principles of the paper are described. Then, the possible operation modes in the boost structure are given. By considering available modes in the input and output conditions for charging a battery, the control strategies are also provided. Finally, the performance of the boost OBC is evaluated, through simulation data by comparing with the five circuits charging OBC. For these reasons, previous research has been performed with the following considerations [5,9]. High-frequency switching control is applied to the OBC for small volume and light weight using transformer, both step-up operations are realized to satisfy the wide input and output voltage range requirements. Zero-voltage-switching (ZVS) technique using resonant converter topologies such as series resonant converter (SRC) or LLC resonant converter are mainly regarded for reducing switching losses [4,6].

In order to achieve high efficiency, nonisolated topologies by eliminating a stage with the high-frequency transformer are more reasonable. In the point of view of the number of elements, isolated topologies need much more components than nonisolated topologies. In addition, the transformer and additional elements are directly connected with increasing the space and cost of the total system. The output voltage should be stably controlled for a wide input-voltage range the input current should comply with the standards of the unity PF, High-frequency switching control should be applied to the OBC for small volume and light weight, Simple or verified structure to ensure reliability is needed according to these technical requirements. Table 2, summarizes the characteristics of each topology [7,11].

Table 1. Summarized Characteristics of Circuit Charging

Topology	Feature	PF	Galvanic Isolation	Number of Elements	Total Stages
Boost PFC+ SRC	-Low Ripple of the output -Switching frequency of wide –ranging variation -Susceptive to the variation of output impedance	High	Isolated	S : 5/D : 5 C : 3/L : 2 T : 1	2
Boost PFC+ PSFB	- Low Ripple of the output - Low efficiency under light load condition	High	Isolated	S : 5/D : 5 C : 2/L : 3 T : 1	2
Cuk (with PFC)	-small Size of input and output filter -High voltage stress (V_{in}+V_{out}) and high current stress (I_{L1}+I_{L2}) on switching devices -Reversed ground polarity between the input and the output -Line frequency ripple on the output	High	Non isolated	S : 1/D : 1 C : 2/L : 2 T : 0	1
Sepic (with PFC)	-High performance of PF - High voltage stress (V_{in}+V_{out}) on switching devices -Susceptive to parameters and thermal condition -Line frequency ripple on the output	High	Non isolated	S : 1/D : 1 C : 2/L : 2 T : 0	2
Buck-Boost (with PFC)	-High voltage stress (V_{in}+V_{out}) on switching devices - Reversed ground polarity between the input and the output -Discontinuous input current -Line frequency ripple on the output	High	Non isolated	S : 1/D : 1 C : 1/L : 2 T : 0	2
Interleaved Boost (with PFC)	- To increase power factor -To increase the battery efficiency -To reduce switching losses -To increase current and maintaining temperature	High	Non isolated	S : 3/D : 3 C : 1/L : 3 T : 0	2

S: switch, D: diode, C: capacitor, L: inductor, T: transformer

Therefore, the nonisolated topologies which can perform step-down/step-up and compensate PF in single stage are considerable to attain high-efficiency and high-power density. Although it needs two additional semiconductors switching devices, this topology has the same polarity of the input and the output and lower voltage stress than other nonisolated topologies. There has been no application of cascade boost circuits in the OBC, which has wide-band input and output ranges. Therefore, it is necessary to establish a strategy for the implementation and operation of cascade boost converter with theoretical analysis.

Nonisolated Three-Stage On-Board Battery Charger

Boost converters are popularly employed in equipments for different applications. For high-power-factor requirements, boost converters are the most popular candidates, especially for applications with dc bus voltage much higher than line input. Boost converters are usually applied as pre regulators or even integrated with the latter-stage circuits or rectifiers into single-stage circuits [7]. Most renewable power sources, such as photovoltaic power systems and fuel cells, have quite low-voltage output and require series connection or a voltage booster to provide enough voltage output. Several soft-switching techniques, gaining the features of zero-voltage switching (ZVS) or zero-current switching (ZCS) for dc/dc converters, have been proposed to substantially reduce switching losses, and hence, attain high efficiency at increased frequencies. There are many resonant or quasi-resonant converters with the advantages of ZVS or ZCS presented earlier. The main problem with these kinds of converters is that the voltage stresses on the power switches are too high in the resonant converters, especially for the high-input dc-voltage applications. Passive snubbers achieving ZVS are attractive, since no extra active switches are needed, and therefore, feature a simpler control scheme and lower cost. However, the circuit topology is complicated and not easy to analyze. Auxiliary active snubbers are also developed to reduce switching losses. These snubbers have additional circuits to gate the auxiliary switch and synchronize with the main switch. Besides, they have an important role in restraining the switching loss in the auxiliary switch Converters with interleaved operation are fascinating techniques. Interleaved boost converters are applied as power-factor-correction front ends. An interleaved converter with a coupled winding is proposed to provide a lossless clamp. Additional active switches are also appended to provide soft-switching characteristics.

Converter composed of two shunted elementary boost conversion output ripple. This paper proposes a soft-switching interleaved boost these converters are able to provide higher output power and lower units and an auxiliary inductor. This converter is able to turn on both the active power switches at zero voltage to reduce their switching losses and evidently raise the conversion efficiency.

The rated input voltages are 80 to 120V rms with the frequency range from 50 Hz in accordance with the universal specifications of single-phase line input for industrial applications. As the OBC system is based on residential power sources, the upper limit of the input current should be less than 12A rms. According to these conditions, the rated power of the OBC is set to 3.7 kW. Considering the charging range of a Li-ion battery, the output voltage is able to vary from 370 to 570V dc. From this specification, previous topologies should be reviewed to satisfy the requirements for the OBC. Topologies are determined by evaluating the suitability to attain high-efficiency and high-power density, which are essential factors for the OBC system. The resonant switch is said to operate in half-wave mode. If a diode is connected in anti-parallel with the unidirectional switch, the switch current can flow in both directions. In this case, the resonant switch can operate in full-wave mode. At turn-on, the switch current will rise slowly from zero. Finally, the switch can be commutated at the next zero current duration. The objective of this type of switch is to shape the switch current waveform during conduction time in order to create a zero-current condition for the switch to turn off.

Circuit Description

In the paper, AC voltage is given in the circuit the AC voltage is converted into DC using diode rectifier. This output has ripples. It is filtered with a help of Capacitor filters. The DC voltage is entered into interleaved boost conveter, simultaneously each switch can turn on the 60’ interval. diode is used to the current didn’t come in reverse direction. Pi filter is reduce ripple in the output voltage.the output has DC output votlage. It is used to run the motor, battery charging, high voltage application and telecommunication applications. The paper having two techniques can be used, soft switching and PWM techniques. The output voltage control with this method can be obtained without any additional components with this method; lower order harmonics can be eliminated or minimized along with its output voltage control. As higher order harmonics can be filtered easily, the filtering requirements are minimized The lower order harmonics can be eliminated or reduced by selecting the number of pulses per cycle however increasing the number of pulses would also increase the magnitude of higher order harmonics, which could easily be filtered out. The nonisolated topologies shown in Table 1 have some problems, which are reversal of the ground between the input and the output, and additional passive components, to attach on the OBC. In addition, these topologies have extra problems with the high-voltage stress of each component, because semiconductor switches (including diodes) should tolerate the summation of the input voltage and the output voltage during the operation.

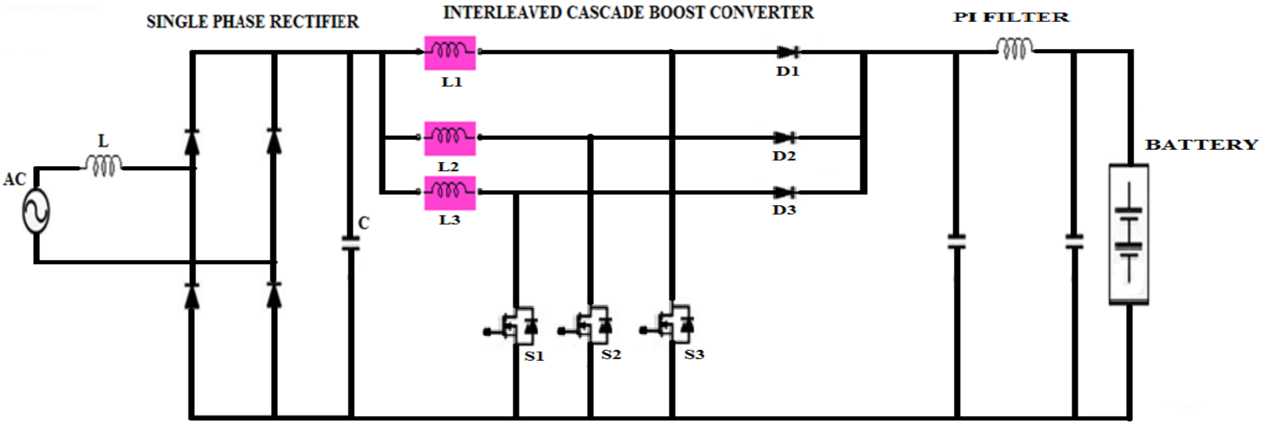

Fig. 1. Configuration of the interleaved boost converter circuit diagram

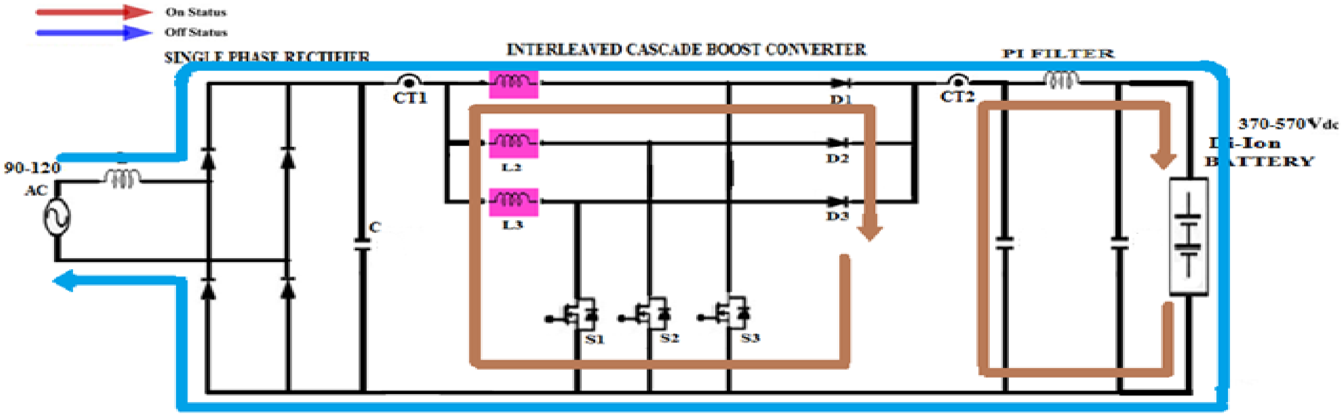

Fig. 2. Operational principle

The proposed system consists of a series connected single-phase rectifier, parallel connected boost unit with a three-phase interleaved method for achieving high efficiency and reducing current ripple of the input and the output by dividing the input current.

Operational Principle

In boost-operation mode, the output voltage is greater than the rectified input voltage. Cascade mode operates in both conditions of the input and the output, including the state that the input voltage is similar to the output voltage [8,10]. In three modes, PFC is feasibly operated in the continuous conduction mode for high-power capacity of the OBC. It is desirable to make a practically sinusoidal input current, in the same phase as the line voltage. Furthermore, the output voltage is controlled according to the demand of the battery while the unity PF is corrected. In addition, the proposed circuit has the following advantages compared with the other nonisolated dc–dc converters. The input and the output have the same polarity. Voltage stress on semiconductor switching devices is less than that in other charging topologies. The stability of operation is better than that in other topologies due to the potential of sharing inductor. The basic operational principle of the proposed non isolated OBC .Switches in the boost units of the cascade boost converter execute step up by synchronous switching. When switches are on, the input supplies energy to the inductor with power flow. When the switches are off, the output stage receives energy from the inductor.

Consequently, the input current of an ordinary Cascade boost converter becomes discontinuous due to the switch in the unit. During interleaved control, the switch of the other phase is conducted when the switch turns off. Therefore, the power flow according to the switching operation is the same as in a conventional boost converter. Based on this principle, the voltage gain of the input and output can be expressed as follows:

$$i_{L,on} = \frac{1}{L}\int_0^t V_{in}\,dt + I_{min} \qquad (1)$$

$$i_{L,off} = \frac{1}{L}\int_{DT}^t (-V_{out})\,dt + I_{max} \qquad (2)$$

$$I_{max} - I_{min} = \frac{V_{in}}{L}\,.\,DT \qquad (3)$$

$$I_{min} - I_{max} = \frac{-V_{out}}{L}\,.\,(1-D)T \qquad (4)$$

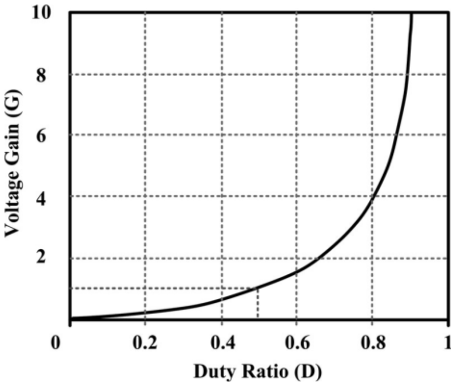

Fig. 3. Voltage transfer gain against duty ratio

In addition, the final converter gain according to duty ratio is perfectly the boost converter. However, the change of the voltage gain is sensitive, more than twice as sensitive compared with a conventional buck or boost converter. In other words, the control precision decreases by half. Therefore, the charging voltage of the battery is controlled in the variation of duty ratio from 0.42 to 0.782, to control the output voltage from 360 to 570V dc within the full range of line input. In PFC, the low frequency from the line input is reflected in the ripple of the output. Thus, the capacity of dc-link capacitor has to be big enough for the regulation performance of the charging voltage.

$$\Delta i_{L,max\ \_boost} = \frac{V_{in,max}\,D_{max}}{L_{min} f_s} \qquad (5)$$

$$\Delta i_{L,max\ \_cascade} = \frac{V_{out,max}(1 - D_{avg,min})}{L_{min} f_s} \qquad (6)$$

For the CCM over the full spectrum of the input and output conditions, the minimum inductances are

$$L_{min\ \_boost} = \frac{P_{o,max} D_{avg,max}}{2I_{out,min}^2 f_{sw}} \qquad (7)$$

$$L_{min,cascade} = \frac{(1-D_{avg,min})^2 P_{o,max}}{2I_{out,min}^2\, f_{sw}} \qquad (8)$$

Therefore, the inductance for cascade mode, which is the biggest one between both modes, is chosen for the total system. For the stable CCM performance in the worst case, the final designed inductance with 10% margin is set to 800μH. Then, the material and size of the core are decided according to following design criteria: The number of turns with consideration of core type should fit into a provided space the temperature rise caused by the copper loss and core loss should be maintained below the thermal limitations the area of the core can be reduced by laminating of cores the final designed inductors are made up of “high flux” which has good dc bias characteristics.

Results and Discussion

As described in the above section one approach of maximizing the functionalities of the system components is to replace the on-board charger according to the current state of technology by integrating the voltage source inverter of the traction operation into the charging operation for the traction battery and thus the performance of the traction system during the charging operation a simulation model is built with MATLAB/SIMULINK and PLECS. Based on the design tradeoffs, the total system is divided into a power circuit and a control circuit. For decreasing the volume of the OBC, both circuits are constructed with two level structures. On the first level, the power circuit is located on a heat sink. Above the power circuit, the control circuit is placed with auxiliary power. Under the power board, the semiconductor switching devices are in contact with the heat sink to improve the thermal characteristics of the proposed OBC.

The power circuit, includes an EMI filter to reduce switching noise toward the line input, a relay is applied to the recharging circuit to protect the in-rush current from the input to the battery. In addition, the main power delivery path employs three-phase interleaving to enhance the efficiency and performance of the proposed OBC. It indicates the waveforms of each mode in accordance with the full spectrum of the input and output. The input conditions are based on the rated input voltages of 80 to 120V rms. The operating waveforms with the outputs 370 and 560V dc when the input voltage is 120V rms (boost-operation mode). The waveforms of the output power 10,000 watts respectively (Fig. 4 to 8).

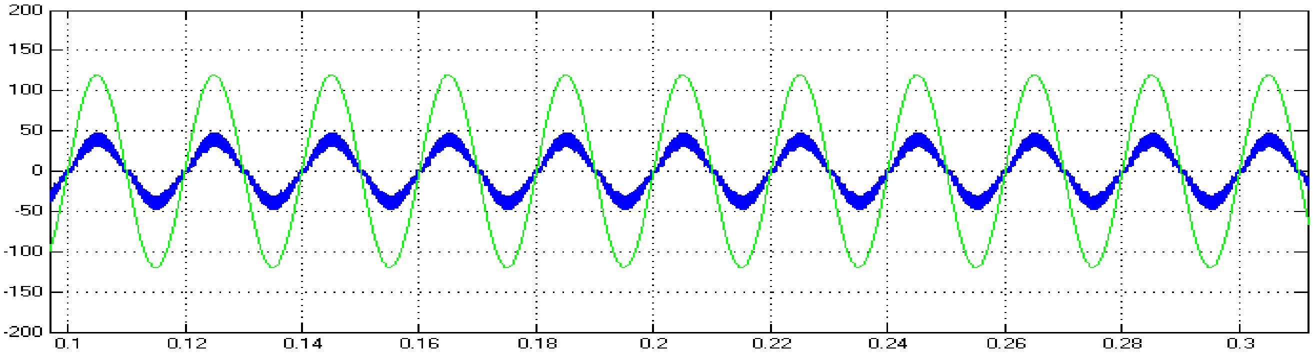

Fig. 4. Input voltage and current

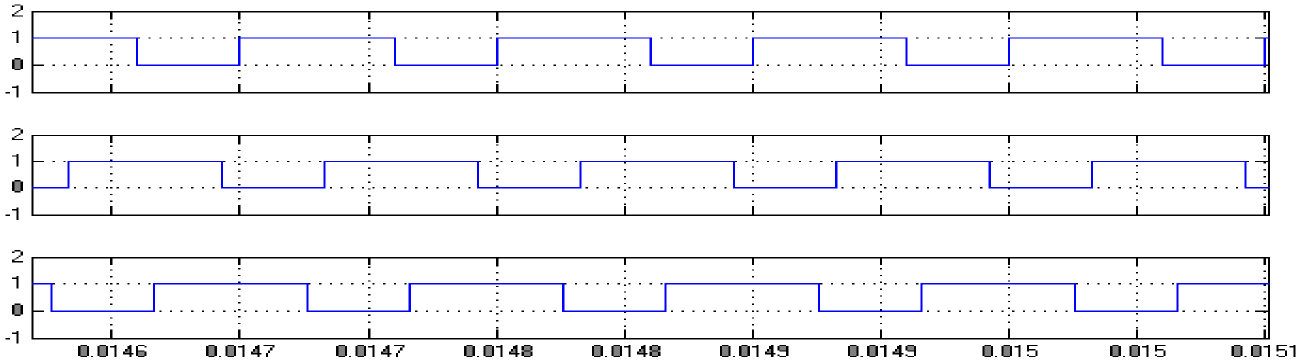

Fig. 5. Switching pluses

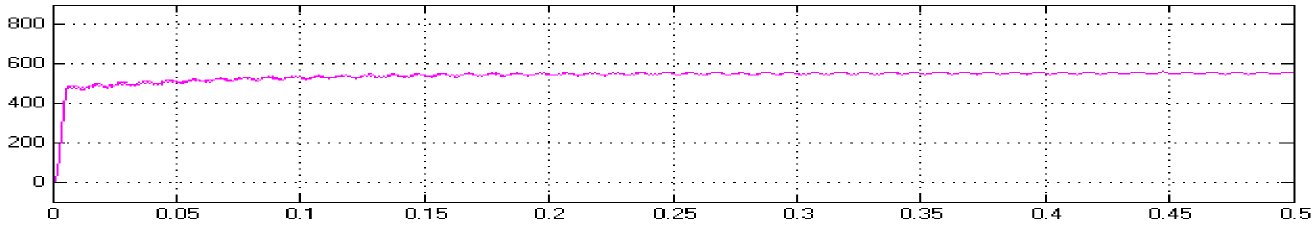

Fig. 6. Output Voltage

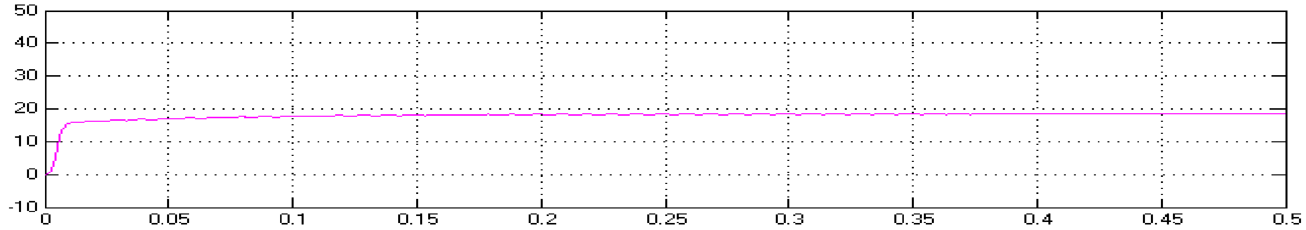

Fig. 7. Output Current

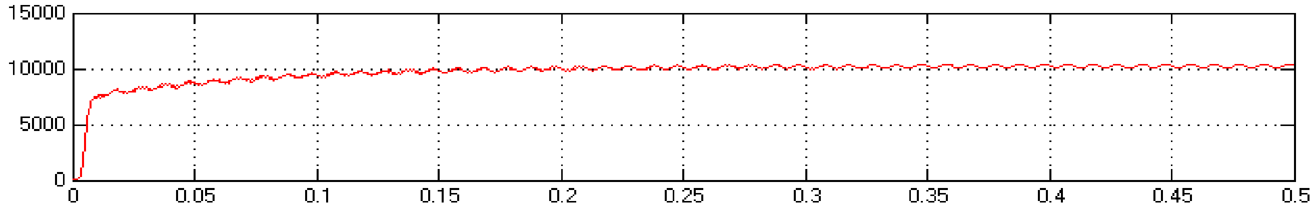

Fig. 8. Output Power

Experimental Verification

In order to verify the effectiveness of proposed converter, prototype is built and tested. The specifications of the tested converter are listed in Table 1. The experimental results of the Three phase interleaved boost converter and the proposed converter are shown. The duty cycle of each converter is about 0.5.Therefore, the proposed converter is able to minimize the output voltage ripple and also output current ripple.

Fig. 9. Experiment result of interleaved soft switching boost converter

Conclusions

The design and implementation of a nonisolated OBC for high voltage application has been presented, with focus placed on a minimal total size and improved efficiency, as the main requirements for eco-friendly used battery, vehicle, DC drives, Telecommunation. For the design of this system, an overview of conventional topologies has been discussed, for application to the OBC. For achieving the targeted high- power density and high efficiency, a nonisolated cascade boost converter has been selected. The theoretical operation of the proposed OBC has been analyzed in detail. According to the design considerations of the OBC and the results of the analysis, a sequential control strategy is determined in the full spectrum of the input and output conditions. The proposed system was verified simulation try to achieving 87% efficiency and PF of 0.94. The advantages of the proposed OBC can be summarized as follows. The number of components is less than conventional OBC high-power density and high efficiency is obtained by the three-stage structure without the high-frequency transformer.

Conflict of interest

Authors declare there are no conflicts of interest.

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