New Single-stage Interleaved Totem-pole AC-DC Converter for Bidirectional On-board Charger

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ABSTRACT

In this paper a new single-stage ac-dc converter with high frequency isolation and low components count is introduced. The proposed converter is constructed using two interleaved boost circuits in the grid side and non-regulating full bridge in the DC side. An optimized switching is implemented on the two interleaved boost circuits resulting in a ripple-free grid current without a ripple cancellation network; hence very small filter inductors are used. A simple and reliable closed-loop control system is easily implemented, since the phase-shift angle is the only independent variable. Moreover, current imbalance is avoided in the presented topology without current control loop in each phase. The proposed charger charges the battery with a sinusoidal-like current instead of a constant direct current. ZVS turn on of all switches is achieved throughout the operation in both directions of power flow without any additional components.

1. Introduction

In recent years, great attention is paid to plug-in electric vehicle (PEV) due to the increased fossil-fuel cost and greenhouse gas emissions. Despite the great development of EV, battery charging remains always a challenge that hinder its wide spread.
EV chargers are two types: onboard type and off-board type. The off-board chargers are capable of charging an EV battery fully in short time since they are of high power ratings [1]. However, these fast chargers might be limited by the infrastructure requirements as petrol stations. In the other hand, on-board chargers that is built in the EV offer other alternative to the fast chargers. It worthy to mention that on-board chargers add more components that have an impact on the vehicle cost, weight, and volume [2].
On-board chargers are ac/dc converters that offer the following requirements: 1) single-stage power conversion with reduced passive components count; 2) bidirectional power flow; 3) pushing for high frequency of operation, high power density, and high efficiency; 4) isolation and voltage matching; and 5) simple active power control.
Usually ac/dc converters for on-board charging are two stages made of an active front-end rectifier followed by a high frequency isolated DAB [3]. The mentioned configuration is partially soft switched and uses more passive component of large sizes. Hence efficiency, reliability, and power density are decreased. In order to overcome aforementioned problems, single-stage isolated bidirectional topologies have gained special attention [4].
Several single stage solutions for On-board EV chargers were introduced in the literature [5-9]. Full bridge type topologies somewhat meet the earlier mentioned on-board charging requirements; and provide better power density since boost cell in the PFC stage is eliminated [5]. However, DAB can't get rid of the bulky DC electrolytic capacitor between the rectifying and DC/DC
stages. Decreasing the volume of the DC-link threaten the soft-switching range of the converter.
Current-fed topologies are good alternative to decrease the size of capacitance [6]. However, these topologies require a clamping circuits or snubbers in order to prevent voltage spike attributed to the leakage and input inductances [7].
Authors in [8-9] have considered Matrix type topologies for single stage on-board charging for the purpose of eliminating front-end diode rectifier. However, clamping is still an issue for unidirectional topologies; but Matrix converters based AC/DC with active secondary side shows good performance without snubbers or clamping circuit. Moreover, matrix converters that suffer from large number of switching device doesn't guarantee soft-switching throughout all the varying AC input.
The totem-pole boost bridgeless PFC rectifiers provide some attracting features such as: simplicity; no CM interference problem, since the output is clamped to the input by slow diodes or switches for each grid half-cycle [10]. Moreover, Totempole PFC rectifiers have the potential capacity for bidirectional power flow. Further improvements in terms of input current quality and switching device current rating by interleaving two boos converters in [11]. Unfortunately, all Totempole PFC rectifiers introduced in the literature lack one of main OBCs requirement which is isolation.

2. Proposed Topology

Fig. 1 shows the power circuit of the proposed interleaved bidirectional AC/DC converter. In the grid side, two interleaved boost circuits are connected in parallel.
Lg1 and Lg2 are of the same inductance; and Cc is a small clamp film capacitor. The ac inductor L_k represents the sum of the external
inductances and the high frequency transformer leakage inductance.

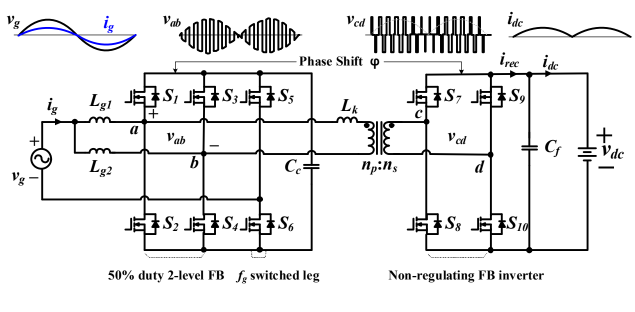

Fig. 1. Proposed bidirectional interleaved AC/DC Converter.

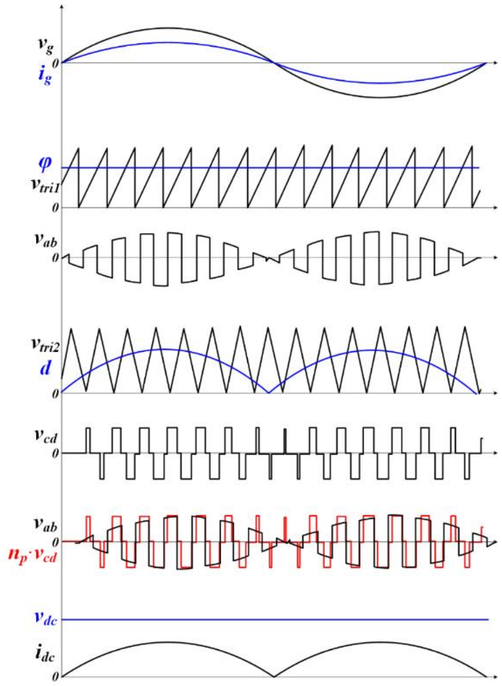

Fig. 2. Operating waveforms for grid period f_g.

Switches S_1~ S_4 are switched at 50% duty whereas S5 and S6 are switched at the grid frequency. Hence the primary-side voltage of the transformer is a two-level waveform. It is worthy to mention that switching two-phase interleaved boost converter at 0.5 duty cancel the ripple at grid current. As a result, a ripple-free grid current is drawn without a ripple cancellation network.

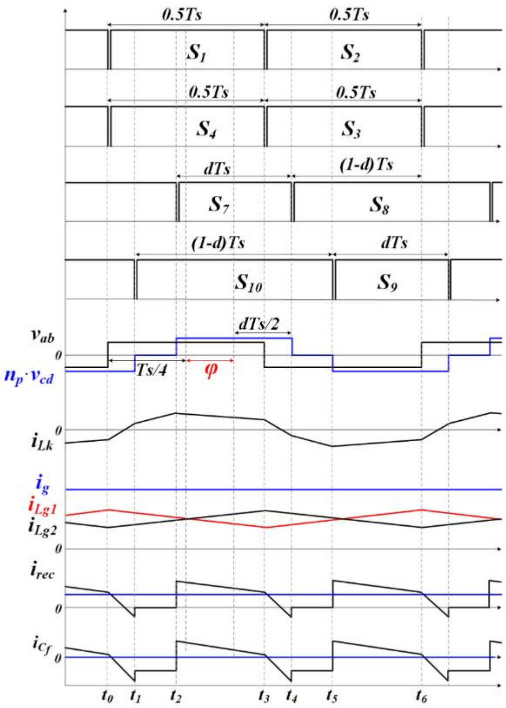

Fig. 3. Operating waveforms for switching period Ts.

Since the grid frequency is considerably small in comparison with switching frequency; the switching loss of S_5 and S_6 can be neglected in practice; and low conduction loss devices like IGBT can be used. The dc-side H-Bridge applies a voltage pulse to the secondary of the transformer in which the width of the pulse is set by the duty ratio d, defined as follows:

$$d = k\left|sin\left(2\pi f_g t\right)\right| \tag{1}$$

Where k ϵ]0,1]. Therefore, the secondary-side voltage of the transformer becomes a three-level waveform. The active power P is varied according to the phase-shift angle φ between the primary side and secondary side. Fig. 2 and Fig. 3 illustrates the operating principles of the proposed charger.

The battery voltage v_{dc} and grid current are fed back to the controller. The implemented controller maintains sinusoidal current that meet the grids' requirements. As depicted in fig. 4; for the current control loop an all-pass filter is required in order to generate the β-axis component of the grid current. Additionally, a phase-locked loop (PLL) is used to get the grid current and voltage synchronized. There is no control loop for q component of grid current since the displacement angle between the grid current and voltage is inherently kept zero. The transferred power is given in equation (2).

$$p(t) = \frac{\left(4\varphi^2 + d^2 - 2\varphi - d + 0.25\right) n \cdot v_{dc} \cdot \left|v_g\right|}{f_s \cdot L_k} \tag{2}$$

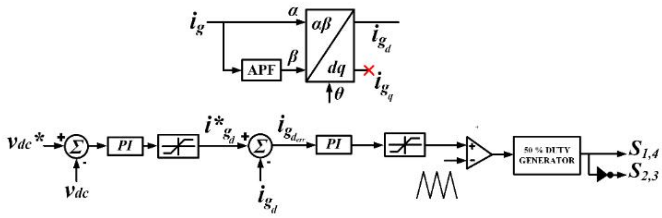

Fig. 4. Controller block diagram.

3. Results and Discussions

A sinusoidal grid current is injected with very high power factor as depicted in Fig. 5. The proposed charger maintains balanced currents with interleaving effect on the input side. The switching characteristics in Fig. 6 shows that the ZVS turn on is achieved for all switches.

The voltages applied to both transformer sides are low-frequency-harmonics free. Therefore, a high frequency transformer of light weight is utilized.

Table 1. Comparison of the proposed charger with other counterparts

	Topology proposed in [8]	Topology proposed in [9]	Proposed topology
Charging method	Sinusoidal	Sinusoidal	Sinusoidal
Number of switches	12	12	8
Soft-	Unguaranteed	Unguaranteed	Fully soft-

switching			switched
Controller	Open-loop	Complex	Simple
Filter size	Small	Small	smaller

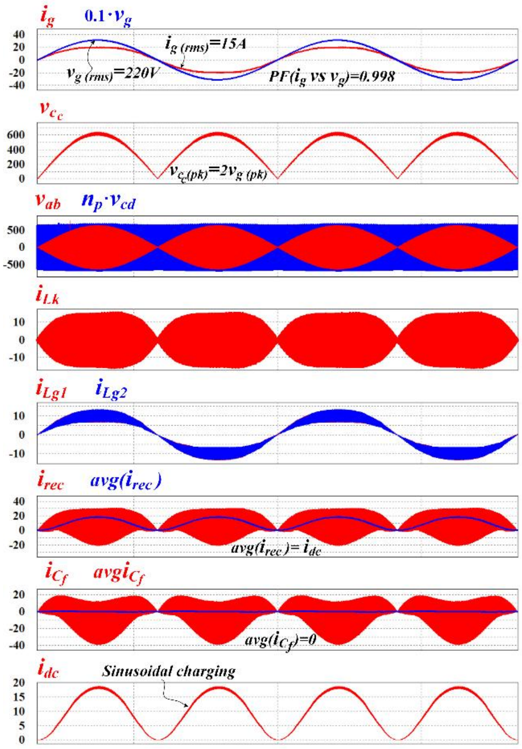

Fig. 5. Key waveforms of the proposed converter

In Table 1 two single stage chargers introduced in [8] and [9] are considered and compared with the introduced converter in terms of methodology of control, soft-switching range and filter size.

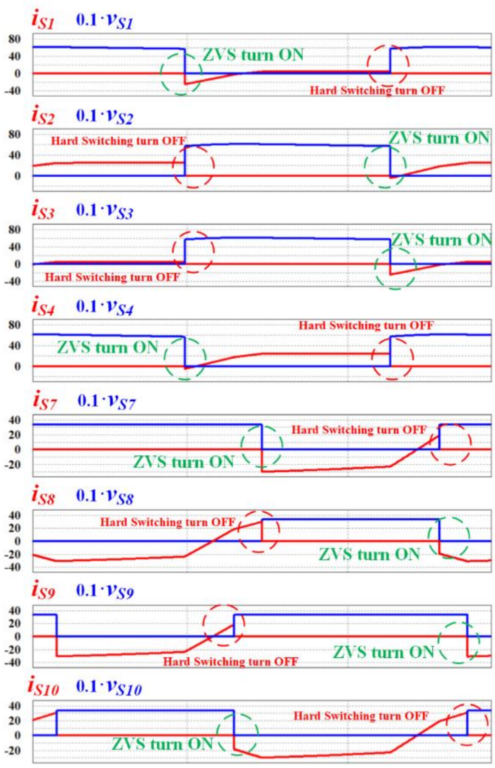

Fig. 6. Switching characteristics

4. Conclusion

In this paper a new single-stage ac-dc converter with high frequency isolation and lower component count is introduced. The adopted switching scheme and the implemented controller on the proposed configuration brought significant advantages in terms of reliability, efficiency and power density on the onboard AC charging.

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