Differential type Single-stage Isolated AC-DC Converter with AC Power Decoupling for EV Battery Charger

알리 타우시프, 김형진, 김재훈, 눌 바누 사흐파자르, 최세완
Seoul National University of Science and Technology

ABSTRACT

In this paper a single-stage single-phase differential type isolated AC-DC converter is proposed. This converter eliminates the requirement to use bulky electrolytic capacitor from the system and at the same time provides DC charging by employing the AC Power Decoupling waveform control method. All the switches of the converter achieve ZVS turn on during half line cycle and all diodes achieve ZCS turn off during entire line cycle. A conventional controller is implemented for PFC control and output regulation, whereas a power decoupling controller is added to compensate 2nd harmonic ripple power. In addition, an interleaving technique is applied to increase the power range of the converter and reduce the input inductor size. In the end simulation verification is performed and results are obtained for 6.6KW.

1. Introduction

With the growing market for EVs, a lot of research is being going on that is mainly focusing on improving the efficiency, reliability and power density of the EV on-board battery chargers. A conventional approach for EV OBC is a two- staged structure which consists of an AC-DC converter for rectification and Power Factor Correction and isolated DC-DC converter for output regulation [1]-[3]. However, the two-staged converter has some disadvantages related to low efficiency and high cost due to increased component count.

A viable and cost effective solution to improve efficiency of the system is to use single stage AC-DC converter. For this reason, several single-stage topologies have been presented in [4] and [5]. But the 2nd harmonic ripple associated with single phase AC-DC converter put tight restriction on using bulky electrolytic capacitors to absorb 2nd harmonic ripple. Hence the reliability of the converter is affected as lifespan of electrolytic capacitor is very short and the power density of the converter is also reduced.

The aforementioned problem is solved by eliminating bulky electrolytic capacitors from the system and using film capacitors instead. Currently, single-stage electrolytic capacitor-less EV chargers are very attractive and hot topic for the research. Several single stage structures have been proposed in [6] and [7]. These single stage chargers are more efficient, reliable and cost effective but poses problems for Li-Ion EV batteries as they charge the battery with sinusoidal charging current which heats the battery and reduces its lifetime.

To overcome this problem several Power Decoupling techniques have been proposed. These techniques have been classified into 2 major categories: 1) AC Power Decoupling, 2) DC Power Decoupling.

One of the good methods for AC Power Decoupling for non-isolated AC-DC converter is discussed in [8]. In this approach no additional semiconductor is used and power decoupling is successfully achieved by using autonomous closed loop controller. Hence, this concept is extended to obtain new isolated AC-DC converter which is suitable for EV on-board battery chargers.

The proposed converter has the following features: 1) Interleaving technique 2) High frequency isolation 3) AC Power Decoupling 4) ZVS turn on of all switches and ZCS turn off al all diodes and 5) Electrolytic capacitor-less system.

2. Proposed Converter

The input grid side of the converter consists of two interleaved current fed converters connected in series. The battery side is isolated by two high frequency transformers which are connected between interleaved legs at the primary side of the converter. Moreover, at the battery side two transformers are connected in parallel through two diode bridge rectifiers to form differential type isolated AC-DC converter as shown in the Fig. 1.

The proposed converter employs AC Power Decoupling waveform control method to store 2nd harmonic ripple power in Decoupling Capacitors C_1 and C_2 at input AC side as shown in Fig. 2.

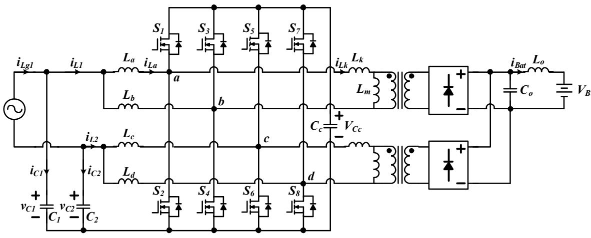

Fig.1 Proposed converter

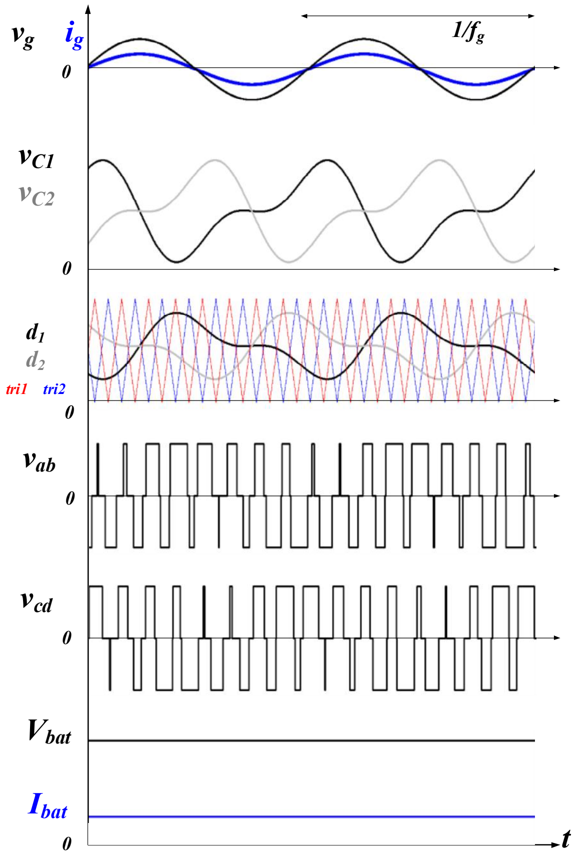

Fig.2 Key waveforms of the proposed converter for grid period

The voltage across decoupling capacitors can be shaped as,

$$v_{c1} = \frac{V_g}{2} sin\omega t \ + \frac{V_{cc}}{2} + V_c sin(2\omega t + \phi\ ) \quad (1)$$

$$v_{c2} = \frac{-V_g}{2} sin\omega t \ + \frac{V_{cc}}{2} + V_c sin(2\omega t + \phi\ ) \quad (2)$$

$$\text{So,} \quad v_{c1} - v_{c2} = v_g = V_g sin\omega t \quad (3)$$

where, V_g is peak grid voltage, v_{cc} is clamping capacitor voltage, V_c and ϕ are load dependent parameters. It is evident from the above equations that although the 2nd harmonic ripple power is stored in the decoupling capacitors in the form of 2nd harmonic voltage component but it doesn't affect the grid voltage.

The modulating signal d_1 is used for leg *a* and leg *b*, however modulating signal d_2 is used for leg *c* and leg *d*. In order to obtain interleaving 180° phase shift is provided between leg *a* and leg *b* and between leg *c* and leg *d*.

During positive half cycle, the switches associated with leg *a* and leg *b* act as a interleaved boost converter and switches associated with leg *c* and leg *d* act as interleaved buck converter. Similarly, opposite is true for the negative half cycle. So, for ease of understanding only positive half cycle waveforms for switching period are provided in Fig. 3.

The proposed converter achieves ZVS turn on for all switches during half line cycle and ZCS turn off of all diodes during entire line cycle. During positive half cycle S_1, S_3, S_6 and S_8 always turn on with ZVS condition while remaining switches turn on with hard switching. Similarly, opposite is true for negative half cycle.

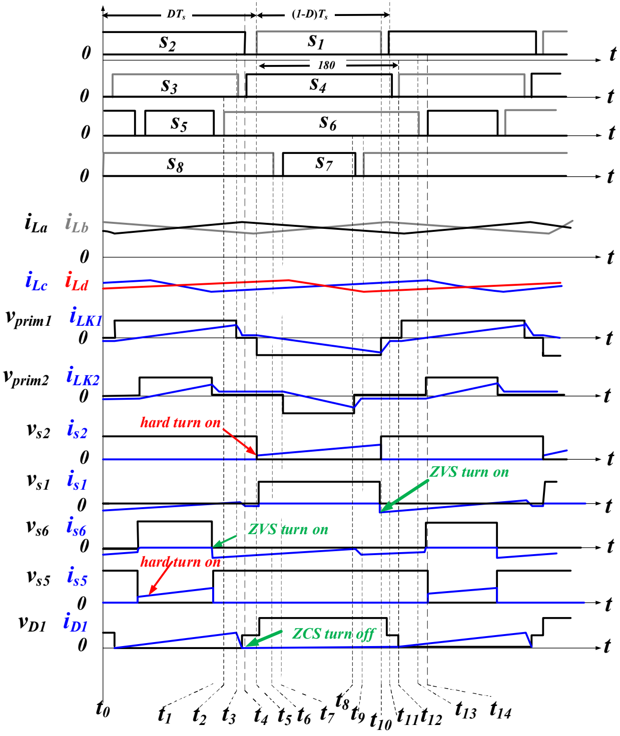

Fig 3 Key waveforms of the proposed converter for switching period

3. Control strategy

The controller for the proposed topology is divided into two parts: Differential Mode Controller and Common Mode Controller. The Differential Mode Controller is responsible for PFC control and output voltage regulation. In this controller, the difference of sensed inductor currents is compared with the reference to generate error which is compensated by inner current loop PI controller. Due to interleaving and nonlinear duty, the inductor current imbalance problem may occur, but it can be resolved by dividing the reference into half and using two separate controllers for each interleaving legs as shown in Fig. 4

In addition to this, Common Mode Power Decoupling Control is applied in which output voltage 2nd harmonic ripple is subtracted from *0* reference to generate error. This error is minimized by using PR controller and 2nd harmonic compensated signal is

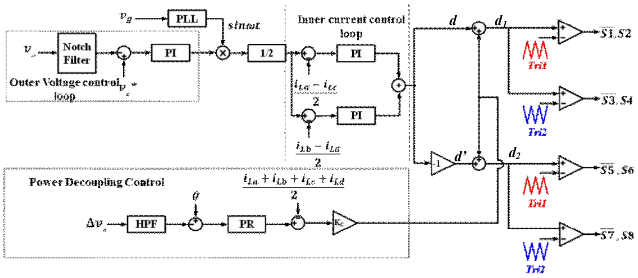

Fig. 4 Controller block diagram

generated.

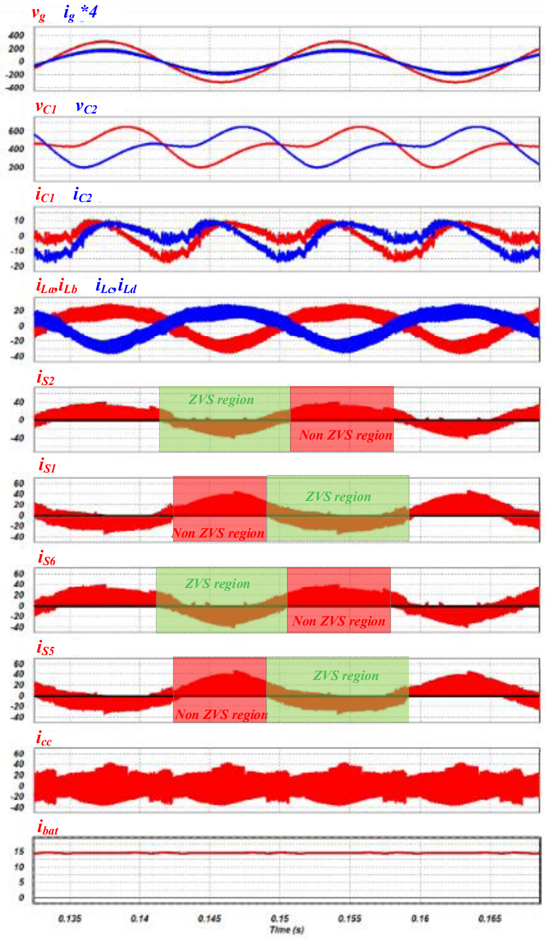

Fig. 5 Simulation waveforms

The compensated signal is the reference signal and it is compared with the sum of all sensed inductor currents. The resulted signal is then fed to the Proportional controller with gain Kc which is added

to the differential mode controller duties *d* and *d'* to obtain final duties d_1 *and* d_2.

4. Results and Discussion

The simulation results are obtained for proposed converter with specifications given in the Table 1.

Table 1. Circuit parameters used in simulation

Output power	P_o	6.6KW
Switching frequency	fs	200KHz
Grid voltage	v_g	220V$_{rms}$
Output voltage	V_o	450V
Input inductors	L_a, L_b, L_c, L_d	60μH
Decoupling Capacitors	C_1, C_2	100μF
Clamping capacitor	C_c	40μF
Output capacitor	C_o	20μF
Turns ratio	n	2

Fig 5. Shows the simulation results for the proposed on-board battery charger simulated for 6.6KW, at grid side PF=0.99 and THD= 5.2% is obtained. Power decoupling control has been successfully applied to obtain 2nd harmonic ripple free battery current (i_{bat}).

Both transformers used for implementation have turns ratio of $n=2$, $L_k=5\mu H$ and $L_m=5mH$. The output battery voltage is kept at 450V, so the clamping capacitor voltage v_{cc} appears to be above 900V. This high voltage occurs because of n which results in high voltage stress on switches, therefore this topology is suitable for 1.2KV *SiC* MOSFETs. All switches achieve ZVS turn on and all diodes achieve ZCS turn off. However, the ZVS range of switches is limited to half line cycle.

5. Conclusion

In this paper a new single stage isolated Differential type AC-DC converter is proposed which is suitable for on-board EV chargers. AC power Decoupling is successfully applied to obtain dc charging and requirement to use bulky electrolytic capacitor is completely eliminated. Hence film capacitors with small capacitance is used to enhance reliability and power density of the converter. The simulation results show the suitability of the proposed converter for the aforementioned application. the ZVS range of switches is limited to half line cycle.

References

[1] F. Musavi, W. Eberle, and W. G. Dunford, “A high-performance single-phase bridgeless interleaved PFC converter for plug-in hybrid electric vehicle battery chargers,” *IEEE Trans. Ind. Appl.,* vol. 47, no. 4, pp. 1833–1843, Jul./Aug. 2011.

[2] Gautam, D., Musavi, F., Edington, M., Eberle, W., Dunford, W.G.: “Anautomotive onboard 3.3-kW battery charger for PHEV application”,*IEEE Trans. Veh. Technol.,* 2012, 61, (8), pp. 3466–3474

[3] B. Whitaker et al., "A High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing Silicon Carbide Power Devices," *in IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2606-2617, May 2014.

[4] J. G. Cho, C. H. Jeong, H. S. Lee, and G. H. Rim, “Novel zero voltage transition current fed full bridge PWM converter for single stage power factor correction,” *IEEE Trans. Power Electron.,* vol. 13, no. 6, pp

[5] P. Das, M. Pahlevaninezhad, and G. Moschopoulos, “Analysis and design of a new AC-DC single-stage full-bridge PWM converter with two controllers,” *IEEE Trans. Power Electron.,* vol. 60, no. 11, pp. 4930-4946, Nov. 2013

[6] Y. D. Yoon, S. M. Kwon and J. Y. Lee, "Single-stage battery charger for light electric vehicles based on DC-SRC with current-boosting circuit," *in Electronics Letters*, vol. 49, no. 16, pp. 1023-1025, Aug. 1 2013.

[7] Byeongwoo Kim, Minjae Kim and S. Choi, "Single-stage electrolytic capacitor-less AC-DC converter with high frequency isolation for EV charger," *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, Hefei, 2016, pp. 234-238.

[8] W. Yao, Y. Tang, X. Zhang, X. Wang, P. C. Loh and F. Blaabjerg, "Power decoupling method for single phase differential buck converter," *2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)*, Seoul, 2015, pp. 2395-2402