Hybrid-Bridge LLC Series Resonant Converter for Deeply Depleted PEV Battery Charging

M. Imran Shahzad, Shahid Iqbal and Soib Taib

Abstract In this paper, a hybrid-bridge LLC series resonant converter with low circulating current and reduced switching losses for on-board battery charging of plug-in electric vehicle (PEV) is presented. Full-bridge (FB) is utilized in LLC converter with narrow range switching frequency within below resonance frequency region for depleted battery charging. To cover the charging voltage range for deeply depleted battery, the converter operates using half-bridge (HB) in both above and below resonance frequency regions. For both modes, the converter uses two fixed voltage levels at input to keep the switching frequency in narrow range. MATAB Simulink is used to simulate the converter with 3 kW maximum output power. Simulation results show that the LLC converter covers the wide charging voltage range 100–420 V for deeply depleted to fully charged battery using the constant-current, constant-voltage (CC-CV) charging, having lower turn-off current of power switches and low circulating current in resonant tank.

Keywords LLC converter · Hybrid-bridge · On-board charger · FHA

1 Introduction

Due to global warming issues and the threat of fossil fuel depletion, the interest is growing in hybrid electric vehicles (PEVs) [1]. These vehicles are usually equipped with lithium-ion (Li-ion) battery packs having many attractive features like high energy density, slow charge loss, and no memory effect [2]. Figure 1 shows a

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M.I. Shahzad (✉) · S. Iqbal · S. Taib
School of Electrical and Electronics Engineering, University Sains Malaysia,
14300 Nibong Tebal, Pulau Pinang, Malaysia
e-mail: ishzd@yahoo.com

S. Iqbal
e-mail: shahidsidu@hotmail.com

S. Taib
e-mail: soibtaib@usm.my

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commonly used power architecture of an on-board PEV battery charger [1] with power factor correction (PFC) and DC/DC conversion stages. Due to its simple structure and good performance for THD reduction, boost converter is commonly used as PFC converter [2].

At DC/DC stage, among different available solutions, LLC resonant converter has become an attractive topology due its desirable features including high efficiency, high power density, wide operation range, and high frequency operation [1]. These features fit the demands of an on-board PEV charger. A topological analyses in [3] shows that among other resonant topologies, the LLC converter out performs for PEV battery charging. This paper is focusing the DC/DC stage of the battery charger in Fig. 1.

A typical charging profile of a single cell lithium-ion battery is shown in Fig. 2 [2]. From this profile, the voltage range of a PEV battery pack can be extracted which maps to the wide range of 100–420 V. The deeply depleted battery have voltage range as 100 V $\leq V_{bat} < 250$ V whereas the depleted battery have voltage range 250 V $\leq V_{bat} \leq$ 420 V. Consequently, the battery charger must be compatible with this wide range [2].

Various battery charging solutions with fixed [1, 4] as well as variable DC-link voltage [2, 5] have been proposed. Both [1] and [4] use LLC converter for depleted battery charging voltage range without considering deeply depleted battery. Also in [5] depleted battery is considered, following the battery voltage at DC-link for operating LLC converter around resonance frequency. This approach reduces the

Fig. 1 Typical power architecture of a battery charger

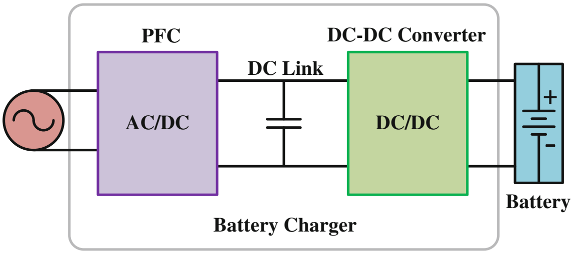
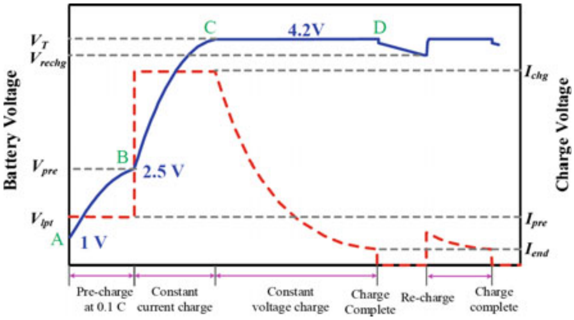


Fig. 2 Charging profile of a Li-ion battery cell



switching and conduction losses of LLC but deeply depleted battery is not considered. In [2] deeply depleted battery charging is considered using SEPIC converter at PFC stage but the turn-off current of the switches is in the range of 1.2–5.1 A, which is still high.

In this paper, hybrid-bridge LLC converter is considered for deeply depleted PEV battery charging as well having low turn-off current range 1.02–4.023 A. For depleted battery charging, LLC operates with full-bridge. For charging of occasionally deeply depleted battery, full-bride operates as half-bridge using only two power switches. The rest of paper is organized as in Sect. 2, LLC resonant converter is described and its DC gain equation is given with resonant tank parameters calculation steps. In Sect. 3, simulation results are presented and Sect. 4 gives some conclusion.

2 LLC Resonant DC-DC Converter

LLC resonant converter has gained a lot of attention for having simple structure and desirable features like reduced switching losses, zero voltage switching (ZVS), zero current switching (ZCS) [1–5]. LLC series resonant converter with hybrid-bridge is shown in Fig. 3. For usual case of depleted battery charging, LLC resonant converter operates using full-bride (FB). Half-bridge (HB) mode will only be used for charging occasionally deeply depleted battery by operating switches S_1 and S_2 and keeping S_3 OFF and S_4 ON. Thus the transition from HB to FB will only occur during charging when battery voltage reaches 250 V. Figure 4 shows the mode transition circuit with S as selector. When battery voltage is less than 250 V, S becomes 0 and HB is selected with $V_{gs3} = 0$ and $V_{gs4} = 1$, where V_{gs} represents the gate pulse of switch. For depleted battery, S = 1 and FB is selected with $V_{gs3} = V_{gs2}$ and $V_{gs4} = V_{gs1}$. To avoid any possible damage to switches the bridge transition will occur only during dead time of switching pulses.

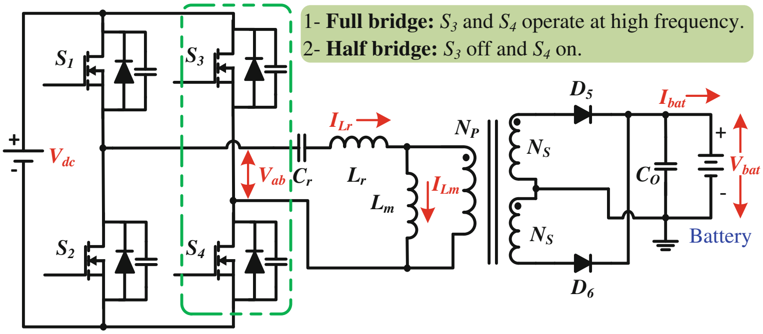

1- **Full bridge:** S_3 and S_4 operate at high frequency.
2- **Half bridge:** S_3 off and S_4 on.

Fig. 3 Hybrid-bridge LLC series resonant converter

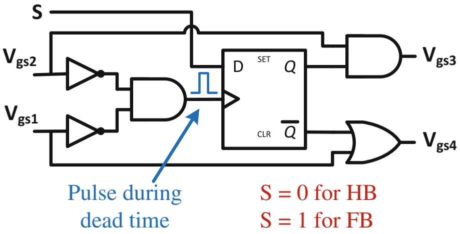


Fig. 4 Circuit for mode selection of LLC

For LLC converter there are two resonant frequencies which are given by:

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

$$f_{r2} = \frac{1}{2\pi\sqrt{(L_r + L_m) C_r}} \tag{2}$$

To fulfill the gain requirements for wide charging voltage range, LLC converter with fixed input voltage have to operate with wide switching frequency (f_{sw}) range. But the LLC converter have maximum efficiency operation around the resonance frequency f_{r1} with minimum circulating current in resonant tank [2]. In above f_{r1} region, secondary rectifier diodes do not have ZCS operation and, in below f_{r1} region, the power switches have non-zero turn-off current causing switching losses. Circulating current increases as f_{sw} moves away from f_{r1}, particularly in below f_{r1} region, and it does not contribute to the power transfer but generates the conduction losses [2]. To minimize the circulating current, the magnetizing inductance must be chosen maximum possible which satisfies the gain requirements and f_{sw} must have narrow range.

To keep f_{sw} in narrow range, the converter is designed to operate with two levels of DC-link voltage (V_{dc}) for both FB and HB operating modes. The V_{dc} values and their corresponding charging voltage ranges are given in Table 1. The DC gain of the LLC converter using first-harmonic approximation (FHA) approach, is given as [1]:

$$G(Q, k, f_n) = \frac{k}{\sqrt{\left(1 + k - \frac{k}{f_n^2}\right)^2 + k^2 Q^2 \left(f_n - \frac{1}{f_n}\right)^2}} \tag{3}$$

where $k = \frac{L_m}{L_r}$, $f_n = \frac{f_{sw}}{f_{r1}}$, $Q = \frac{Z_0}{R_{ac}} = \frac{\sqrt{L_r/C_r}}{R_{ac}}$, $R_{ac} = n^2 \frac{8}{\pi^2} \frac{V_{bat}^2}{P_0}$ with P_0 as output power.

Table 1 DC-link voltage for FB/HB and corresponding V_{bat} ranges

Half bridge		Full bridge	
V_{dc} (V)	V_{bat} range (V)	V_{dc} (V)	V_{bat} range (V)
390	100–160	400	250–320
540	160–250	520	320–420

Using (3) the DC characteristics of LLC converter can be derived. The resonant tank parameters of LLC converter with full-bridge configuration using FHA can be calculated using following steps:

Step 1. Step 1. Calculate the transformer's turns ratio (n), minimum and maximum gain values using the following equations with V_0 as output voltage and V_i as input:

$$n = \frac{V_i}{\left(V_0 + V_f\right)},\ G_{min} = \frac{n\left(V_{0min} + V_f\right)}{V_{imax}},\ G_{max} = \frac{n\left(V_{0max} + V_f\right)}{V_{imin}}.$$

where for diodes $V_f = 0.8$ V.

Step 2. Select the suitable values of inductance ratio k and quality factor Q from the gain versus normalized frequency f_n plot of (3) satisfying G_{min} and G_{max}.

Step 3. Choose the resonance frequency f_{r1} and calculate R_{ac} to calculate $Z_0 = QR_{ac}$. Using values of f_{r1}, Z_0 and k calculate:

$$C_r = \frac{1}{2\pi f_{r1} Z_0},\ L_r = Z_0^2 C_r \text{ and } L_m = kL_r.$$

Using above procedure with $f_{r1} = 200$ kHz, $n = 1.5949$, $Q = 0.4$, and $k = 4$, the converter is designed in ZVS region below resonance frequency to have maximum efficiency. The tank parameters are calculated as: $C_r = 10.072$ nF, $L_r = 62.87$ µH, and $L_m = 251.48$ µH.

3 Simulation Results

LLC resonant converter for DC/DC stage of PEV battery charger has been simulated using MATLAB Simulink and results for both depleted and deeply depleted battery charging, considering battery as resistive load [5], are shows in Figs. 5, 6 and 7. The DC-link voltage is assumed to be regulated by PFC converter at required value using state of charge of battery. When V_{dc} level changes during charging, f_{sw} becomes equal to f_{r1}. The waveforms of tank input voltage V_{ab}, magnetizing current I_{Lm}, resonant inductor current I_{Lr}, resonant capacitor voltage V_{cr}, and the charging current I_{bat} are shown in the results.

3.1 Deeply Depleted Battery Charging

For deeply depleted battery charging, LLC converter uses HB with two V_{dc} levels given in Table 1, for charging in CC mode with $I_{bat} = 1.02$ A, operating in both

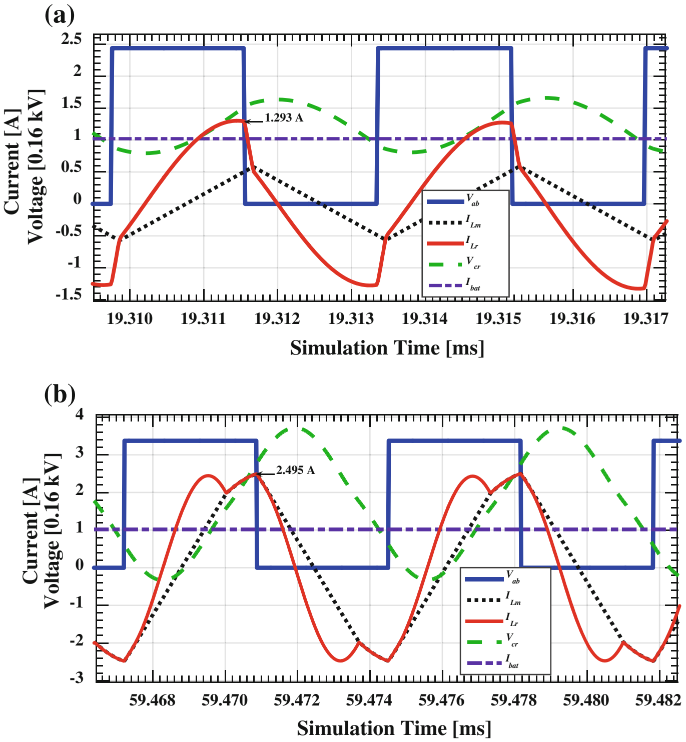
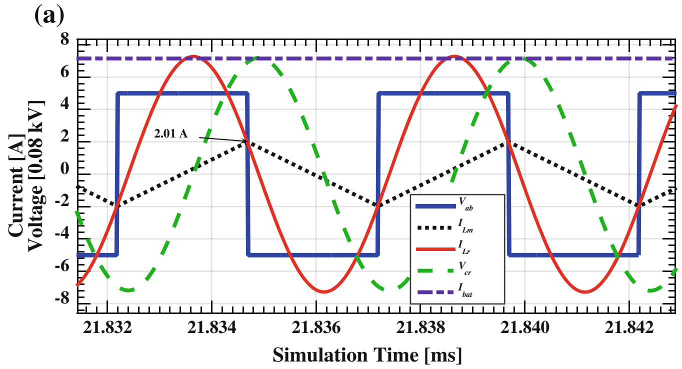


Fig. 5 LLC converter with $I_{bat} = 1.02$ A operating at two key points using half-bridge in CC mode **a** at point A with $V_{dc} = 390$ V, $V_{bat} = 100$ V **b** at point B with $V_{dc} = 540$ V, $V_{bat} = 250$ V

below and above f_{r1} regions. Figure 5 shows the waveforms at two key operating points A and B in Fig. 1. In Fig. 5a the converter is operating at $f_{sw} = 276.417$ kHz with $V_{bat} = 100$ V and turn-off current as 1.293 A resulting low switching losses. Figure 5b shows the operation at $V_{bat} = 250$ V using HB at $f_{sw} = 136.87$ kHz and turn-off current 2.495 A.

3.2 *Depleted Battery Charging*

Figure 6 shows the operation of LLC using FB for depleted battery charging using CC charging mode with $I_{bat} = 7.15$ A at two V_{dc} levels given in Table 1. Figure 6a shows the operation at $V_{bat} = 250$ V with $V_{dc} = 400$ V and $f_{sw} = 200.15$ kHz. Figure 6b shows the operation at $V_{bat} = 420$ V with $V_{dc} = 520$ V and $f_{sw} = 146.432$ kHz when charging mode transition occurs from CC to CV. Figure 7 shows the operation of the converter in CV mode when the current falls down to 0.51 A and charging process is terminated.



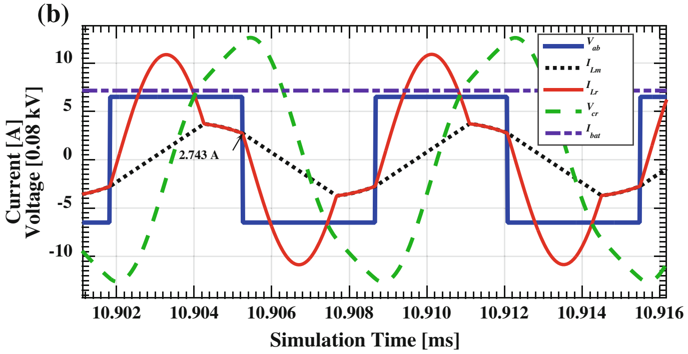


Fig. 6 LLC converter with $I_{bat} = 7.15$ A operating at two key points using full-bridge in CC mode **a** at point B with $V_{dc} = 400$ V, $V_{bat} = 250$ V **b** at point C with $V_{dc} = 520$ V, $V_{bat} = 420$ V

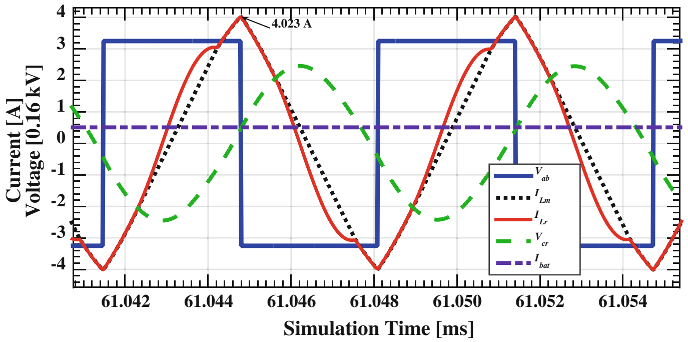


Fig. 7 LLC converter operating at terminating point D using FB with $I_{bat} = 0.51$ A in CV mode

4 Conclusion

In this paper LLC converter with hybrid-bridge has been presented for PEV battery charging taking into account the deeply depleted battery charging also. The converter used FB for depleted battery charging and HB for deeply depleted battery charging with low turn-off current of switches which reduced switching losses and circulating current. Simulation results showed that the converter covers the wide charging voltage range of 100–420 V for CC-CV charging of PEV battery pack.

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