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LLC Resonant Converter with Series-Connected Primary Windings of Transformer for PEV Battery Charging

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ABSTRACT

This paper proposes a half-bridge LLC resonant converter with two resonant tanks for plug-in electric vehicle (PEV) battery charging. Each resonant tank is connected with one of the centre-tapped primary windings of the power transformer. Both resonant tanks are fed alternately by a half cycle of the switching pulse in one period. The converter is designed to operate below resonance zero-voltage switching (ZVS) region to reduce switching losses and to achieve output DC voltage range 250V-420V with 400V input DC voltage for depleted PEV battery. MATLAB Simulink is used to simulate the circuit with 1.5 kW maximum power and the simulation results show that the converter can meet the constant-current, constant-voltage (CC-CV) charging requirements of the depleted PEV battery.

Keywords: LLC resonant converter, PEV battery charger, FHA

INTRODUCTION

Due to the threat of fossil fuel depletion, global warming and environmental issues, the interest in PEVs is growing continuously. High power density, high efficiency, smooth and quick charging are the desired features expected from onboard PEV chargers. Lithium-ion (Li-ion) battery packs are preferred for PEVs due to their salient features including slow depletion of energy, high energy density, and no memory effect and a charging profile of single cell Li-ion battery is shown in Figure 1 (a) (Wang et al., 2014c). In this profile, 1V-2.5V is a deeply depleted battery voltage range and 2.5V-4.2V is the normally depleted battery voltage range. Thus, the depleted battery voltage range of 100 cells in series for PEV battery pack can be extracted from this profile which maps to 250V-420V. The battery charging consists of constant-current (CC) and constant-voltage (CV) charging

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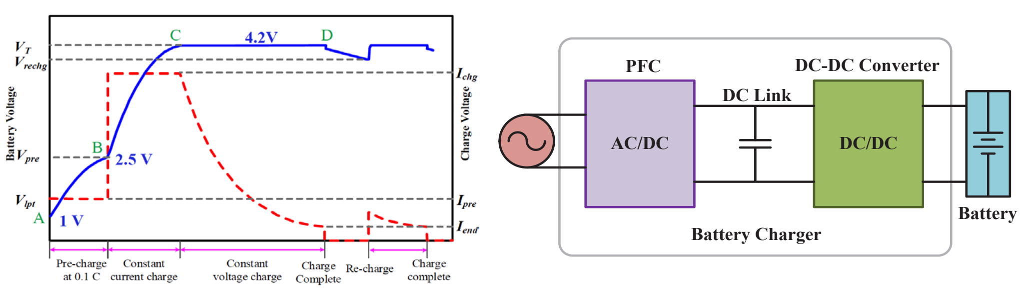
stages. In CC charging stage, the voltage varies between 250V and 420V range starting from the initial voltage of the battery using constant charging current. In CV charging stage, the charging voltage is kept constant at 420V while the current decreases and when it drops down to a minimum threshold, charging stops.

Figure 1 (b) shows a commonly used power architecture of a two stage PEV battery charging system with power factor correction (PFC) stage and DC/DC conversion stage (Junjun et al., 2014). The PFC stage converts the line AC voltage to a regulated DC voltage and takes care of harmonic distortion to keep the power factor near unity. The DC/DC converter regulates current for CC charging and voltage for CV charging modes providing galvanic isolation. At this stage, ZVS resonant converters are preferred to enhance charging efficiency. In particular,, LLC series resonant converters have desired features such as ZVS operation on primary and ZCS operation on secondary side, short circuit protection capability and good voltage regulation over light load (Wang et al., 2014a, 2014b). This paper is focused on DC/DC stage of battery charger (see Figure 1).



(a) (b)

Figure 1. (a) Charging profile of a Li-ion battery cell; (b) Power architecture of a battery charger

Researchers proposed many PEV battery charging solutions using LLC resonant converter with constant or variable DC-link voltage. For fixed DC-link voltage case, around 400V DC is regulated at DC-link and charging voltage range is achieved by switching frequency variation of LLC converter. Wang et al. (2014a) achieved 320V-420V range using full-bridge LLC converter and 250V-420V range is achieved by (Wang et al., 2014c) and simulation results are given. Junjun et al. (2014) achieved 250V-450V range and presented the design methodology. Wang et al. (2014b) achieved 320V-420V output voltage range using LLC converter operating around resonance frequency and variable input voltage at DC-link. The DC-link voltage is controlled at AC/DC conversion stage. All these studies used full-bridge LLC converter with four switches.

This paper proposed an LLC resonant converter with two resonant tanks for DC/DC stage of PEV battery charger using half-bridge configuration with only two switches which will eventually reduce cost. The converter achieved the charging voltage range of 250V-420V with below resonance frequency operation using only two power switches compared to full-bridge used by (Wang et al., 2014a, 2014b). Simulation results are presented to verify the operation of the converter. The rest of the paper is organised as follows: Section 2 describes the proposed converter while in section 3, equivalent AC circuit of the converter with gain characteristics and design procedure are presented. In section 4, simulation results are given and conclusion is drawn in section 5.

PROPOSED LLC CONVERTER WITH TWO RESONANT TANKS

The schematic of proposed LLC resonant converter with series-connected primary windings of the centre-tapped transformer is shown in Figure 2. The proposed converter consists of a DC source, half-bridge, two resonant tanks *RCT1* and *RCT2*, a centre-tapped transformer, a bridge rectifier with output filter capacitor C_0, and the output load R_L. *RCT1* consists of resonant capacitor C_{r1}, resonant inductor L_{r1}, and magnetising inductance L_{m1} and similarly *RCT2* consists of C_{r2}, L_{r2}, and L_{m2}. The two power switches are connected to the primary windings N_{p1} and N_{p2} through *RCT1* and *RCT2.* The series resonant tanks *RCT1* and *RCT2* are alternatively fed from DC source by turning on power switches S_2 and S_1 respectively with complimentary half switching cycles. Therefore, double power is transferred to the load in every switching cycle and input current is fetched twice in a switching cycle compared with half bridge converter.

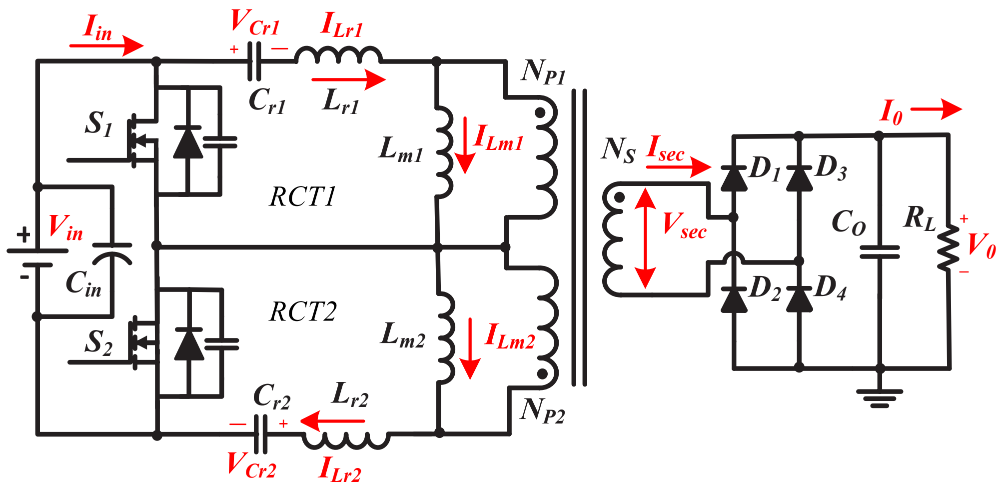


Figure 2. Proposed converter schematic

The primary windings Np_1 and NP_2 share the load equally and thus, half of the total current flows through each resonant tank. This reduces the components' stress to half in the resonant tanks compared with the conventional half-bridge LLC resonant converter topology which reduces the associated ohmic losses. Since there is only one transformer in the circuit, the core losses are also reduced compared with the topology proposed by (Lin & Wu 2011) with two transformers.

GAIN CHARACTERISTICS OF LLC CONVERTER

As the resonant tanks *RCT1* and *RCT2* are symmetrical, therefore, the analysis of gain characteristics of only one resonant tank will be sufficient. The AC equivalent circuit of *RCT1* is shown in Figure 3 (a). The input to the tank is a square wave with minimum zero to maximum value equal to the input voltage. To analyse the gain characteristics we apply fundamental harmonic approximation (FHA) approach. The fundamental components of tank input voltage and resonant current are given as;

$$V_{ab1}(t) = \frac{2}{\pi}\sin(\omega_s t) \text{ and } i_{Lr1}(t) = \sqrt{2}I_{Lr1}\sin(\omega_s t - \phi) \tag{1}$$

where I_{Lr1} is the RMS value of tank current i_{Lr1} and ϕ is the current phase shift relative to tank voltage. The fundamental component of voltage across Np_1 is given as:

$$V_{Lm1}(t) = \frac{4nV_0}{\pi}\sin(\omega_s t) \tag{2}$$

Where V_0 is the output voltage and n is the transformer turns ratio. The primary windings share the current equally and the maximum primary current in each winding in terms of output current I_0 is given as:

$$i_p(\max) = \frac{i_s(\max)}{2n} = \frac{\pi I_0}{4n} \tag{3}$$

Thus, the equivalent AC resistance reflected to the primary side is given as:

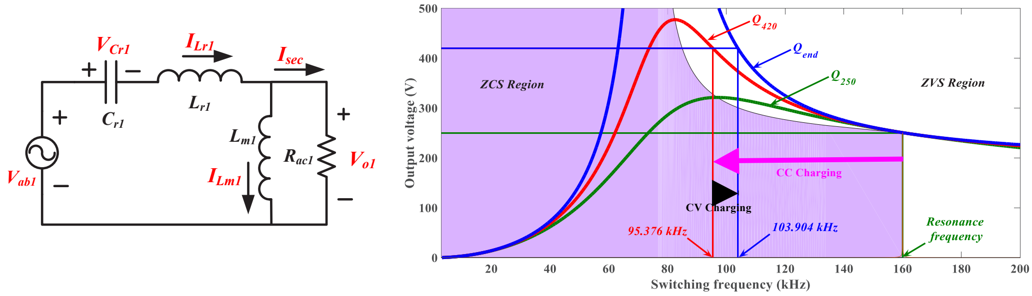
$$R_{ac1} = \frac{V_{Lm1}(\max)}{i_p(\max)} = \frac{16n^2}{\pi^2}R_0 \tag{4}$$

With $R_0 = V_0/I_0$, and this shows that the reflected load is four times of that reflected in converter presented by (Lin & Wu, 2011). The voltage gain can be obtained from AC equivalent circuit in Figure 4 (a) as:

$$G = \frac{2nV_{01}}{V_{ab1}} = \left|\frac{sL_{m1}\|R_{ac1}}{Z_{in1}(s)}\right| = \left|\frac{sL_{m1}\|R_{ac1}}{\frac{1}{sC_{r1}} + sL_{r1} + sL_{m1}\|R_{ac1}}\right| = \frac{k}{\sqrt{\left(1+k-\frac{1}{f_n^{\,2}}\right)^2 + Q^2k^2.\left(f_n - \frac{1}{f_n}\right)^2}} \tag{5}$$

Where $k = L_{m1}/L_{r1}$, $Q = Z_{in1}/R_{ac1} = \left(\sqrt{L_{r1}/C_{r1}}\right)/R_{ac1}$, $f_n = f_s/f_{r1}$, $f_{r1} = 1/2\pi\sqrt{L_{r1}C_{r1}}$,

with f_s as switching frequency and fr1 as resonant frequency. The output voltage curves versus switching frequency with quality factor Q for the three key operating points B, C and D in the charging profile in Figure1 (a) are shown in Figure 3 (b). Using design procedure by (Shahzad et al., 2014) the tank parameters are calculated as: $L_{r1} = L_{r2} = 46.6\ \mu$H, $L_{m1} = L_{m2} = 141.5\ \mu$H, $C_{r1} = C_{r2} = 23.8$ nF, $n = 0.7974$, $k = 3.4$, and $Q = 0.44$.



(a) (b)

Figure 3. (a) AC Equivalent circuit; (b) Output voltage versus switching frequency curves for three key operating points B, C and D

SIMULATION RESULTS

Figure 4 shows simulation model of the proposed LLC resonant converter using MATLAB Simulink. The simulation results show the operation of converter at key operating points B, C and D in charging profile using CC-CV method. The converter achieves the charging voltage range of 250V-420V operating below resonance frequency in the ZVS region. At each key operating point, simulation results are presented in two combinations. Each combination shows the operating waveforms of tanks input voltages V_{ab1} and V_{ab2}, resonant capacitor voltages V_{Cr1} and V_{Cr2}, resonant currents I_{Lr1} and I_{Lr2}, and magnetising currents I_{Lm1} and I_{Lm2}. The second combination shows the waveforms of secondary voltage V_{sec} and secondary current I_{sec}, rectifier diode currents I_{D1} and I_{D2}, and switches current I_{sw1} and I_{sw2}.

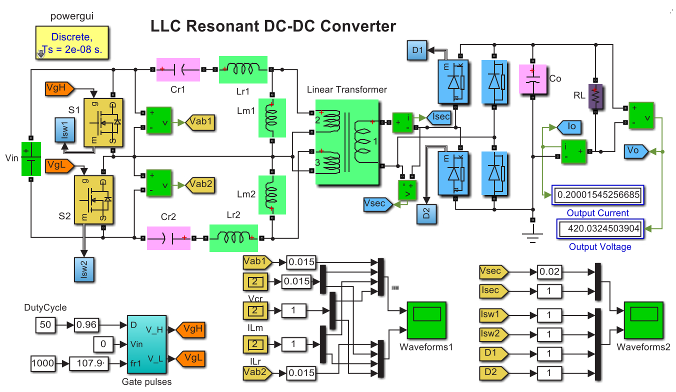


Figure 4. MATLAB simulation model of the proposed LLC converter

Figure 5 shows the operation of converter at resonance frequency with minimum circulating current. The power switches have ZVS turn-on and the turn-off current is 2A, whereas the secondary rectifiers have ZCS operation. The converter is operating at key operating point B with charging voltage $V_0 = 250$V at constant current as $I_0 = 3.57$A and is the minimum voltage point in a normally depleted battery. From this voltage to 420V, the battery is charged at constant maximum current.

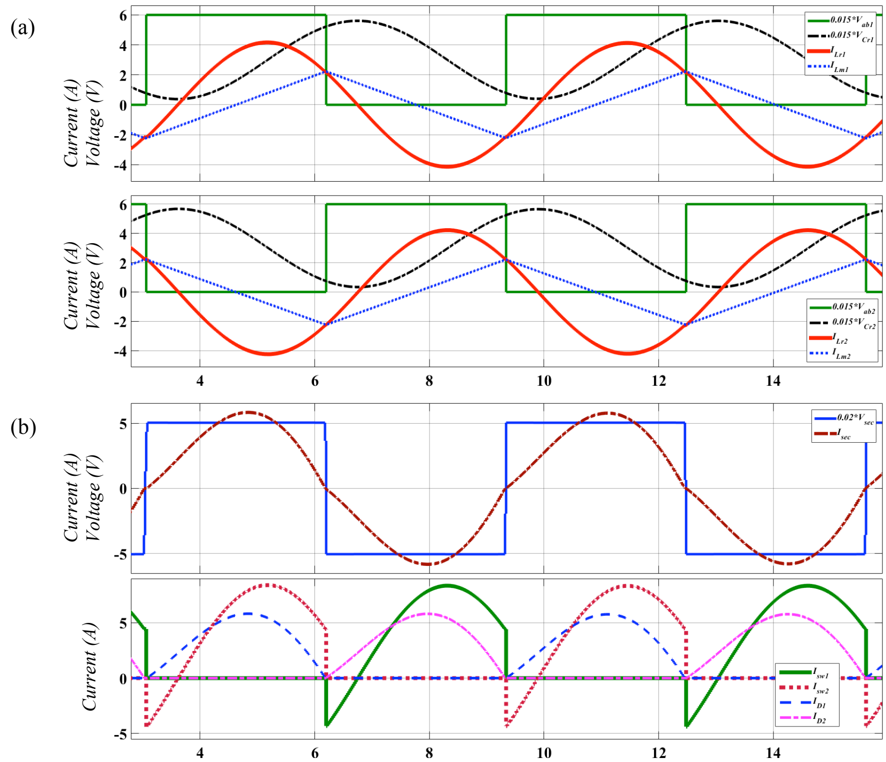


Figure 5. Operation waveforms at key point B. (a) First Combination; (b) Second Combination

Figure 6 shows the operation of converter at minimum switching frequency 98.6 kHz which is the point with maximum power during charging operation. The power switches have ZVS turn-on and the turn-off current is 3.7A with ZCS operation of secondary diodes. The converter is operating at key operating point C with output voltage V_0 = 420V and constant current I_0 = 3.57A. At this point, the mode transition from CC charging to CV charging occurs.

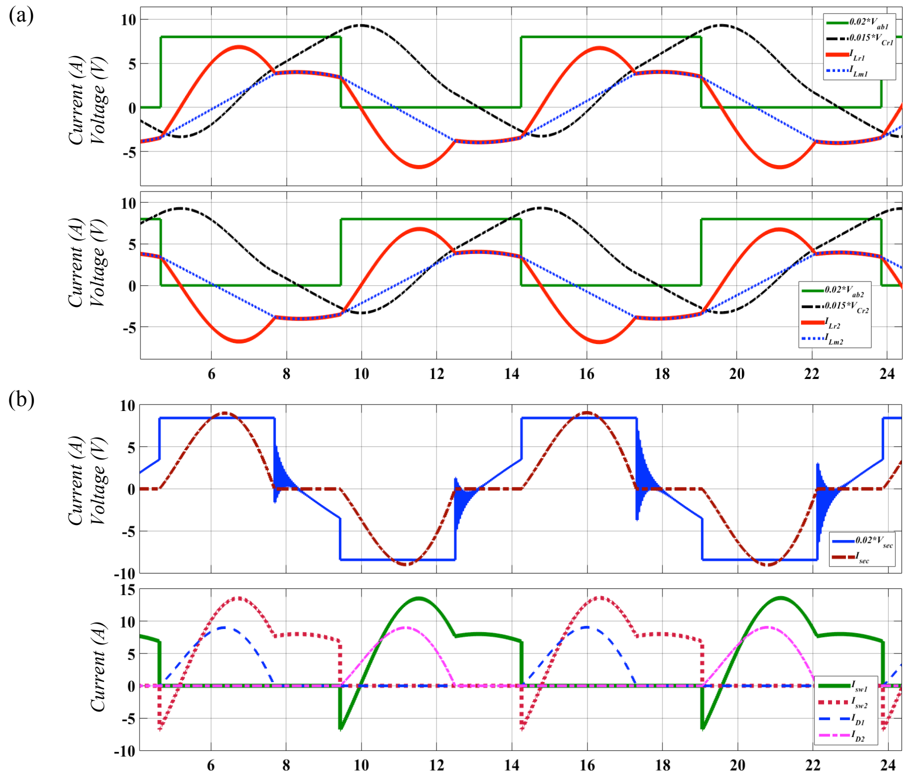


Figure 6. Operation waveforms at key point C. (a) First Combination; (b) Second Combination

Figure 7 shows the operation of converter at switching frequency 104.3 kHz which is the key operating point D with minimum power during charging process. The power switches have ZVS turn-on and the turn-off current is 3.7A with ZCS operation of secondary rectifier diodes. The converter is operating with output voltage V_0 = 420V and threshold current as I_0 = 0.2A. At this point the charging process is terminated.

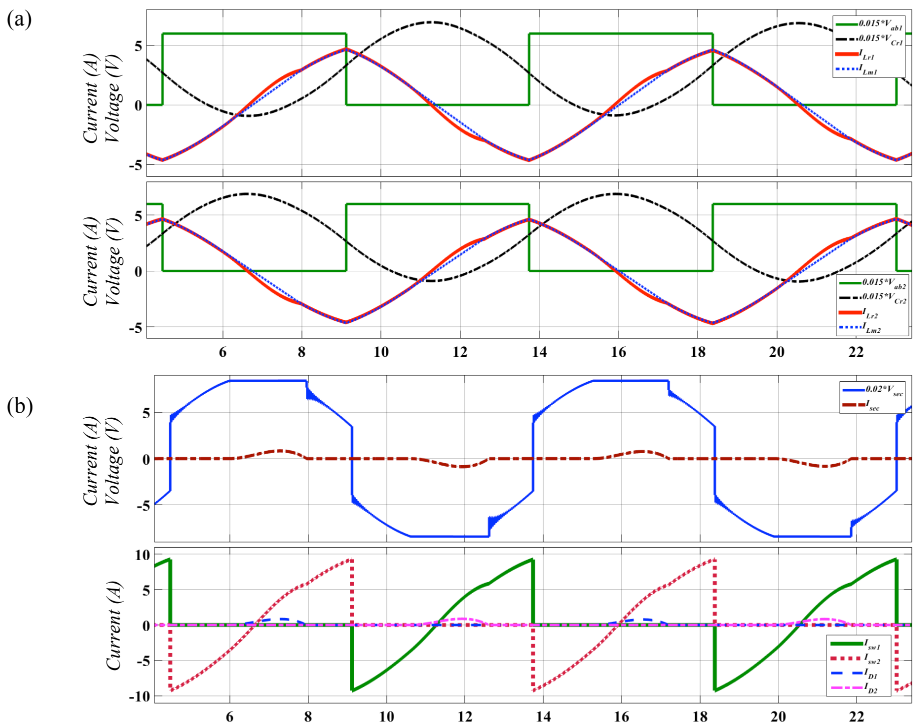


Figure 7. Operation waveforms at key point D. (a) First Combination; (b) Second Combination

CONCLUSION

This papers proposed an LLC resonant converter with half-bridge configuration, two resonant tanks, and series-connected primary windings of the transformer for depleted PEV battery charging. The converter has been designed to operate below resonance frequency in the ZVS region to achieve primary switches ZVS and secondary rectifier diodes ZCS operation. The Converter has been simulated in MATLAB to achieve output voltage range of 250V-420V with 1.5 kW maximum power and 400V input DC voltage. Simulation results showed that the converter can successfully achieve all the key operating points in the charging profile of Li-ion battery pack using half-bridge configuration instead of full-bridge in conventional topologies.

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