Optimal design of line level control resonant converters in plug-in hybrid electric vehicle battery chargers

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Abstract: The series–parallel resonant converter (also called line level control (LLC) resonant converter) is one of the most suitable topologies for dc–dc power supply. This study introduces the LLC resonant converter into the on-board battery chargers for the plug-in hybrid electric vehicle (PHEV) applications. Different from the previous literature which has focused on the wide operation range and hold-up time requirement in the LLC design, this study is mainly focused on battery load characteristics and its impact on the charger design. First, to guarantee high efficiency in the light-load condition in the constant voltage charging stage, the optimum LLC switching frequency range is derived. Second, considering the constant current charging function in the battery charger, the impact of peak load current on the LLC converter is discussed. The boundary between zero-voltage switching (ZVS) and zero-current switching (ZCS) in the constant current charging application is analysed. The trade-off among the minimum load voltage, maximum charge current and resonant capacitor is studied in detail. Finally, the optimal design method for the LLC resonant converter used in the PHEV battery charger is proposed. The proposed methods are validated through experiments on a 400 V/6 kW PHEV charger system with 97% efficiency.

1 Introduction

High efficiency, small size and high reliability are the basic requirements for an on-board battery charger in plug-in hybrid electric vehicle (PHEV) and electric vehicle (EV) applications. The size, cost and mechanical packaging are well discussed from practical aspect in [1]. A comprehensive topological survey of the currently available charging solutions is presented in [2]. The conventional pulse width modulation (PWM) technology with hard-switching suffered from severe switching losses and electromagnetic interference (EMI) issues. Resonant converters were reported in many papers recently because of their simple structure, high efficiency and low EMI [3, 4]. Among many resonant converters, the full bridge series–parallel resonant converter (SPRC, also called line level control (LLC) resonant converter) is more suitable than other resonant converters for PHEV charger applications [3, 4]. Compared with series resonant converters, the LLC converter can work in both buck and boost mode [3]. The integration of the inductors into a transformer makes the volume of a LLC converter smaller than a parallel resonant converter. However, the load-dependent properties of LLC resonant converters make the design more complicated. Researchers have mainly focused on the design method based on the first harmonic approximation (FHA) method [3–6]. Choi [4] and Yang et al. [5] analysed the dead-time optimal method with FHA. Beiranvand and Rashidia [7] discussed the FHA method in the wide output range LLC converter design. Hu and Qiu [8] presented a switch-controlled capacitor modulated LLC converter with a constant switching frequency for multiphase paralleling. This can help multiply the load capacity. Tomokazu and Mizutani [9] added an anti-resonant circuit into the LLC converter to improve the voltage conversion ratio in the dc voltage step-down area.

In the previous literature, the load characteristics is usually assumed to be passive, such as a resistor, in the theoretical analysis and experiments for the optimisation. The load characteristics and its impact are not well researched. For a battery charger, however, the optimal design requirements are quite different [10, 11].

First, more non-linear characteristic exists in the design for a resonant converter with a battery load. Table 1 shows the comparison of a PWM converter and a resonant converter with a passive load and a battery load.

For a dc power supply is connected with a passive load, the load voltage is largely determined by the load current. When the load is a battery, the load voltage is related to the battery state-of-charge (SOC) during the charging process. The charger output voltage is clamped by the battery voltage and is less dependent on the load current. From the converter topology aspect, the conventional PWM voltage source converters are largely unaffected by the load current.
Consequently, the switch current is proportional to the load current. Meanwhile, the conduction loss turned to be small at light load, leading to good light-load efficiency. These properties, however, are not exhibited in the resonant converters. In a resonant converter, the switch current is equal to the resonant tank current $i_1$ and is less dependent on load current.

From Table 1, we can find that the design for a resonant converter with a battery load is more complicated than other applications. Both of the non-linear characteristics in the resonant tank and the battery need to be considered.

Second, the load voltage varies significantly in the whole charging process. For a single cell lithium-ion battery (4.2 V/cell), the voltage increment could be more than 0.6 V per cell asSOC reaches the full level from zero. That means at least 60 V increment for a whole battery package applied for a 400 V PHEV drive system. As a result, the system should be capable to work in a wide operation range.

Third, the charge process for a lithium-ion battery contains two stages: a constant current (CC) charging stage and a constant voltage (CV) charging stage. The design requirements are not the same in the two stages. For the benefits of saving charging time, in the CC charging stage, a large charge current is preferred. While in the CV charging stage, the charge current is much smaller than in the CC stage. Hence, the light-load efficiency and overcharging issues are more important. Most of previous researches focused on charging currents, battery performance and overcharging problems in each charging process. Dickinson and Gill [12] analysed the issues and benefits with fast charging for the industrial batteries, and Li et al. [13] explored the charging method for lead-acid batteries of EVs based on the battery model; however, the optimum design for both charging stages on a battery charger needs more investigation.

Based on the above analysis, the design of a PHEV battery charger based on LLC converters is more challenging compared with the design with a regular passive load. In this paper, the operation frequency range for the battery load is derived and analysed in Section 3 to achieve high efficiency in the CV charging stage. Section 4 focused on the impact of battery load on the CC charging stage of the LLC converters. The optimal design procedure is presented in Section 5 and the experimental results are presented in Section 6. All of the analyses are validated through experiments on a 400 V/6 kW PHEV on-board battery charger.

## 2 Operation principle of LLC resonant converters with a battery load

A typical schematic of a full bridge LLC multi-resonant dc–dc converter is shown in Fig. 1, where $C_r$ is the resonant capacitor, $L_m$ is the magnetising inductance and $L_r$ is the leakage inductance in the primary side. The advantages of LLC resonant converters include primary-side zero-voltage switching (ZVS), secondary-side zero-current switching (ZCS), integrated magnetic component and buck/boost operation capability [5].

As shown in Fig. 1, different from a conventional PWM converter, the output of a resonant converter is controlled indirectly through the resonant tank [14]. The tank exchanges a large amount of energy with the source and load. The input voltage $V_{\text{tank}}$ is a symmetrical square waveform with a magnitude of $V_{\text{in}}$, frequency $f_s$ and duty ratio of 50%. When $f_s$ is close to $f_r$, the resonant tank primarily responds to the fundamental ($f_1$) component $V_{s1}$ of $V_{\text{tank}}$ and the harmonics voltage at frequencies ($f_2$) of $V_{\text{tank}}$ have negligible response. Hence, the input voltage waveform $V_{\text{tank}}(t)$ can be well approximated by its fundamental component $V_{s1}$, which is in phase with the square wave $V_{\text{tank}}(t)$

$$V_{s1} = \frac{4V_{\text{in}}}{\pi} \sin(\omega_1 t)$$

ZVS occurs when the impedance of the resonant tank is inductive, that is, tank current $i(t)$ lags voltage $V_{s1}$, while ZCS occurs when the impedance of resonant tank is capacitive, that is, tank current leads voltage $V_{s1}$.

Different from conventional resonant converters, the LLC resonant circuit is a kind of multi-resonance circuit. There are two resonant frequencies that can be expressed as

$$f_1 = \frac{1}{2 \pi \sqrt{L_r C_r}}$$

$$f_2 = \frac{1}{2 \pi \sqrt{(L_r + L_m) C_r}}$$

The dc gain of output voltage in a LLC converter is not only related to $f_1$ but also related to the load situation [15]. The frequency response of the output voltage under load variations is shown in Fig. 2. The load quality factor $Q$ is defined by $\sqrt{L_r/C_r}$/$R_{\text{load}}$.

Soft-switching is one of the advantages of a LLC resonant converter because of its effect on the reduction of switching loss and EMI. Various forms of soft-switching such as ZVS

![Fig. 1 Schematic of a full bridge LLC converter](image-url)
and ZCS methods can be achieved in a LLC converter for different applications. For power MOSFET, ZVS is preferred because ZCS results in current spike during turn on transient leading to high-current stress and high-switching loss [16]. Fig. 2 depicts the ZVS and ZCS regions in a LLC resonant converter. The converter has three operation modes in responding to the switch frequencies. In mode 1 ($f_s > f_{r1}$), the impedance of the resonant tank is inductive, the converter operates under ZVS condition. The converter works in buck mode. In mode 3 ($f_s < f_{r2}$), the impedance of the resonant tank is capacitive, so the converter operates under ZCS condition. Mode 2 ($f_{r2} < f_s < f_{r1}$) is multi-resonant converter mode. The load situation determines the converter operation under ZVS or ZCS conditions. In both regions 2 and 3, the load situation determines the converter operation under ZVS or ZCS conditions. In both regions 2 and 3, the converter works in boost mode.

Based on the analysis above, we can see that for the design of LLC converters applied to on-board battery chargers, both the soft switching and the impact of battery load properties should be considered to ensure high performance and efficiency.

3 Design of switching frequency range

As mentioned in Section 1, different from a PWM converter, the switch current in a resonant converter is equal to the resonant tank current $i_t$ and is less dependent on load current. The tank current is determined by the tank input impedance $Z_{in}$ ($j\omega_s$) that can be expressed as

$$Z_{in}(j\omega_s) = \frac{V_{s1}(j\omega_s)}{I_s(j\omega_s)} \quad (4)$$

The asymptotes of the magnitude of input impedance $|Z_{in}|$ in the open circuit and short circuit cases are illustrated in Fig. 3. The variation of $|Z_{in}|$, according to different load situations, is between the two limits. As the load increases, $|Z_{in}|$ curve moves from $|Z_{in0}|$ to $|Z_{in0}|$ that is given by

$$Z_{in0} = Z_{i}|_{R_{load} \rightarrow 0} = j\omega_sL + \frac{1}{j\omega_sC} \quad (5)$$

$$Z_{in0} = Z_{i}|_{R_{load} \rightarrow \infty} = j\omega_sL + j\omega_mL + \frac{1}{j\omega_sC} \quad (6)$$

Fig. 3 depicts the behaviour of $|Z_{in}|$ for intermediate load values between the open-circuit and short-circuit conditions. In region A, $|Z_{in}|$ decreases as the load increases. In region B, $|Z_{in}|$ increases as the load increases. Consequently, the tank current in region B increases as the load decreases. Such a converter has a poor efficiency in the CV charging stage where the load current is small. Even if the load is reduced and removed, the system would approach point C in Fig. 3, resulting in the largest tank current. Thus, to improve light-load efficiency, $|Z_{in}|$ should increase as the load decreases, such as in region A. The switching frequency edge between region A and region B can be calculated as $|Z_{in0}|$ equals $|Z_{in0}|$. The switching frequency in the CV charging stage should be higher than the value of $f_L$.

$$f_L = \frac{\sqrt{2}}{2\pi\sqrt{(2L_r + L_m)C_r}} \quad (7)$$

4 Impact of battery load property on the LLC resonant converter

As shown in Fig. 2, both ZCS and ZVS exist in the region $f_{r2} < f_s < f_{r1}$. In the previous literature, the design of the LLC resonant converter with ZVS focused on the selection of inductance $L_m$ and $L_r$ because $Z_{in}(j\omega_s)$ is dominated by the tank inductor [12]. The effect of the resonant capacitor $C_r$ is often ignored.

In the PHEV charger application, however, the battery load has significant impacts on the converter through resonant capacitor $C_r$. An upper limit of capacitor voltage can be calculated as

$$V_{cr}^* = n\left(1 + \frac{L_r}{L_m}\right)V_{Load} + V_{in} \quad (8)$$

When the voltage across capacitor $V_{cr}$ is lower than $V_{cr}^*$ in
after the tank current $i_1$ resonates back to the level of $L_m$ current, it would be clamped by the $L_m$ current, as shown in Fig. 4a. The secondary-side diodes do not conduct during this period and the direction of the tank current would not change until switch devices turn on, allowing ZVS to be achieved. If the switching current keeps increasing and makes voltage $V_{cr}$ on the resonant capacitor higher than $V_{cr}^*$ in (8), the energy stored in the capacitor could be high enough to make the secondary-side diode conduct, as shown in Fig. 4b. This can force the tank current to

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**Fig. 4** Comparison of the waveforms when converter works in

(a) ZVS region

(b) ZCS region

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**Fig. 5** Simulation results when the system approaches the boundary between ZVS and ZCS
resonate to the other direction [17]. If the tank current resonates to negative, current leads voltage $V_{m}$. The converter operates in ZCS condition.

The influence of resonant capacitor $C_r$, however, is not significant with a passive load. When connected to a passive load, the load voltage $V_{load}$ increases as the load current increases, allowing the upper limit $V^{*}_{Cr}$ to increase. For the battery load, however, the load voltage, $V_{battery}$, is a relatively constant value. It is related to the SOC and is less dependent on load current. It can clamp the upper limit $V^{*}_{Cr}$, allowing $V_{m}$ to exceed $V^{*}_{Cr}$ in a heavy load condition. Then the converter fails to achieve ZVS condition.

Hence, the passive load assumption is not suitable for the design of a PHEV battery charger. For the battery load consideration, the boundary between ZVS and ZCS with a CV load needs to be figured out. The waveform of current $i_1$, $i_2$ and voltage $V_{cr}$ when the converter approaches that boundary is shown in Fig. 5.

In Fig. 5, during $[t_0 \sim t_2]$: at the time $t_0$, switch $S_2$ turns off, the resonant current flows through the body diode of $S_1$, voltage across $S_1$ decrease to zero. After a short interval from $t_0$, switch $S_1$ turns on with ZVS. The equation for the whole procedure can be written as:

$$
\begin{align*}
|V_m - V_{cr} - nV_{load}| &= L_i \frac{di_1}{dt} \\
C_r \frac{dV_{cr}}{dt} &= i_1 \\
L_m \frac{di_{in}}{dt} &= nV_{load}
\end{align*}
$$

In Fig. 5, during $[t_0 \sim t_2]$: at the time $t_0$, switch $S_2$ turns off, the resonant current flows through the body diode of $S_1$, and the initial conditions are $i_1(t_0) \approx i_{in,0}(t_0) = I_{in,0}$, $u_{cr}(t_0) = V_{cr,0}$. We can obtain the solution as (see (10))

$$
h_{\omega} = 1/\sqrt{L_i C_r}. \text{ At time } t_2, i_1(t_2) = i_{in,0}(t_2) = I_{in,0}. \text{ diodes } D_i \text{ and } D_j \text{ turn off. Current } i_2(t_2) \text{ in the secondary side is zero.}
$$

Equation (10) describes the voltage and current waveforms in the capacitor during $[t_0 \sim t_2]$.

The initial value of current and voltage contained in (10) needs to be figured out. In Fig. 9, when the waveform in the ZVS/ZCS boundary: (1) The current value $I_{in,0}$ at $t_0$ is close to zero; (2) the peak value of the voltage in resonant capacitor $C_r$ is achieved near time $t_0$. According to that, (10) can be simplified as (see (11))

$$
\begin{align*}
\frac{nV_{load}}{2} + V_{m} - V_{cr} - nV_{load} &= L_i \frac{di_1}{dt} \\
C_r \frac{dV_{cr}}{dt} &= i_1 \\
L_m \frac{di_{in}}{dt} &= nV_{load}
\end{align*}
$$

From (11) and (8), the critical $V^{*}_{load}$ at the boundary between ZVS and ZCS can be derived as:

$$
\frac{nV_{load}}{2} + V_{m} - V_{cr} - nV_{load} > nV^{*}_{load}(2 \cdot L_m + L_i)
$$

From (13), and (14) and (15), $V_{cr}$ can be eliminated and the relationship between $I^{*}_{load}$. $V^{*}_{load}$ and resonant frequency $\omega_{r1}$ can be derived as

$$
\omega_{r1} = -\frac{1}{2} \frac{L_m \cos(\alpha) \pi}{V_{load} 2 L_m + L_i} I_{in} \frac{\pi}{2} < \alpha < \pi
$$

$$
\begin{align*}
V_{cr}(t) &= \frac{nV_{load}}{2} + V_{m} - V_{cr} - nV_{load} \\
i_1(t) &= I_{in,0} + \frac{nV_{load}}{L_m}(t - t_0) \\
i_{in}(t) &= I_{in,0} + \frac{nV_{load}}{L_m}(t - t_0)
\end{align*}
$$
Equation (16) represents the lowest resonant frequency $\omega_r$ to ensure ZVS with the desired load current $I_{\text{load}}^\ast$ in $V_{\text{load}}^\ast$. For a LLC converter whose resonant frequency is $\omega_{r1}$ and if the charging current exceeds $I_{\text{load}}^\ast$ with load as $V_{\text{load}}^\ast$, ZVS would disappear. Let $\omega_{r1} = 1/\sqrt{L C_i}$, we can obtain the expression of resonant capacitor value as

$$C_i = \left(\frac{1}{2 n^2 V_{\text{load}}^2 (2 L_m + L_i)} I_{\text{load}}^\ast\right)^2$$  \hspace{1cm} (17)

The resonant capacitor value should be larger than the value calculated in (17) to ensure ZVS with given $I_{\text{load}}^\ast$ in $V_{\text{load}}^\ast$. The characteristic of the LLC converter at boundary condition between ZVS and ZCS in the CC charging stage has been derived. Next, it is instructive to consider the maximum current $I_{\text{outmax}}$ the LLC converter can output at the boundary. Only if $I_{\text{outmax}}$ turns to be larger than $I_{\text{load}}^\ast$ the whole system can output $I_{\text{load}}^\ast$ with a battery load in the ZVS condition. From (10), we can obtain the transformer secondary-side current

$$i_2(t) = i_{c1}(t) - i_{L_m}(t)$$  \hspace{1cm} (18)

Take the derivative of (18) with respect to $t$, the peak value of $i_2(t)$ can be derived when the derivative is set to zero at time $t_{1a}$

$$\frac{d(i_{c1} - i_{L_m})}{dt} = 0$$  \hspace{1cm} (19)

$$t_{1a} = \cos^{-1}\left(\frac{n V_{\text{load}}^*}{\omega_r^2 C_i (V_{\text{in}}^* - n V_{\text{load}}^* - V_{\text{cr0}}) L_m}\right) \omega_r^{-1} + t_0$$  \hspace{1cm} (20)

From (18) and (20) and we can obtain the maximum value of $i_2(t)$

$$I_2 = \omega_r C_i (V_{\text{in}}^* - n V_{\text{load}}^* - V_{\text{cr0}})$$

$$\times \left[1 - \frac{n^2 V_{\text{load}}^2}{\omega_r^2 C_i^2 (V_{\text{in}}^* - n V_{\text{load}}^* - V_{\text{cr0}})^2 L_m^2} - n V_{\text{load}}^*-\cos^{-1}\left(\frac{n V_{\text{load}}^*}{\omega_r^2 C_i (V_{\text{in}}^* - n V_{\text{load}}^* - V_{\text{cr0}}) L_m}\right) t_{1a}^{-2} \omega_r^{-1} + I_{\text{Lm0}}\right]$$  \hspace{1cm} (21)

In (21), $V_{\text{cr0}}$ can be estimated by (14) and (15) and $I_{\text{Lm0}}$ can be calculated from (10)

$$I_{\text{Lm0}} \approx \frac{n V_{\text{load}}^*}{4 \omega_r}$$  \hspace{1cm} (22)

From (21) and (15), we can obtain

$$I_{\text{max}} = \frac{\pi}{2} \left(\frac{\omega_r C_i (V_{\text{in}}^* - n V_{\text{load}}^* - V_{\text{cr0}})}{1 - \frac{n^2 V_{\text{load}}^2}{\omega_r^2 C_i^2 (V_{\text{in}}^* - n V_{\text{load}}^* - V_{\text{cr0}})^2 L_m^2}}\right)$$

$$- n V_{\text{load}}^* \cos^{-1}\left(\frac{n V_{\text{load}}^*}{\omega_r^2 C_i (V_{\text{in}}^* - n V_{\text{load}}^* - V_{\text{cr0}}) L_m}\right)$$  \hspace{1cm} (23)

Equation (23) demonstrates the maximum current at the boundary between ZVS and ZCS with a given load voltage $V_{\text{load}}^*$ in the CC charging stage.

5 Optimal design of LLC converter in a PHEV battery charger

Based on the analysis presented in the previous sections, the optimal design of LLC converter for the PHEV battery charger application is proposed in this section. First, for the CC charging stage, the minimum switching frequency needs to be calculated following (7).

In the first step, the system is designed following the normal design procedure in [3, 5, 14] with the system parameters. The value of $L_m$, $L$, and $C_i$ in the LLC resonant tank can be calculated. Then, the minimum switching frequency $f_{\text{min}}$ can be calculated as $f_L$ in (7). If $M_{\text{max}}$ at the minimum switching frequency $f_{\text{min}}$, is smaller than the desired value $M_1 = V_{\text{outmax}}/V_{\text{outmin}}$, then the design should go back to the first step to reselect the component values.

For the CC charging function, additional design steps are needed. The resonant frequency $\omega_{r1}$ is calculated from (16), according to the desired maximum output current $I_{\text{load}}^\ast$. Then, the minimum resonant capacitor $C_r^\ast$ can be calculated in (17) and the maximum output current $I_{\text{max}}$ can be estimated by (23). Only if $I_{\text{max}}$ is higher than $I_{\text{load}}^\ast$ the system is capable to output the desired current $I_{\text{load}}^\ast$ for the constant charging.

6 Simulation and experimental results

The aim of this section is to design a 6 kW LLC resonant dc–dc converter used in a PHEV on-board battery charger using the procedures proposed in the previous sections. The input voltage of the resonant dc–dc converter is 400 V. The output voltage range is from 330 to 500 V. According to
the optimal design proposed in Section 4, the values of the resonant tank components are selected as: \( L_r = 40 \mu H \), \( L_m = 80 \mu H \), \( C_r = 68 \) nF and the turn ratio value is 1.3. The two resonant frequencies are \( f_{r1} = 97 \) kHz, \( f_{r2} = 55 \) kHz, respectively. Frequency \( f_s \) is 68 kHz. Maximum operation frequency is 160 kHz. The system consists of following components: MOSFET (IPW60R045CP) and Diode (FFH60UP60S3).

Fig. 7 shows the profiles of \( I_1 \) and \( I_{load} \) under different switching frequencies. It can be seen that when \( f_s > f_{r1} \), \( I_1 \) would increase as \( I_{load} \) increase. when \( f_s < f_{r1} \), however, \( I_1 \) would increase as \( I_{load} \) decreases, resulting in poor efficiency in the CV charging stage. The simulation results agree with the analysis in Section 3.

To verify the analysis presented in Section 4, a lithium-ion battery pack rated at 400 V is utilised as the battery load for the charge experiments. The experiments are conducted in the region \( f_L < f_s < f_{r1} \) with a battery load at load current of 3 A. Fig. 8 shows the current and voltage waveforms in the resonant tank when the system crosses the ZVS/ZCS boundary and enter ZCS region. It can be seen that the tank current resonates to negative before the device turns on. The failure of ZVS caused severe EMI in the switch signal \( V_g \). The EMI issue would caused false triggering in devices resulting in short-circuit fault.

After improvement according to the procedures in Section 4, ZVS could be guaranteed in the whole output voltage range. Fig. 9 shows steady-state experiment at CC charge of 10 A with load voltages from 340 and 380 V. The input of LLC converter is provided by a PFC stage in the on-board charger that transfers 200 V ac voltage to 400 V dc voltage. It can be seen that the PFC current gets well controlled with LLC converter. The designed resonant tank in the on-board charger can output desired large current with ZVS in different load voltage situations.

Fig. 10 shows the tank current and voltage experiment waveforms operating at output voltage 400 V and output current 10 A with a battery load. At time \( t_1 \), the low side
8 References


7 Conclusions

This paper introduced the LLC resonant converter topology into PHEV battery chargers. For this purpose, the requirement and challenges for the LLC converter applied in battery charger systems have been discussed. The deficiency of previous LLC topology studies based on passive load assumption is investigated. Then the paper studied the optimal design method for the LLC converter applied in PHEV battery chargers in two approaches. First, to improve the efficiency in the light-load conditions during the CV charging stage, the optimum LLC switching frequency range is derived. Second, considering the CC charging function of PHEV battery chargers, the impact of battery load on the LLC converter was discussed. The characteristics of the LLC converter with a battery load at the boundary between ZVS and ZCS is analysed. A trade-off among the minimum load voltage, maximum charging current and resonant capacitance has been studied in detail. Finally, an optimal design method for the LLC resonant converter used in the PHEV battery charger for CV/CC charging is proposed. The proposed methods are validated through experiments on a 400 V/6 kW PHEV charger system with 97% efficiency.