AN IMPROVED DESIGNED METHOD FOR LLC RESONANT CONVERTER TO DESCRIBE THE VOLTAGE GAIN PRECISELY

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Abstract

This paper provides the review of LLC resonant converter to determine the precise voltage gain with battery charger as a load based on First Harmonics Approximation. Among all the resonant converters the LLC resonant converter has become more popular due to its special features like wide range of soft switching capability, better efficiency and high frequency current ripple on the battery as a load. In this review, the implementation methodology of LLC resonant converter is widely used in the structure of medium to high power charger applications. Including of parasitic components in LLC resonant converter during the high frequency operation and their effects in the behavior of converter operation are proposed using a traditional analysis based on FHA method were discussed in detail. This review paper is intended to serve as a convenient reference.
to future for resonant converter with parasitic components
users.

Index Terms: battery charger, LLC converter, PID controller. Parasitic components, zero current switching (ZCS)

1 Introduction

Power supply designers will require and considering the soft switching topologies to increase the efficiency and also allow the better frequency operation. Practical design considerations and resonant tank design procedure are offered for a better performance of LLC resonant dc-dc converter with battery charger for electric vehicle applications. The conventional analysis of LLC Resonant Converter with Fundamental Harmonic Approximation (FHA) without parasitic components cannot explain the practical operation of LLC Resonant Converter. In this paper, the output voltage regulation of a full bridge LLC series resonant DC-DC converter using a PID controller in feedback loop for the battery charging application is presented. The PID controller is used to adjust the frequency of gate pulses generated by the Pulse Width Modulation (PWM) for deriving the MOSFETs to regulate the output voltage. The PID controller can also set the output voltage level for both step and linear variations in the reference signal and it helps in reducing steady state errors and also getting steady state conditions quickly.

For an LLC converter connected with a passive load, the output voltage is largely determined by the load current, whereas for battery load, the output voltage is related to the battery state-of-charge (SOC) and the charging profile.
Fig. 1 shows the structure of the LLC resonant converter. It is difficult to determine the voltage gain precisely. When converter operating in resonant mode, the impedance between the output and input of the circuit maintain as the minimum value and it provides improved efficiency. With a resonant converter, by supplying the MOSFETs with either a sinusoidal voltage or a sinusoidal current and switching in close proximity to the zero crossing of the sinusoidal voltage or current, the power dissipated in the MOSFETs can be significantly reduced.

Switching the MOSFET when the drain to source voltage is near zero, Zero Voltage Switching (ZVS), and transitioning from one MOSFET state to another while the current through the switch is zero, Zero Current Switching (ZCS), minimizes MOSFET switching losses. This soft-switching approach also reduces noise in the system and provides improved electromagnetic interference (EMI) performance. ZVS is preferred in high-voltage, high-power systems.

Two main technologies used in power electronics are (PWM) Pulse Width Modulation and Resonance. Resonance occurs in a circuit when Inductive Reactance is equal to capacitive Reactance. An inductor stores Magnetic Energy and a Capacitor stores Electrical Energy. At Resonance, these both elements Charge and discharge continuously. The converters using this as the principle are called as resonant converters. Due to the resonant elements in LLC resonant converter (resonant inductor, resonant capacitor and magnetizing inductance), resonant switch converter generate the sinusoidal voltage or current. This paper is comprised as follows, In section 2, Overview Of LLC Resonant Converter, In section 3, Analysis Of LLC Resonant Converter With Parasitic Components, In section 4, High Reverse Current Flow Due To Parasitic Capacitance, In section 5, Influence Of Parasitic Components On Power MOSFET Switching Operation In Power Conversion Circuit, In section 6, LLC Resonant Converter For Battery Charging Application, In section 7, Design Calculation, In section 8, Conclusion.


2 OVERVIEW OF LLC RESONANT CONVERTER

In Series Parallel Resonant Converter (SPRC), the tank circuit is a combination of the series and parallel converters and can be either a LCC or LLC configuration. Similar to the SRC and PRC, a SPRC LCC design cannot be optimized at high input voltage. As a result, the preferred alternative for many applications is an LLC.

The LLC converter can operate at resonance, at nominal input voltage, and is able to operate at no load. In addition, it can be designed to operate over a wide input voltage. Both zero voltage and zero current switching are achievable over the entire operating range.

The performance of a resonant converter is measured by the quality factor (Q), of a resonant circuit is a dimensionless parameter. It is defined as the ratio between the power stored and the power dissipated in the circuit. A higher Q indicates a narrower bandwidth for the resonant tank.

Quality is a key parameter in the tank circuits gain, also called the voltage conversion ratio or M. By considering the families of M curves that are generated when varying either l, the normalized frequency, or Q, it is possible to obtain an indication of a resonant converters performance before all the parameters have been computed. M is defined as:

$$M(f_{sw}) = f(f_n, l, Q)$$

Where:

- $$f_n$$ = normalized frequency, $$f/f_r$$
- $$l$$ = the inductance ratio, $$L_r/L_m$$
- $$Q$$ = quality, a function of the output impedance

As shown in Fig.1 there are two resonant frequencies, one due to the presence of $$L_r$$ and $$C_r$$, the series inductor and capacitor at $$f_n=1$$, and the second one due to the parallel inductor ($$L_m$$), $$L_r$$ and $$C_r$$ at $$f_n \sim 0.5$$.

Different operating modes of the LLC include at resonance, below resonance and above resonance. At resonance, the MOSFETs are switched at the resonant frequency within a very narrow timing window, as determined by the selected components. This produces very low losses.
Below resonance, the circuit behaviour is similar to that at resonance, but the tank current is limited by the magnetizing current for a portion of the cycle. If MOSFETs are used for synchronous rectification in the secondary instead of diodes, the gates must be turned off at the right time. This usually requires a current-sensing technique, such as measuring the voltage drop across the MOSFETs.

Above resonance, instead of being limited by the magnetizing current, the tank current is higher than the magnetizing current. In this region, the synchronous switches can be turned on and off at the same time as the primary switches simplifying their control.

Since zero-voltage switching is used, an inherent benefit of the LLC resonant supply is low electromagnetic and radio interference. Up to a point, increasing switching frequency reduces transformer size and size of filter inductances and capacitances. LLC resonant converter ability to handle at no load conditions so it does not require infinite frequency at no load conditions.

A complete description of the LLC circuit includes the DC input, switch network (square wave generator), LLC resonant tank, transformer, rectifier, filter and load. To provide the variable DC application purpose, the LLC converter is widely used as the DC/DC converter following a fly-back converter. This converter provides multiple isolated voltage and it can operate over wide range of input voltage variation.

3 ANALYSIS OF LLC RESONANT CONVERTER WITH PARASITIC COMPONENTS

Fig. 2. The Circuit diagram of LLC resonant converter including parasitic components
Analysis of LLC resonant converter is mostly based on Fundamental Harmonic Approximation (FHA). This method always consider the fundamental components of the square wave voltage only that will be transfer the power to output. In traditional analysis of LLC resonant DC/DC converter without parasitic components (leakage inductance in primary and secondary sides of transformer) gives the approximate value of voltage gain. So some deviations occurs between practical and theoretical value.

Each parasitic components and for as follows.
- Coss : Output capacitance of MOSFET
- CTR : Transformer wiring capacitance
- L1ks : Leakage inductance at transformer secondary side
- Cjc : Junction capacitance of rectifier diode

Among these parasitic components, Coss can affect the applied voltage, \( V_{in} \). However, since the fundamental component of \( V_{in} \) is almost same to when Coss is excluded, the effect of Coss can be neglected in the proposed analysis. The effect of each parasitic component will be discuss in following section.

A. Leakage Inductance at Transformer Secondary Side

By including the leakage inductance at transformer secondary side (L1ks), the AC equivalent circuit and voltage conversion ratio equation of LLC Resonant Converter are as shown in Fig.

![AC equivalent circuit diagram of the LLC resonant converter with L1ks](image)

Fig.3. AC equivalent circuit diagram of the LLC resonant converter with L1ks

Concluded that including of L1ks at transformer secondary side cannot explain the voltage gain increase at high switching frequency in LLC Resonant Converter based on experimental result \( \frac{V_O}{V_S} \)

\[
= \frac{1}{2n} \left[ \frac{n^2 R_e}{n^2 R_{ac}} \left\{ j\omega n^2 L_{1ks} \left( \frac{\omega^2}{\omega_0^2} \times 1 + \frac{\omega^2}{\omega_0^2} \right) - L_M \times \frac{\omega^2}{\omega_0^2} \times 1 + L_M \times \frac{\omega^2}{\omega_0^2} \right\} \times \left\{ 1 + \frac{\omega^2}{\omega_0^2} \right\} \times 1 + \frac{\omega^2}{\omega_0^2} \right] \right]
\]
where $\omega_R = \frac{1}{\sqrt{C_R L_R}}$, $\omega_M = \frac{1}{\sqrt{C_R L_M}}$

**B. Transformer Wiring Capacitance**

By including the transformer wiring capacitance (CTR), the AC equivalent circuit and voltage conversion ratio equation of LLC Resonant Converter are as shown in Fig.

![AC equivalent circuit diagram of LLC resonant converter with CTR, L_{iks}](image)

Fig.4. AC equivalent circuit diagram of LLC resonant converter with $C_{TR}, L_{iks}$

\[
\frac{V_O}{V_S} = \frac{1}{2n} \left\{ n^2 R_{ac} \right\} \left\{ 1 - \frac{\omega_m^2}{\omega_R^2} \right\} + j \omega [n^2 L_{iks} \left\{ 1 - \frac{\omega_m^2}{\omega_R^2} \right\} \times \frac{\omega_m^2}{\omega_R^2} \times \left\{ 1 - \frac{\omega_m^2}{\omega_R^2} \right\}]
\]

where $\omega_R = \frac{1}{\sqrt{C_R L_R}}$, $\omega_M = \frac{1}{\sqrt{C_R L_M}}$, $\omega_{TR} = \frac{1}{\sqrt{C_{TR} L_{TR} L_{1ks}}}$

Generally, transformer wiring capacitance (CTR) is several Pico Farads (pF). In simulation, it is not the problem of increasing voltage gain with increasing switching frequency.

**C. Junction Capacitance of Rectifier Diode**

Fig.5 represents the AC equivalent circuit diagram of LLC Resonant Converter with all parasitic components and voltage conversion ratio follow as respectively

![AC equivalent circuit diagram of LLC resonant converter with all parasitic components and voltage conversion ratio follow as respectively](image)

Fig.5. AC equivalent
circuit diagram of LLC resonant converter with Llks ,CTR and Cjc

\[
\frac{V_O}{V_S} = \frac{1}{2n} \left[ \frac{n^2 R_{ac}}{(1 - \frac{\omega_C}{\omega} \omega^2) \left(1 - \frac{\omega_C}{\omega} \times (1 - \frac{\omega_C}{\omega}) \right)} \right]
\]

\[
= \frac{1}{2n} \left[ \frac{n^2 R_{ac}}{(1 - \frac{\omega_C}{\omega} \omega^2) \left(1 - \frac{\omega_C}{\omega} \times (1 - \frac{\omega_C}{\omega}) \right)} \right]
\]

where \( \omega_R = \frac{1}{\sqrt{C_R L_R}} \), \( \omega_M = \frac{1}{\sqrt{C_R L_M}} \), \( \omega_{TR} = \frac{1}{\sqrt{C_{TR} L_{1ks}}} \)

\( \omega_{jcM} = \frac{1}{\sqrt{C_{jc} L_M}} \)

Among these parasitic components, Junction Capacitance of Rectifier Diode is the main element. When the switching frequency increases correspondingly the voltage gain increases. Therefore voltage conversion ratio of LLC Resonant Converter varied depends on load condition and value of junction capacitance. His resonant frequency can be expressed as follows.

\[
F_{jc} = \frac{1}{2\pi \sqrt{C_{je} - C_{eq} L_r}}
\]

4 HIGH REVERSE CURRENT FLOW DUE TO PARASITIC CAPACITANCE

Transformers have parasitic Components that can cause them to deviate from their ideal characteristics. If the parasitic capacitance associated with the secondary can cause large resonating current spikes on the leading edge of the switch current waveform. These spikes can cause the regulator to exhibit erratic operating conditions that manifests itself as duty cycle instability. This effect is worsened in very high voltage designs. Attention to transformer design will cure this problem.

The transformers secondary provides the AC current path for parasitic capacitors. The current flowing through the secondary
produces \( N \) times the current in the primary. As the parasitic capacitance and turns ratio increase, the primary current becomes progressively larger. High reverse current flow can induced by the parasitic capacitance due to the oscillatory nature of the transformer. Well known transformer winding techniques can be used to minimize parasitic capacitance in transformers.

5 INFLUENCE OF PARASITIC COMPONENTS ON POWER MOSFET SWITCHING OPERATION IN POWER CONVERSION CIRCUIT

The parasitic components intrinsic in Printed Circuit Board (PCB) can cause the effects in power conversion circuit. The considerable value of parasitic components and their link in PCB provide Electromagnetic compatibility (EMC) problem for the switching operation of MOSFETs in the power conversion circuit with high frequency switching. When increase the lengthened of the circuit wiring, it will provide major impact due to the parasitic components. The switching transient response can be identified in DC-DC converter based on the Partial Element Equivalent Circuit (PEEC) method and modeled with circuit simulation.

6 LLC RESONANT CONVERTER FOR BATTERY CHARGING APPLICATION

The significant characteristics of the resonant converters are Low conduction loss, low switching loss, wide operating range, high efficiency, low electromagnetic interference, high power density, soft switching at both primary and secondary sides. Due to that feature makes the LLC resonant converter in the application of battery charging and also eliminates the main drawbacks of low and high-frequency current ripple on the battery, thus increase the life of battery becomes more vital in battery storage system. A constant
voltage charger consists a step down transformer with rectifier to provide a DC supply to charge the battery. This lead-acid cell battery used for cars. The output voltage regulation of LLC series resonant DC-DC converter consuming a PID controller can be used in feedback loop for the battery charging application. The PID controller is used to adjust the frequency of gate pulses generated by the pulse width modulation for deriving the MOSFETs to regulate the output voltage. The feature of the controller can set the output voltage level for both step and linear variations in the reference signal.

Fig.6. General Block Diagram Of Closed Loop System For Battery Charging Application

7 DESIGN CALCULATIONS

The design procedure for the converter is summarized in following steps.

STEP 1: The input power specification is

\[ P_{in} = \frac{P_0}{\eta} \]

STEP 2: The minimum resonant voltage is

\[ M_{min} = \frac{K}{K + 1} \quad M_{max} = \frac{V_{max}}{V_{in}} \cdot M_{min} \]

Here K is the gain of the converter, which will be in the range of 2-5.

STEP 3: The transformer turns ratio is calculated as

\[ \frac{V_{in}}{(V_G + V_f)} \]

Here \( V_f = 0.6 \)
STEP 4: Resonant parameters of a proposed converter to obtain a soft switching in converter.

\[ C_r = \frac{1}{2\pi Q f_0 R_{ac}} \]

\[ L_r = \frac{1}{4\pi^2 f_0^2 C_r} \]

\[ L_m = K L_r \]

8 CONCLUSIONS

Conventional analysis of LLC Resonant Converter cannot explain the practical phenomena such as increase of voltagegain at high switching frequency and unregulated output voltage during soft-start at no load condition. To overcome this limitation, analysis and design of LLC resonant converter including parasitic components are proposed in this paper. The proposed design guideline handles various aspects to design the LLC resonant converter. Therefore, the proposed design guideline is greatly suited for practical design of LLC resonant converter. The LLC resonant type converter will reduce the switching losses with improving the efficiency. Thus, with small switching frequency variations, compensation of the load variations and adjustment of the regulated output voltage in a wide range has been achieved. Soft switching is achieved for all power devices under all operating conditions that a constant output voltage is obtained without any distortion because of the filter capacitor used across the load. The steady state error is reduced in close loop system. Hence resonant converters can be used for battery applications because of their constant output voltage with reduced switching losses.

References


