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Implementation of 480W LLC Resonant Converter

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Abstract: This study presents the design of an LLC resonant converter as using the leakage inductance of the transformer instead of the inductance in the resonance tank. With serial resonant characteristics, the power MOSFETs are conducted at zero voltage switching and secondary diodes are commutating under soft switching, so the switching power losses on the semiconductor components are decreased. Using the proposed power stage and feedback control loop design considerations, the LLC resonant converter can achieve high power conversion efficiency and stability enhancement. This study provides the working principle of the resonant LLC converter topology by designing the simulation model.
Keywords: LLC Resonant Converter, Resonant Tank, Soft Switching, Switching Losses, Zero Voltage Switching

INTRODUCTION

The LLC resonant converter is the most suitable topology for designing switch mode power supply with stable output voltage [1]. It is able to regulate the output over wide line and load variations with a relatively small variation of switching frequency. Because the resonant converter has ZVS or ZCS function for reducing switching losses and keeping EMI in minimum, the resonant converter has been notably used in the power industry [2].

A massive quantity of literature deal with a guiding principle considering magnetic components, switching frequency f_s variation range, efficiency, and size [3]. The traditional isolated LLC resonant converter can success ZVS for the primary-side switches and ZCS for the secondary-side rectifiers [4,5,6]. For the conventional LLC resonant converter, three magnetic components are required for the series resonant inductance, parallel inductance, and the isolated transformer. To lessen the magnetic component count, the leakage inductance and the magnetizing inductance of the transformer are utilized as the series resonant inductance L_r and the parallel resonant inductance L_m, respectively [7,8] as shown in Fig. 1. The leakage inductance of the transformer is utilized as a resonant inductance. Advantages:

- Low cost, only one magnetic component is required
- The generally smaller size of the converter
- Insulation between primary and secondary side is easily performed
- Better cooling conditions for transformer winding

In latest years, the digital control for switching power supplies is gaining attention to acquire the high-performance characteristic power converters. The digital control has the advantages of realizing high-performance control and it is able to easily communicate to the other components [9,10].

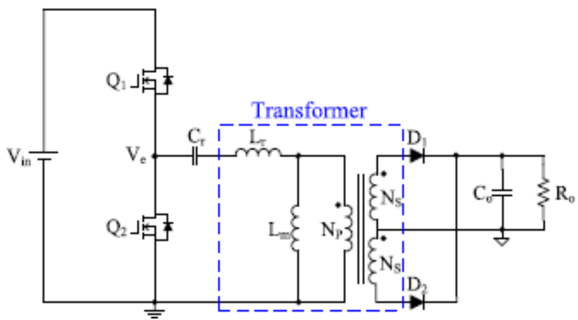

Figure 1. Integrated transformer employed for LLC resonant converter

The PI controller is common to give control signals on LLC resonant tank. The PI algorithm is

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also used to keep the output voltage regular and success the steady state error zero.

In this study, we present the modeling, design, and implementation of an LLC converter which is controlled digitally with PI control algorithm. The leakage inductance of the transformer was utilized as serial inductance and parameters of converter were calculated with the effect of this leakage inductance. The use of frequency control, LLC resonant converter can handle regulated output voltages even in the case of wide input voltage or output load variations.

MATERIAL AND METHOD

LLC Converter Configuration

Operation

The operation of an LLC resonant converter may be characterized through the relationship of the switching frequency, denoted as f_s, to the series resonant frequency (f_{r1}). Fig. 2, Fig. 3 and Fig. 4 illustrate the typical wave-forms of an LLC resonant converter with the switching frequency at, below, or above the series resonant frequency [11,12]. The graphs show, from top to bottom, the $Q1$ gate (V_{g_Q1}), the $Q2$ gate (V_{g_Q2}), the switch-node voltage (V_{sq}), the resonant circuit's current (I_r), the magnetizing current (I_m), and the secondary- side diode current (I_s). Here the primary-side current is the sum of the magnetizing current and the secondary-side current referred to the primary.

a. ***Operation at Resonance:*** In this mode, the switching frequency is the similar to the series resonant frequency. When switch Q_1 turns off, the resonant current falls to the value of the magnetizing current, and there is no in addition transfer of energy to the secondary side. Through delaying the turn-on time of switch Q_2, the circuit achieves primary-side ZVS and achieves a soft commutation of the rectifier diodes on the secondary side.

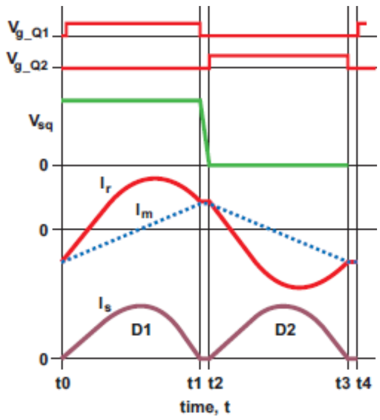

Figure 2. At resonant frequency

b. ***Operation Below Resonance***: Here the resonant current has fallen to the value of the magnetizing current before the end of the driving pulse width, causing the power transfer to cease despite the fact that the magnetizing current continues. Operation below the series resonant frequency can still accomplish primary ZVS and success the soft commutation of the rectifier diodes on the secondary side. The secondary-side diodes are in discontinuous current mode and need more circulating current in the resonant circuit to deliver the same amount of energy to the load. This additional current results in higher conduction losses in both the primary and the secondary sides.

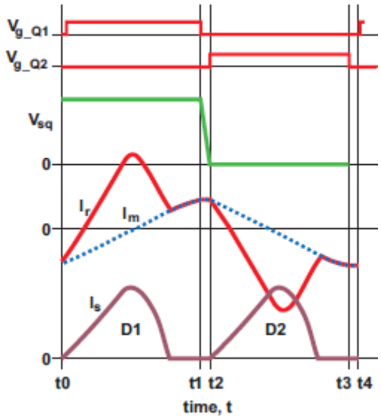

Figure 3. Below resonant frequency

c. ***Operation Above Resonance:*** In this mode, the primary side presents a smaller circulating current in the resonant circuit. This reduces conduction loss due to the fact the resonant circuit's current is in continuous-current mode, resulting in less RMS current for the same amount of load. The rectifier diodes are not softly switched, and reverse recovery losses exist, but operation above the resonant frequency can still success primary ZVS.

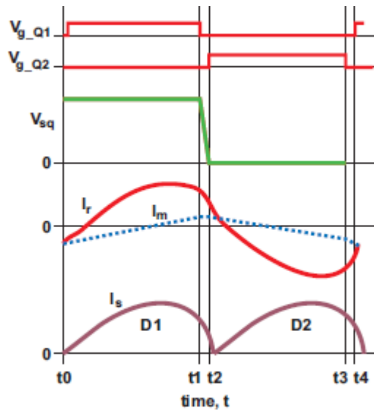

Figure 4. Above resonant frequency

Selection of Optimum Design Parameters

In order to validate the converter, the converter was designed as 48V/10A output, nominal 230 V AC input, 480 W. The usage of the traditional model, a power stage design method has been properly derived using first harmonic approximation (FHA) that could attain the design equations [11]. These design equations for the transformer turns ratio (n), coefficient factor from leakage inductance (M_k), the equivalent load resistance (R_{ac}), primer inductance (L_p), the transformer's magnetizing inductance (L_m), resonant inductance (L_r) and resonant capacitor (C_r) are shown as below [13,14,15]:

$$V_o = \frac{V_i . K(\omega)}{2.n} \quad (1)$$

$$M_k = \sqrt{\frac{L_p}{L_p - L_r}} \quad (2)$$

$$R_{ac} = \frac{8.n^2.V_o}{\pi^2.M_k.I_o} \quad (3)$$

The resonant tank parameters equations are below:

$$C_r = \frac{1}{2.\pi.f_s.Q.R_{ac}} \quad (4)$$

$$L_r = \frac{1}{(2.\pi.f_s)^2.C_r} \quad (5)$$

$$L_p = m.L_r \quad (6)$$

There are two resonant frequency f_{r1} and f_{r2}. The gain is fixed at resonant frequency f_{r1} regardless of the load variation. Peak gain frequency exists between f_{r1} and f_{r2}. f_{r1} is short circuit resonant frequency and f_{r2} is open circuit resonant frequency. The best way to operate the LLC resonant converter on the efficiency point of view is to let it work directly at the resonant frequency f_{r1}. Under this condition, the switching loss is minimized, and the circulating energy in the resonant network is also low. This optimal operating point can be reached only for one given input voltage and load resistance value. Thus, in the practice, the LLC resonant converter usually designed under the f_{r1} for a full load.

$$f_{r1} = \frac{1}{2.\pi.\sqrt{L_r.C_r}} \quad (7)$$

$$f_{r2} = \frac{1}{2.\pi.\sqrt{(L_r + L_m).C_r}} \quad (8)$$

$$K(\omega) = \frac{(\frac{\omega}{\omega_r})^2.(m-1).M_k}{(\frac{\omega^2}{\omega_p^2} - 1) + j.\frac{\omega}{\omega_r}(\frac{\omega^2}{\omega_r^2} - 1).(m-1).Q} \quad (9)$$

Where Q is the quality factor chosen by 0.4, f_{r1} and f_{r2} are resonant frequencies calculated by L_r and C_r, m is the ratio between leakage and primer inductance chosen by 4. f_s is selected as 120 kHz.

Table 1. The Used Simulation Parameters of The Converter

Parameters	Values
Nominal Input Voltage	230V AC/ 325V DC
Minimum Input Voltage	130V AC/ 184V DC
Maximum Input Voltage	270V AC/ 382V DC
Output Voltage	48V DC
Maximum Power	480W
Series Resonant Capacitance	100nF
Resonant Inductance	20uH
Primer Inductance	81,5uH
Transformer Turn Ratio	3,33

RESEARCH FINDINGS

The operation of the resonant LLC converter is performed in LTSpice simulation tool. In the simulation, the resonant converter's behavior modeled for different load and line variations. The parameters of the resonant converter are summarized in Tab. I.

f_{r1} and f_{r2} are calculated from (7) and (8) as 113kHz and 56 kHz. According to these frequencies and gain characteristic formula (9), maximum gain is 1,92 in full load and the gain is 1,15 in the resonant situation.

Fig. 5 shows output voltage and resonant current in 270V nominal input voltage and 113 kHz switching frequency. Switching frequency is same as the resonant frequency. And the resonant current is the pure sinusoidal wave.

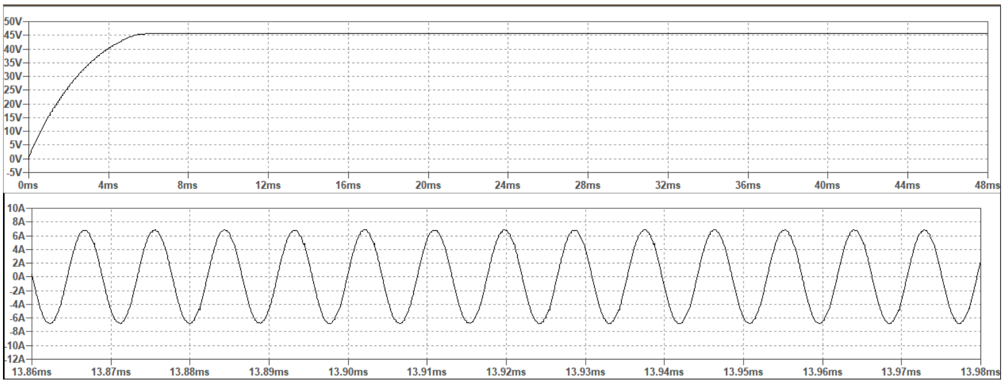

Figure 5. Vo and Ir at resonant frequency

Resonant LLC converter could work at frequency beneath and above the oscillation frequency. Fig. 6 shows the below resonance operation of the converter for 48V/10A. In this situation, input voltage is the minimum as 184V and the switching frequency is 72 kHz. I_r is higher than the current at resonant frequency but the wave-form is far from pure sinusoidal.

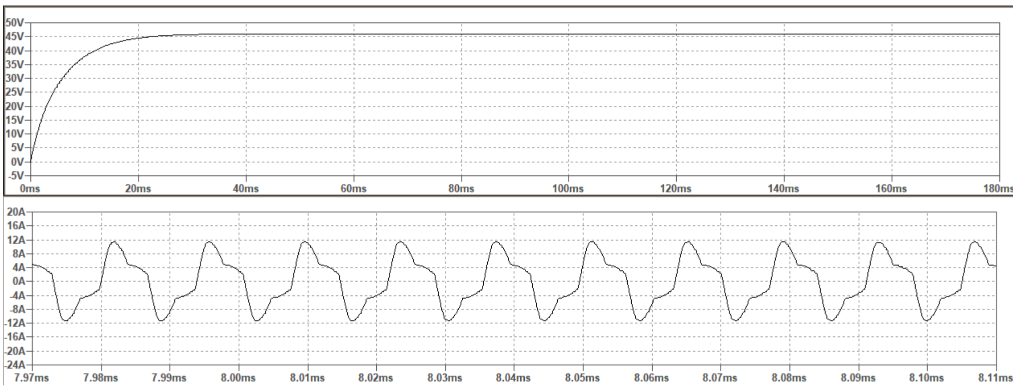

Figure 6. Vo and Ir at below resonant frequency

Fig. 7 shows the above resonance operation of the LLC converter. In this situation input voltage is the maximum as 325V and switching frequency is 172 kHz. Below the oscillation frequency, working condition permits the zero current soft commutation of the secondary part diodes while circulating current is larger. It moves further upward as the operation frequency moves downward from the resonant frequency. Again wave-form is not purely sinusoidal. To provide appropriate gain value that achieved output voltage according to considerations.

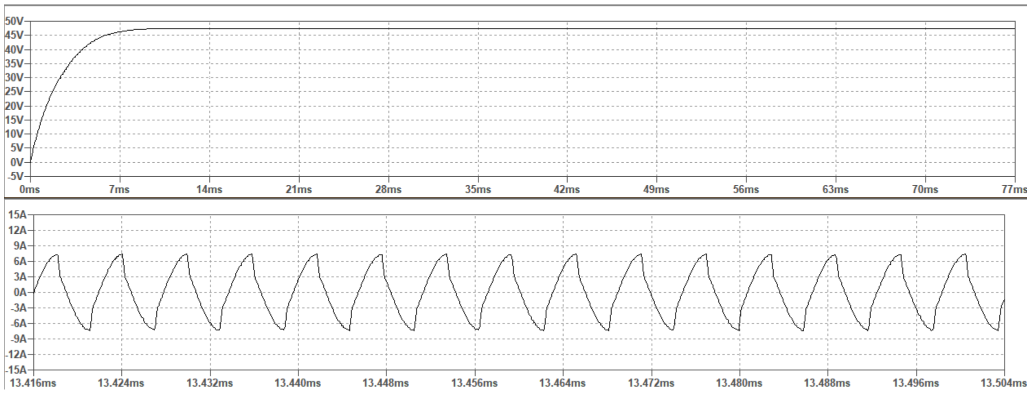

Figure 7. Vo and Ir at above resonant frequency

CONCLUSIONS AND DISCUSSION

This work gives design and implementation of a resonant LLC converter which is controlled digitally through PI control method. The resonant LLC converter's simulation circuit are shown, and operations of the converter are discussed. The efficiency and cost-optimal designations are suggested by focusing on the resonant components and switching frequencies. Design is realized with the impact of leakage inductance of the transformer. The converter is properly operating under the soft switching condition.

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