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Research Article

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LLC Power Converter for Low-Power Application

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Abstract: The LLC resonant converter topology is known for its ability to achieve high efficiency, wide input voltage range, and soft-switching characteristics. These half-bridge power stages are known to achieve higher efficiency; however, they come with the added complexities of operating in the resonant mode. This paper presents detailed calculations for designing an LLC configuration resonant half-bridge converter that uses a capacitor (C) and two inductors (LL). This paper also discusses key design considerations, such as the selection of the resonant frequency, transformer design, and control strategies to optimize the converter's performance. The design approach was verified using bench-testing measurements, which demonstrated the effectiveness of the proposed converter.

Keywords: LLC resonant converter, half-bridge converter, high efficiency, low power application, LED drivers, EMC, EMI, Energy star rating

1. Introduction

DC-DC power converters are essential components in a wide range of applications, from renewable energy systems to home automation. Among the various converter topologies, LLC resonant half-bridge converters have gained significant attention owing to the popularity of the Energy Star rating, their high efficiency, and their ability to operate at low switching losses. Their ability to operate at high switching frequencies reduces the overall size and weight of the system. However, designing LLC resonant half-bridge converters presents significant challenges because they perform power conversion using frequency modulation instead of the more common pulse-width modulation (PWM), which requires a distinct design approach. The LLC topology employs a series resonant capacitor and two inductors that provide soft-switching capabilities, resulting in reduced switching losses and increased efficiency. While the LLC converter topology is widely used in high-power applications, there is a need for optimized designs for low-power applications such as LED drivers, battery chargers, and household electronics.

This paper presents the detailed design and steps involved in designing a 96 W LLC half-bridge converter for low-power applications such as LED drivers, based on the calculations and design methodology outlined in the reference paper "Designing an LLC Resonant Half-Bridge Power Converter" by Hong Huang. Although Huang [1] provided a comprehensive theoretical framework for designing such converters, this study aimed to address these challenges by presenting a practical design methodology for an LLC resonant half-bridge converter, focusing on magnetic design and frequency selection. This paper begins by providing a brief review of the basic operation of the resonant converter and its key design requirements. To demonstrate how a practical design is created step-by-step, this paper presents a 96 W output converter design with 448V VDC input, followed by a conclusion with the results of bench-tested performance measures. The proposed design also considers the effects of electromagnetic compatibility and electromagnetic interference, which are critical factors for ensuring compliance with regulations and standards, particularly in low-power applications where the converter is integrated into a larger system.

A. Review of Resonant Converters

A resonant power converter is a DC-DC power converter that uses resonant circuits to shape the voltage and current waveforms of active switches to achieve ZVS and/or ZCS. Energy circulates in the resonant circuit, and some or all of it is tapped off to supply output. More detailed descriptions and discussions can be found in the literature [1]. They operate by creating a resonant circuit using inductors and capacitors, which allows for soft switching of power semiconductors. This results in lower electromagnetic interference (EMI) and higher overall efficiency compared with traditional hard-switched converters.

Examples of resonant power converters include the following.

1. Series Resonant Converter (SRC)[2]: A series LC circuit is used to achieve resonance. It operates efficiently under light loads but struggles with voltage regulation at higher loads.

2. Parallel Resonant Converter (PRC)[2]: A parallel LC circuit is used for the resonance. It maintains good voltage regulation at heavy loads but is less efficient at light loads.

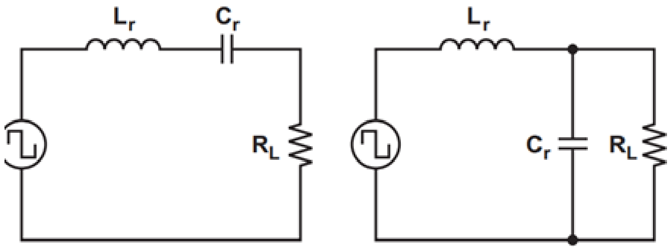
3. Series-Parallel Resonant Converter (SPRC): Combines features of both SRC and PRC to achieve better performance across a wide load range. [2]

4. LLC Resonant Converter [2]: It uses two inductors (L) and one capacitor (C) in its resonant tank. It offers high efficiency, a wide input voltage range, and good voltage regulation across various load conditions.

5. LCC Resonant Converter [2]: One inductor (L) and two capacitors (C) are used in its resonant circuit. It provides good voltage regulation and efficiency over a wide load range.

6. Multi-Element Resonant Converter [2]: Incorporates additional resonant elements to achieve specific performance characteristics or optimize efficiency across a broader operating range.

Among the different types of resonant converters, SRS and PRC form the basic topologies, whereas other topologies, such as LLC and LCC, are combinations that provide superior performance.



a. Series resonant converter.

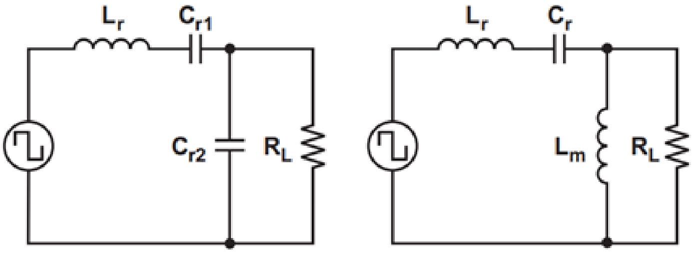
b. Parallel resonant converter.

Figure 1: Basic resonant converter configuration [1]

B. Basic operation of an LLC Half-Bridge Power Converter

The SPRC shown in Fig. 2 is a combination of basic series and parallel-resonant converters. This addresses some of the challenges presented by basic parallel and series converters. The converter uses a resonant tank network consisting of a series inductor, series capacitor, and magnetizing inductor in the LLC formation and an inductor and two capacitors in the LCC formation.

One version of the SPRC, the LCC converter, helps overcome the limitations of the SRC or PRC by having a higher resonant frequency. However, this requires two separate physical capacitors that are typically large, bulky, and often expensive because of their high AC currents. In LLC topology, the two physical inductors can often be integrated into one physical component with both series resonant inductor Lr and magnetizing inductance Lm [1].



a. LCC configuration.

b. LLC configuration.

Figure 2: Two types of SPRC [1]

The LLC configuration offers several advantages over the conventional resonant converters. One of the main advantages is the ability to maintain a high efficiency over a wide range of output voltages, input voltages, and load currents with small variations in the switching frequency. This provides evidence for designing EMI and EMC issues that could restrict product regulators' feasibility. This study focuses on the LLC resonant configuration implemented in an isolated half-bridge topology. The following sections describe this topology in detail and outline the practical design procedure.

2. Literature Review

A. Definition of a Half-Bridge Power Converter

A half-bridge power converter is a type of DC-DC or AC-DC converter topology that is commonly used in power electronics to efficiently convert electrical energy from one voltage level to another. A half-bridge topology typically consists of two power switches (usually MOSFETs or IGBTs), capacitors, and a transformer or inductor. Zero-voltage switching can best be defined as conventional square-wave power conversion during the switch's on-time with "resonant" switching transitions.

B. Key Characteristics of a Half-Bridge Power Converter:

The half-bridge converter operates by energizing the two switches alternately, thereby creating a unipolar or bipolar square-wave voltage across the resonant tank. The two switches are turned on alternately, typically using a PWM based on the power needs and dead time to avoid cross-conduction, where both switches could be ON simultaneously. Due to this dead time, the PWM can have a maximum duty cycle of 50%.

Energy Transfer: Energy is transferred from the primary side of the transformer to the secondary side, where it is rectified and filtered to provide a stable output voltage. The transformer provides electrical isolation between the input and output, which is crucial for the safety of many applications.

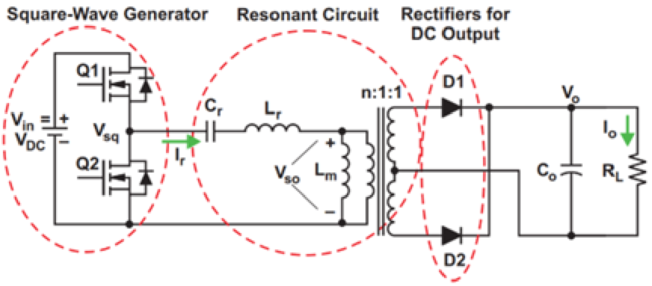
Switching Method: The half-bridge converter can operate in either hard-switching or soft-switching mode. In hard-switching, the switches transition at non-zero voltage and current, leading to higher switching losses. In soft-switching configurations, such as LLC resonant converters, zero-voltage switching (ZVS) or zero-current switching (ZCS) is employed to minimize switching losses[3]. Zero-voltage switching can best be defined as conventional square-wave power conversion during the switch's on-time with "resonant" switching transitions.[4]

Half-bridge power converters are widely used in low-to medium-power applications, such as power supplies, LED drivers, motor drives, and consumer electronics. Their ability to provide a high efficiency, compact design, and electrical isolation makes them suitable for a wide range of power conversion tasks.

C. LLC Topology Operation

The operation of an LLC resonant converter revolves around the resonance between the inductive and capacitive components, which allows efficient energy transfer while minimizing switching losses. The LLC converter utilizes a resonant tank circuit composed of two inductors (series resonant inductance and magnetizing inductance of the transformer) and one capacitor. This design enables the converter to achieve zero-voltage switching (ZVS) and, in some cases, zero-current switching (ZCS), thereby reducing heat generation and improving overall efficiency.

The key feature of the LLC resonant converter is its ability to operate in three distinct frequency modes: below resonance, at resonance, and above resonance. Each mode corresponds to a different energy transfer behavior and influences the efficiency and switching characteristics of the converter.



a. Typical configuration.

Figure 3: LLC resonant half-bridge converter [1]

Below Resonant Frequency (Inductive Mode): In this mode, the converter operates with ZVS, where the switching transistors turn on when the voltage across them is nearly zero, significantly reducing the switching losses. However, operation below the resonant frequency requires more circulating current in the resonant tank to deliver the same power to the load, which leads to increased conduction losses. This mode is typically used under light loads, where ZVS is maintained without causing large energy dissipation.[1][4]

At Resonant Frequency (Optimal Mode): At the resonant frequency, the impedance of the resonant tank is at its lowest, allowing maximum power transfer with minimal losses. The converter operates at peak efficiency in this mode as the switching transistors turn on and off when both the voltage and current are at their minimum. This is the most efficient operating point for LLC converters, making it ideal for full-load conditions.[1][5]

Above Resonant Frequency (Capacitive Mode): In this mode, the converter can achieve zero-current switching (ZCS), but at the cost of increased switching losses. The current flowing through the resonant tank was lower, resulting in reduced energy transfer to the load. Operating above the resonant frequency is generally avoided because it leads to higher switching losses and inefficient power conversion, particularly in low-power applications.[1][4]

The LLC resonant converter's ability to switch between these modes allows it to constantly adjust its function based on the load conditions and input voltage fluctuations. Frequency modulation is used as the primary control method over PWM to regulate output voltage in LLC converters, providing it the ability to control energy transfer while maintaining high efficiency. This flexibility makes LLC converters highly adaptable to various applications, including low-power devices and consumer electronics.

3. Design Considerations

For the calculations, a 96 W LLC converter was used with the following specifications. Detailed definitions of the below parameters can be found in the reference [1]

Output Power (approx)	Pout_nom = 96W
Output Voltage	Vout = 24V
Minimum Input Voltage	Vin_min = 448V
Maximum Input voltage	Vin_max = 475V
Nominal Input voltage	Vin_Nom = 465V
Resonant Frequency	Freq_Res = 80k Hz
Efficiency Considered	LLC_Efficiency = 98%
Line frequency	f = 60Hz
Ambient temperature	Ta 80 °C
Output voltage regulation	Vout_Load_regulation □ 1%

With the above information, we can calculate Input Power as

Pin = Pout_nom*[1 + (1 - LLC_Efficiency)]

$$\text{Pin} = 97.92\ \text{W} \tag{1}$$

Output load resistance at full load

$$RL = \frac{Vout^2}{Pout_{nom}} = 6\Omega \tag{2}$$

Output Current:

$$Iout = \frac{Pout_{nom}}{Vout} = 4\ A \tag{3}$$

Transformer Turn Ratio

The transformer turns ratio is chosen by considering gain as 1

$$n = floor\left(\frac{Vin_{nom}}{2Vout}\right) = 9 \tag{4}$$

Max and Min Gain calculation

$$Min_{gain} = \frac{n{*}Vout{*}2}{Vin_{Max}} = 0.909 \tag{5}$$

$$Max_{gain} = \frac{2n\left(Vout + 0.7V + \frac{Pout_{nom}{*}1-LLC\_Efficiency}{Iout{*}LLC\_Efficiency}\right)}{Vin\_Min} * 1.05$$

0.7V is assumed as the forward voltage for the diode used, and the system is assumed to be at 105% load condition for the maximum load condition.

$$\text{Max\_gain} = 1.063 \tag{6}$$

AC Equivalent Load Resistance.

$$Rac = \frac{8{*}n^2{*}RL}{\pi^2} = 393.937\ \Omega \tag{7}$$

Selection of the Quality Factor and Inductance Ratio

For the transformer core used and the leakage characteristics of the transformer

Quality factory Qe = 0.7677

Inductance ratio Ln = 4.2.

A separate MATLAB simulation was performed to identify the switching frequency for the operation. The detailed code can be found in the reference [K]

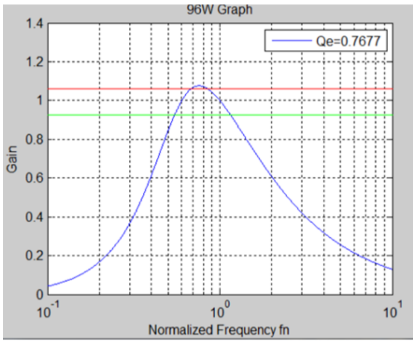
Selected based on gain versus normalized frequency graph 1 and graph 2.

Fn_min = 0.85

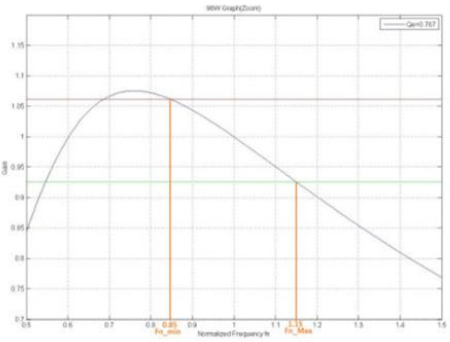
Fn_Max = 1.15

$$\text{Freq\_Sw\_Max} = \text{Fn\_Max Freq\_Res} = 74.75\text{kHz} \tag{8}$$

$$\text{Freq\_Sw\_Min} = \text{Fn\_Min Freq\_Res} = 55.25\text{kHz} \tag{9}$$



Graph 1: Normal frequency vs. Gain at Qe = 0.7677



Graph 2: Zoomed Graph 1 at the peak of the curve

Resonant tank Calculations

Series Resonant circuit: This consists of a series of components Capacitor (Cr) and inductor(Lr), as shown in Fig. 3

Series capacitor

$$Cr = \frac{1}{2*\pi*Qe*Freq\_Res*Rac} = 8.09*10^{-9}\ F \qquad (10)$$

Selecting the capacitor as B32672L8822 [7]
Cr_Sel= $8.09*10^{-9}$ F

Series Inductor

$$Lr = \frac{1}{Cr*(2*\pi*Freq\_Res)^2} = 74.05*10^{-3} H \qquad (11)$$

The parallel resonant inductor is represented by Lm, which can also be the transformer of the half-bridge topology.

$$Lm = Ln*Lr = 3.11*10^{-3} H \qquad (12)$$

The primary current on the primary side of the transformer can be considered a combination of the load-reflected current and RMS magnetizing current at the minimum switching frequency.

$$Ior = \frac{\pi*Iout}{2*sqrt(2)*n}$$

$$ILm = \frac{\pi*n*Vout}{2*sqrt(2)*2*\ \pi*Freq*Lm}$$

Ior = 0.494 A ; ILm = 0.22A
Total Primary side current =

$$I_{pri} = \sqrt{Ior^2 + ILm^2} = 0.541A \qquad (13)$$

By calculating the necessary parameters and measurements, we selected the components as follows:
Designing the practical Series inductor with a 5% tolerance

$$Lr\_sel = \frac{1}{(2*\pi*Freq_{Res})^2 * Cr\_Sel}$$

$$Lr\_Sel = 731*10^{-6} H$$

The core used is JSF/FDK/EE19/16H material 6H20

$$Al_{Lr} = 92.6*10^{-9} H$$

$$Ae_{Lr} = 0.44*10^{-3}(m)^2$$

Primary turns $N_{Lr} = Ceil\left(\sqrt{\frac{Lr_{Sel}*1.05}{(Al)Lr}}\right) = 92$ turns

Parallel Inductor selection

Turns ration n =9

$$Lm_{Sel} = Ln*Lr_{Sel} = 3.071*10^{-3} H$$

Core used B66408G0000X187 gapped

Primary turns N_Pri = $Ceil\left(\sqrt{\frac{Lm_{Sel}*1.1}{Al}}\right) = 117$ turns

Secondary turns N_Sec = $Ceil\left(\frac{Npri}{n}\right) = 13\ turns$

Using the above-calculated and selected parameters, a circuit similar to that shown in Fig. 3 was constructed and measured for functionality and efficiency.

4. Practical Results

A physical converter was built and bench-tested to verify the performance of the design. Based on the above calculation, an LED driver was designed, and the measurement of efficiency, power factor correction, and zero-crossing switching were verified. The major advantage of having the LLC topology is that it eliminates the need for two separate inductors for the magnetizing inductor. A half-bridge transformer was used, and a single transformer acting as both an inductor and a half-bridge transformer was designed. A variable power line from 108V to 277V was applied at 60 Hz frequency based on the US line standards.

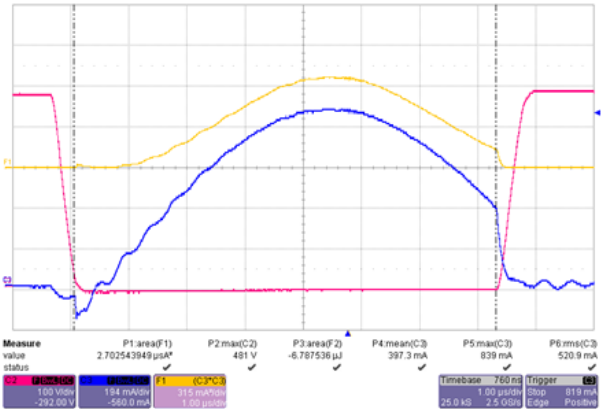


Figure 4: Zero voltage switching

The graph in Fig.4 shows the switching of the voltage and current waveform at the zero crossing to reduce the amount of switching power dissipation. This supports the MOSFETs and other components used to operate at low temperatures, even at higher ambient temperatures.

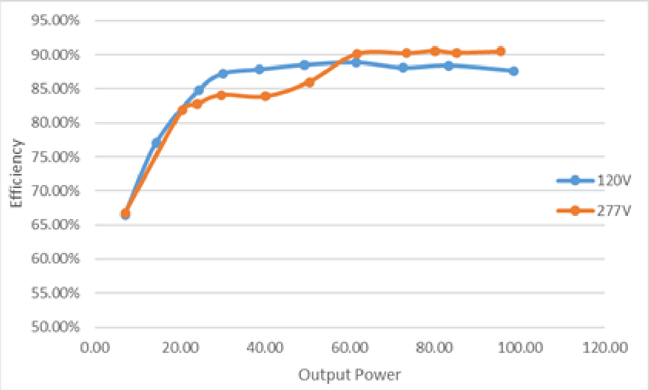


Figure 5: Efficiency measure over variable load variable voltage.

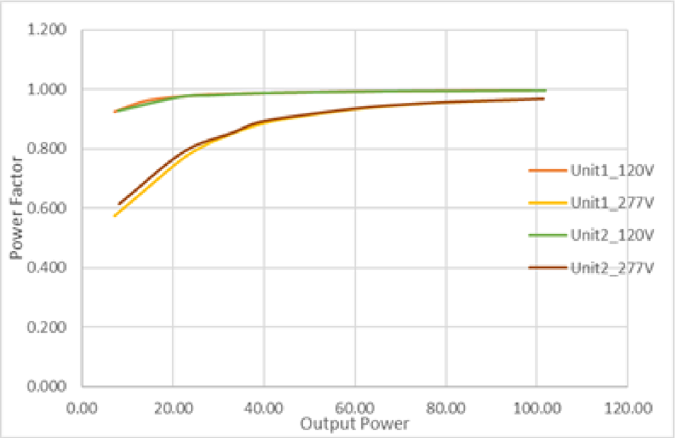


Figure 6: Output power vs Power factor.

Based on the observation with practical measures taken on a power analyzer, the efficiency is higher when the operating power or load is higher, and efficiency significantly drops at a lower operating power. This is because of the boost stage used in the conversion of the AC line to DC voltage, signifying that the LLC topology's efficiency and performance are often limited by the converters used prior to the LLC stages.

5. Conclusion

This study offers extensive insights into the design considerations and step-by-step process of designing an LLC resonant half-bridge converter. The effectiveness of the frequency modulation and first harmonic approximation in LLC demonstrates the high-efficiency yield in low- and medium-power applications, such as LED drivers and consumer electronics. In addition, a detailed example is provided to illustrate the practical approach.

6. Acknowledgements

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