Design and Simulation of Two Proposed LLC DC-DC Resonant Converters

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Abstract
This paper introduces two proposed LLC (Inductor-Inductor-Capacitor) DC-DC resonant converters aimed at electronic applications. The first converter is designed to operate as a positive power supply, while the second functions as a negative power supply, together forming a flexible configuration capable of serving either single output (+V) systems or dual output (±V) systems. Both circuits were modeled and simulated using OrCAD-PSpice, a tool providing high accuracy in replicating real-world circuit behavior and the results of physical experiments. Their performance was validated through integration into a class D audio amplifier, demonstrating effective power delivery and reliable operation of the complete system. By tackling the design struggles, the proposed designs offer efficient and reliable solutions, provide a contribution to the development of modern low-power systems, suitable for both single and dual output configurations.

Keywords : LLC converter, Power supply, Circuit, Design, Orcad-PSpice.

1. Introduction

Recent papers have received significant attention regarding DC-DC converters, emphasizing their essential role in modern power conversion systems. In this context, the LLC resonant converter continues to stand out due to its proven advantages, such as soft switching, low electromagnetic interference (EMI), high efficiency, and compact design, which make it especially suitable for demanding applications. As a result, it has been widely integrated into systems such as data centers, server power supplies, microgrids, and electric vehicle chargers. Furthermore, the ability of LLC converters to accommodate wide input and output voltage variations enhances their adaptability across diverse power electronics environments (Zhang *et al*., 2024).

Historically, LLC resonant converters were primarily employed as energy efficient power supplies for consumer electronics, such as large-screen televisions and household appliances (Jang *et al*., 2015). They are still widely used in modern consumer devices, including LCD and OLED TVs and high-efficiency laptop adapters.

Over time, their role has significantly expanded into more sophisticated and larger-scale energy conversion systems, driven by their superior efficiency and operational reliability. Resonant DC-DC converters are now favored in sectors such as renewable energy, contactless energy transmission, and electric vehicle (EV) technologies (Grigorova *et al*., 2023).
In power converter applications, solid-state devices typically operate at very high switching frequencies. As a result, switching losses often exceed conduction losses, becoming a dominant source of power loss and reduced efficiency in converter circuits (Selvaperumal *et al*., 2009). To address this challenge, resonant converters such as the LLC topology have been proposed.

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In fact, the LLC resonant converter is widely adopted due to its cost-effectiveness, high power conversion efficiency, straightforward design approach, and simple control algorithms. By leveraging resonance, this type of converter achieves zero voltage switching (ZVS) and zero current switching (ZCS) on its power switches, significantly reducing switching losses compared to traditional hard-switching converters. Previous research has introduced several resonant network topologies to achieve soft-switching behavior, including LC series, LC parallel, LLC, LCL, CLL, and CLLC configurations. Among these, the LLC resonant tank stands out by providing ZVS on the primary-side switches, ZCS on the secondary-side rectifier, and minimizing circulating current through the transformer (Park *et al*., 2020).

2. Contributions

Many specialized electronic systems require both positive and negative DC voltages. This paper introduces two proposed, low-power LLC resonant converter circuit designs proposed by the author. The first converter is optimized for generating a stable positive voltage and can operate independently for systems requiring only a positive supply, the second converter is uniquely designed to deliver a stable negative DC voltage.

The core contributions of this work are three-fold:

1. Proposed circuit designs: the development of original, specialized low-power LLC resonant converter circuits (positive and negative) tailored for single/dual rail requirements.
2. Addressing the negative supply gap: the proposal includes a negative LLC resonant converter circuit itself, which is a significant contribution as such designs are rarely explored or published in the specialized literature, offering a unique solution for dual-rail applications.
3. No-load and loaded performance optimization: the proposed converters demonstrate excellent performance under no-load conditions, with accurate voltage regulation and stable operation. Moreover, when a class-D amplifier load is applied, the converters continue to deliver reliable and precise output, confirming their robustness under both no-load and loaded scenarios.

By exploring the fundamental characteristics and control strategies of these author-proposed converters, this work offers a reliable, efficient, and flexible dual-rail DC power generation approach for compact electronic applications.

3. Understanding resonant converter

Figure 1 presents a half-bridge LLC converter with full-bridge rectifier.

Simply put, the switching bridge produces a square waveform that excites the LLC resonant tank, which will resulting in a resonant sinusoidal current that gets scaled by the transformer and rectified by rectifier circuit, and filtered by the output capacitor that provides a smooth DC voltage (Abdel-rahman, 2012).

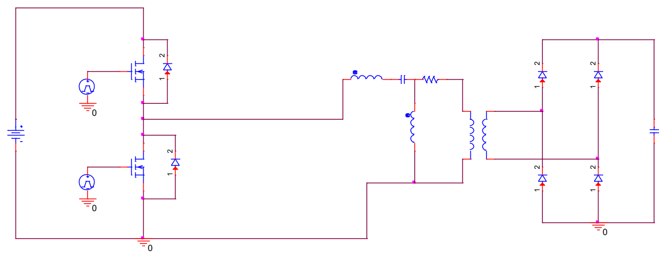

Figure 1. Half-bridge LLC converter with full-bridge rectifier

The structure of the LLC resonant converter can be divided into several key stages, each fulfilling a distinct function, as detailed below: (Hackatronic, n.d.)

1. Switching stage: this stage employs either a half-bridge topology using two MOSFETs or a full-bridge configuration with four MOSFETs, the former being suitable for low power applications like this paper's proposal and the latter being suitable for high power applications.
2. Resonant tank: L_r is a series inductor responsible for resonance, C_r is the resonant capacitor that forms the LC circuit, and L_m is the magnetizing inductance of the transformer, which provides zero current switching (ZCS) at the output rectifiers and helps shape the gain curve.
3. Transformer: provides galvanic isolation and allows for voltage scaling either step-up or step-down.
4. AC source and input filter: a bridge rectifier converts AC to DC, and a DC link capacitor filters the ripple and stabilizes the DC bus.

4. Proposed circuits

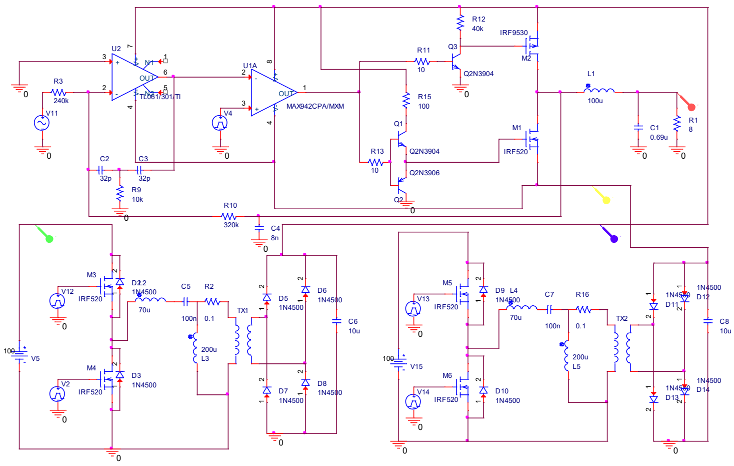

Figure 2. Proposed circuits validated using a class D audio amplifier

To achieve a bipolar supply, two LLC topologies were proposed and designed. While the first converter provides a positive rail, the second converter was modified to deliver a negative rail by mainly reversing the orientation of the diodes within the rectifier bridge (see Figure 2) and tuning the control parameters. This dual-rail structure is essential for applications requiring symmetrical power, such as the class D audio amplifier, while maintaining the advantages of galvanic isolation and soft-switching (ZVS) in both converters under no-load and loaded conditions.

To construct the two LLC resonant converters, I used IRF520 MOSFETs to build the half-bridge stage, to enhance reliability and performance, a 1N4500 diode is placed in parallel with each MOSFET to handle reverse currents, protect against voltage spikes, and enable soft-switching, reducing losses and EMI, along with two inductors and a capacitor to form the resonant tank. A transformer was used, a small 0.1Ω resistor was added between the resonant tank and the transformer for accurate current sensing and slight damping of high-frequency oscillations, 1N4500 silicon rectifier diodes to realize the full-bridge rectifier. Finally, a capacitor was added as a passive output filter to smooth the voltage. (see Figure 2)

The two LLC circuits successfully powered the class D low-power audio amplifier proposed by (Bellili *et al.*, 2022). The system operated reliably, and the output signal is clean and stable.

5. Results and discussion

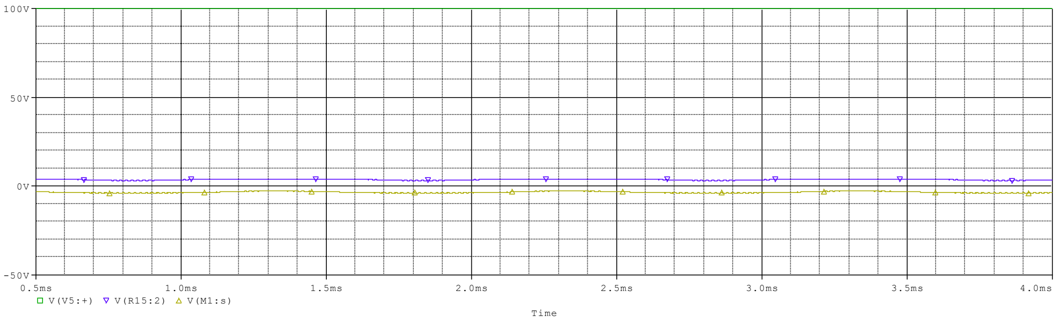

Figure 3. DC outputs of the input supply and the proposed LLC converters

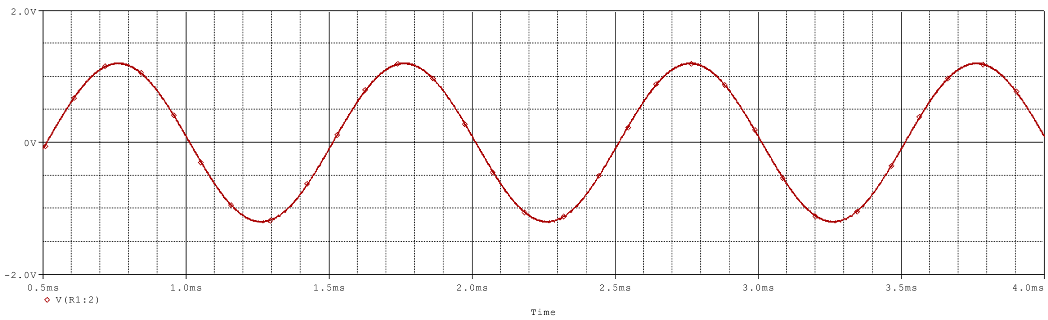

Figure 4. Output voltage of the class D audio amplifier

Figure 3 displays the voltage levels achieved by converting a single DC input into dual low-voltage DC rails using the two proposed LLC resonant converters. The resulting outputs include three stable DC levels: the original input voltage, a positive rail, and a negative rail. This conversion highlights the LLC converters' ability to provide precise voltage regulation and galvanic isolation, making them well suited for applications requiring symmetrical power supplies, such as differential circuits or audio systems, while remaining suitable for systems that require only a positive voltage.

Figure 4 displays the output waveform of the class D audio amplifier powered by the proposed LLC resonant converters. The output signal is a smooth, clean and well-shaped sinusoidal waveform, confirming the amplifier's capability to deliver high-fidelity audio performance. The design of the LLC converters contributes to enhanced efficiency, reduced thermal stress on components, and low electromagnetic noise, ensuring optimal audio quality.

5.1 Analytical background

This analytical background is based on the no-load LLC circuit displayed in Figure 5, with the output voltage considered as a DC quantity displayed in Figure 6.

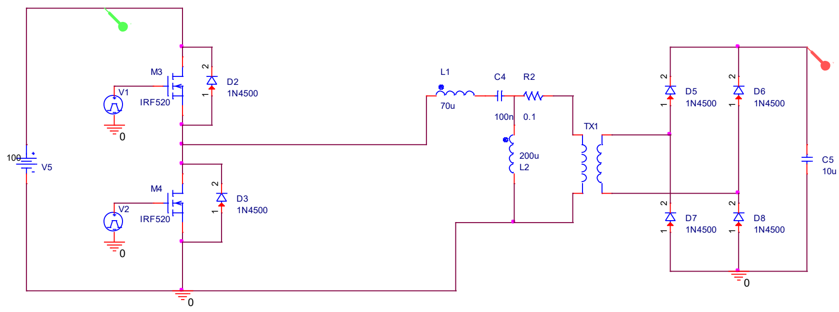

Figure 5. Proposed circuit of the positive rail

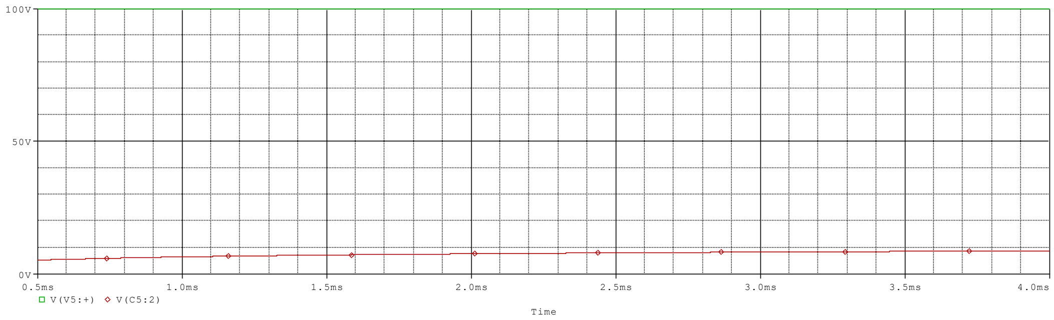

Figure 6. DC outputs of the input supply and the proposed no-load LLC converter

5.1.1 Resonance frequency : (Simone, 2014)

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

$$f_r = \frac{1}{2\pi\sqrt{70.10^{-6}.100.10^{-9}}} \tag{2}$$

$$f_r \approx 60\ kHz \tag{3}$$

L_r : resonance inductance

C_r : resonance capacitance

5.1.2 Voltage gain :

$$M = \frac{1}{\sqrt{(1+\lambda-\frac{\lambda}{fn^2})^2+Q^2(fn-\frac{1}{fn})^2}} \tag{4}$$

$\lambda : \frac{L_r}{L_m}$

$Q = \frac{\sqrt{\frac{L_r}{C_r}}}{R_{ac}}$

$f_n = \frac{f_s}{f_r}$

Under no load condition, Q=0 :

$$M = \frac{1}{\left|1+\lambda-\frac{\lambda}{fn^2}\right|} \tag{5}$$

$$M = \frac{1}{\left|1+0.35-\frac{0.35}{0.83^2}\right|} \tag{6}$$

$$M \approx 1.18 \tag{7}$$

Under no-load conditions described in (Microelectronics, S. T., 2008), the LLC resonant converter enters the so-called cutoff mode when the load current approaches zero. In this state, the secondary rectifier diodes remain non-conducting ((I_{D1}=I_{D2}= 0) throughout the entire switching cycle because the voltage reflected from the primary side never exceeds the output voltage required to forward-bias the rectifiers. As a result, the resonant tank current (I_R=I_{L_p}) circulates exclusively within the primary branch in a nearly triangular waveform, preserving ZVS despite the absence of load. At sufficiently high switching frequencies, the resonant capacitor becomes ineffective, and the converter behavior is governed by the inductive divider formed by L_s and L_p. Under these conditions, the LLC tank exhibits a higher effective gain, leading to an output voltage that rises above the nominal value.

This behavior is fully consistent with the simulation results obtained here (see Figures 3 and 6), where the converter produces a higher output voltage under no-load, whereas under load the output voltage decreases as power transfer to the secondary resumes and the converter returns to normal operating conditions.

5.1.3 Normalized frequency:

$$f_n = \frac{f_s}{f_r} \tag{8}$$

$$f_n = \frac{50}{60} = 0.83 \tag{9}$$

The no-load results (f_n = 0.83, M = 1.18) are in close agreement with the no-load boundary reported by (Deng *et al.*, 2013). This operating point falls within Region 2 (ZVS), demonstrating that the LLC resonant converter successfully maintains Zero Voltage Switching (ZVS) under no-load conditions.

6. Conclusion

Two LLC resonant converters were designed and simulated using OrCAD-PSpice to provide a symmetrical low-power output suitable for various applications. The system consists of two converters delivering +V and –V. These designs are proposed both for systems requiring dual outputs and for applications needing single outputs, where the positive converter can operate independently. Both converters achieve stable output and ZVS operation under no-load and load conditions. The results confirm the converters' efficiency and their suitability for compact, isolated low-power systems.

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