LLC 공진형 컨버터를 위한 가변 권선비 및 통합 인덕터 기능을 추가한 매트릭스 변압기

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Variable Turns Ratio Matrix Transformer with Integrated Inductor for LLC Resonant Converter

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ABSTRACT

As modern power electronics systems demand higher power density and efficiency, LLC resonant converters have emerged as a preferred solution due to their inherent soft-switching capability, cost-effectiveness, and potential for high efficiency. However, the magnetic design of LLC resonant converters presents challenges, particularly due to the number of magnetic components, which can negatively impact power density if not optimized. Matix transformers offer a superior alternative with their distributed elements with lower losses and better thermal performance. This paper introduces an integrated magnetic design featuring a customized “five-leg” matrix transformer with an integrated resonant inductor, optimized for high-performance LLC resonant converters. The proposed design is analyzed using finite element method (FEM) simulations, and a prototype is fabricated and tested in a half-bridge LLC converter to validate its performance.

1 Introduction

The development of wide-bandgap semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), has revolutionized power electronics, enabling converters to operate at megahertz frequencies with significantly enhanced efficiency and power density. However, higher switching frequencies introduce new challenges, such as increased switching losses and electromagnetic interference (EMI). The frequent switching of semiconductor devices leads to energy dissipation due to parasitic capacitances, while higher operating frequencies intensify these effects, creating greater thermal and EMI challenges.

To address the increased losses and EMI at higher frequencies, LLC resonant converters have gained widespread attention. These converters utilize a resonant tank to achieve zero-voltage switching (ZVS) and zero-current switching (ZCS), which significantly reduce switching losses by minimizing the overlap of voltage and current during transitions [1]. This soft-switching behavior also helps lower the rates of change in voltage and current, directly reducing EMI emissions and enhancing overall system performance.

However, the design of magnetic components remains a critical factor in the effectiveness of LLC converters. These converters require transformers and resonant inductors, which must be carefully designed to optimize efficiency and minimize losses. Planar magnetic components, with their compact form factor and higher power density, have become an attractive solution in modern LLC converters. The use of printed circuit board (PCB) windings allows for improved consistency in winding parameters, better magnetic coupling, and reduced core and winding losses. Therefore, optimizing planar magnetic designs is essential to fully harness the benefits of LLC converters in high-frequency power conversion applications.

A matrix transformer configuration is an excellent choice for high-efficiency magnetic components in high-performance LLC converters. It consists of an array of interconnected elements that function as a single transformer, distributing power across multiple windings. This design offers several key benefits, including reduced conduction losses through current splitting in the parallel windings, which decreases the current load on each winding. Additionally, the matrix transformer enhances thermal performance by distributing power loss across the individual elements, leading to more uniform heat dissipation [2]. These advantages collectively improve the overall efficiency and reliability of the system, making the matrix transformer a highly effective solution for LLC converter applications.

This paper proposes a matrix transformer configuration with a distributed winding pattern. The separation of primary and secondary windings introduces leakage inductance, which is utilized as the resonant inductor in the LLC converter. Both the primary and secondary leakage inductances are integrated into the transformer design, eliminating the need for an external resonant inductor and contributing to higher power density. Additionally, the distributed arrangement of the secondary windings allows flexibility in controlling the transformer’s turns ratio by modifying the interconnections of the secondary windings. This makes the matrix transformer a variable turns ratio transformer, enhancing its adaptability and performance in various operating conditions.

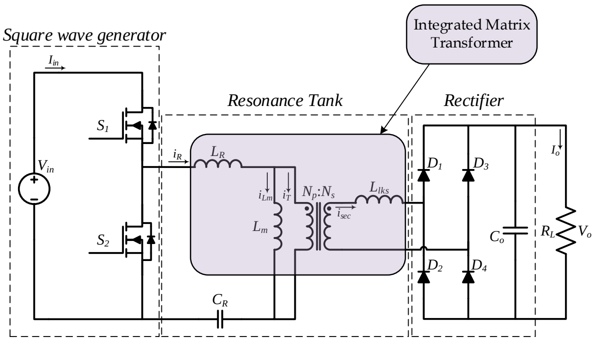
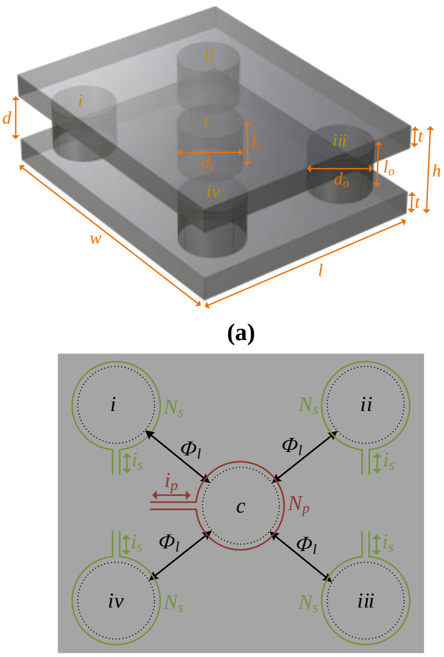


Fig. 1. Schematic of half-bridge LLC with integrated matrix transformer

2 Proposed Matrix Transformer

The proposed matrix transformer structure consists of five magnetic legs positioned between two plates, with one central leg (*leg c*) and four outer legs (*legs i to iv*) arranged at the corners, forming an 'X' pattern. The primary winding (N_p) is wound around the central leg, while the secondary winding (N_s) is distributed across the outer legs. This unique geometry and winding configuration optimize the magnetic flux distribution and support the integrated resonant inductor functionality. The detailed transformer structure and winding arrangement are illustrated in Fig. 2.



(a)

(b)

Fig. 2. Proposed Integrated Matrix Transformer; (a) matrix transformer geometry, (b) proposed winding pattern

The current in the primary winding (i_p) generates a total magnetic flux (Φ_T) in the center leg. As this flux flows outward toward the outer legs, it divides evenly into four parts (Φ_l), creating a parallel magnetic circuit. Since the flux in each outer leg is one-quarter of the flux in the center leg, the cross-sectional area of the outer legs can be reduced to one-quarter of that of the center leg, or half the radius. This parallel distribution of magnetic flux makes the configuration both feasible and practical, optimizing material use and reducing the magnetic component footprint.

The effective turns ratio of the transformer is influenced by the interconnections of the secondary windings. If the turns ratio of the transformer is defined as $N_p/N_s = n$ and the flux linkage ratio between the center leg flux and each outer leg flux is $\Phi_T/\Phi_l = \lambda$, then the effective turns ratio of the transformer, ratio of the primary voltage, V_p to the secondary voltage, V_s, is expressed by equation (1). The flux linkage ratio, λ, is found to be equal to the number of outer legs in the transformer.

$$\frac{V_p}{V_s} = n\lambda \tag{1}$$

The proposed matrix transformer offers flexibility in adjusting the effective turns ratio through various combinations of secondary winding connections. This allows for easy fine-tuning of the voltage transformation to meet different application requirements without altering the physical winding structure. The effective turns ratio for these configurations, along with FEM-simulated verification, is provided in Table I, for $N_p/N_s = n = 1$.

Table I. Effective Turns Ratio of the Proposed Transformer

Secondary Interconnections	**Effective Turns Ratio (V_p/V_s)**	**Calculated Effective Turns Ratio (V_P/V_S)**	**Simulated Effective Turns Ratio (V_P/V_S)**
All Series	n	1:1	26.7/25.0 = 1.07:1
All Parallel	$n\lambda$	4:1	26.6/6.4 = 4.15:1
Half Series + Parallel	$\frac{n\lambda}{2}$	2:1	26.53/12.57 = 2.11:1

The separation of primary and secondary windings across different legs in the transformer results in a magnetic coupling coefficient of 0.88, as calculated through FEM analysis in COMSOL Multiphysics. This less-than-ideal coupling introduces leakage inductance on both the primary and secondary sides. However, this leakage inductance is effectively utilized as the resonant inductance in the LLC converter's resonant tank, reducing the need for additional components and minimizing the overall magnetic component footprint.

The equivalent circuit of the LLC resonance converter in Fig. 1 is shown in Fig.2 with the resonance inductor LR replaced by the primary leakage inductance, Llkp. The transformer magnetizing inductance is represented by Lm and n2Llks is the secondary side leakage inductance as reflected to the primary side across the transformer turns ratio. Rac is the equivalent AC resistance at the rectifier side reflected to the primary side.

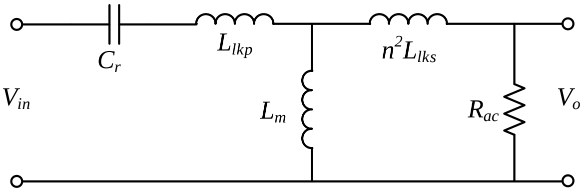


Fig. 3. AC Equivalent Circuit of LLC Resonance Converter

The voltage gain of the converter is given by equation (2) for switching frequency of $\omega_s = 2\pi f_s$ (rad/s).

$$M = \frac{V_o}{V_{in}} = \frac{1}{2n}\left|\frac{{\omega_s}^2 L_m R_{ac} C_r}{j\omega_s\cdot\left(1-\frac{{\omega_s}^2}{{\omega_{r_s}}^2}\right)\cdot(L_m+n^2L_{lks})+R_{ac}\left(1-\frac{{\omega_s}^2}{{\omega_{r_p}}^2}\right)}\right| \tag{2}$$

where:

$$R_{ac} = \frac{8n^2}{\pi^2} R_L \tag{3}$$

$$L_{r_p} = L_m + L_{lkp} \tag{4}$$

$$L_{r_s} = L_{lkp} + L_m//(n^2 L_{lks}) \tag{5}$$

$$\omega_{r_s} = \frac{1}{\sqrt{L_{r_s} C_r}} \tag{6}$$

$$\omega_{r_p} = \frac{1}{\sqrt{L_{r_p} C_r}} \tag{7}$$

3 Hardware Prototype

A prototype of the matrix transformer structure was fabricated and tested with half-bridge LLC resonance converter. The hardware experimentation setup is shown in Fig.4. Fig. 6 gives the voltage gain curve of the LLC resonance converter using equation (2). The parameters of the LLC resonance converter are given in Table II. The secondary side of the hardware prototype was connected in *half series + parallel* configuration.

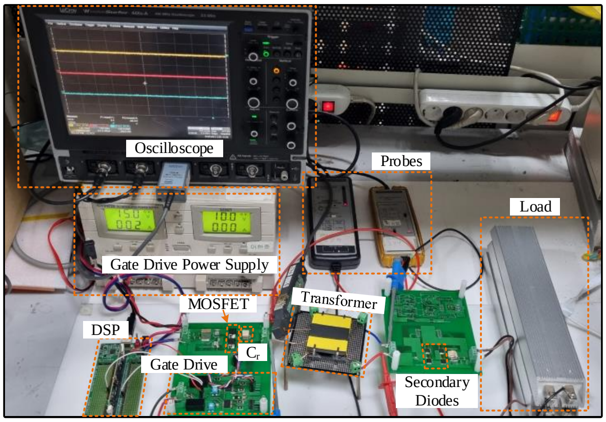


Fig. 4. Hardware experimental setup

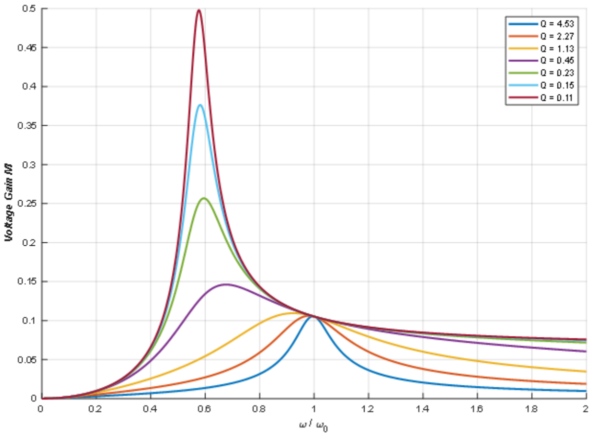


Fig. 5. Voltage Gain Curve of the LLC Resonance Converter

The converter was tested at the resonance frequency and the corresponding waveforms are shown in Fig. 6. V_{prim} is the transformer primary side voltage and V_{sec} is the transformer secondary side voltage. The resonance current, I_R can be seen to be almost perfectly sinusoidal at the resonance frequency.

Table II. LLC Hardware Parameters

Symbol	Quantity	Value
Vin	input voltage	400V
Vo	nominal output voltage	40V
D	duty cycle	0.5
f_{sw}	switching frequency	700kHz
L_m	magnetizing inductance	41µH
L_{lkp}	primary leakage inductance	7µH
L_{lks}	secondary leakage inductance	0.3µH
N_p/N_s	transformer turns ratio	3:1
V_p/V_s	effective turns ratio	6:1
C_R	resonance capacitor	3.6nF
R_{load}	load	4Ω

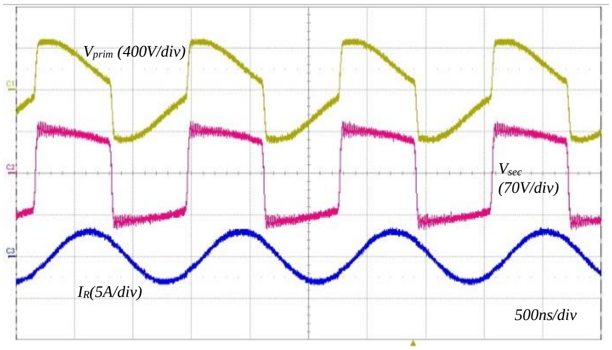


Fig. 6. Hardware Waveforms

4 Conclusion

This paper presents a variable turns ratio transformer that utilizes a matrix magnetic structure and a distributed winding pattern. The transformer's turns ratio can be adjusted by interchanging the connections of the secondary windings, eliminating the need for physical alterations to the winding turns and enhancing flexibility across various operating conditions. The leakage energy present on both the primary and secondary sides is effectively used as the resonant inductor, which helps to minimize the magnetic component footprint. Additionally, the voltage gain and resonance frequency equations account for the leakage inductance, thereby improving LLC operation. The design and performance of the transformer are validated through hardware experimentation.

References

[1] Y. Liang, W. Liu, B. Lu and J. van Wyk, "Design of integrated passive component for a 1 MHz 1 kW half-bridge LLC resonant converter," *Fourtieth IAS Annual Meeting. Conference Record of the 2005 Industry Applications Conference, 2005.*, vol. 3, pp. 2223-2228, 2005.

[2] D. Huang, S. Ji and F. C. Lee, "LLC Resonant Converter With Matrix Transformer," *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 4339-4347, 2014.