How to Design a Half-Bridge LLC Resonant Converter with a Center-Tapped Transformer

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Introduction

LLC resonant converters have become a cornerstone in power electronics, and widely adopted across various markets due to their ability to achieve high efficiency while minimizing electromagnetic interference (EMI) through soft-switching techniques. LLC topology offers several configurations optimized for specific applications. In particular, there are two prominent configurations for the primary side, and two different methods for the secondary side.

This article provides a step-by-step guide for designing an LLC resonant converter with a half-bridge configuration on the primary side and a center-tapped transformer on the secondary side, enabling engineers to optimize performance. This configuration is well-suited for power converters up to 1kW with a low output voltage (V_{OUT}) and high current, making it ideal for battery chargers or power supplies.

Half-Bridge LLC Resonant Converter Design with a Center-Tapped Transformer

This section explores the detailed design process for a half-bridge LLC resonant converter using a center-tapped transformer (see Figure 1). Efficient power conversion can be achieved by combining the advantages of LLC topology with the flexibility of a center-tapped transformer.

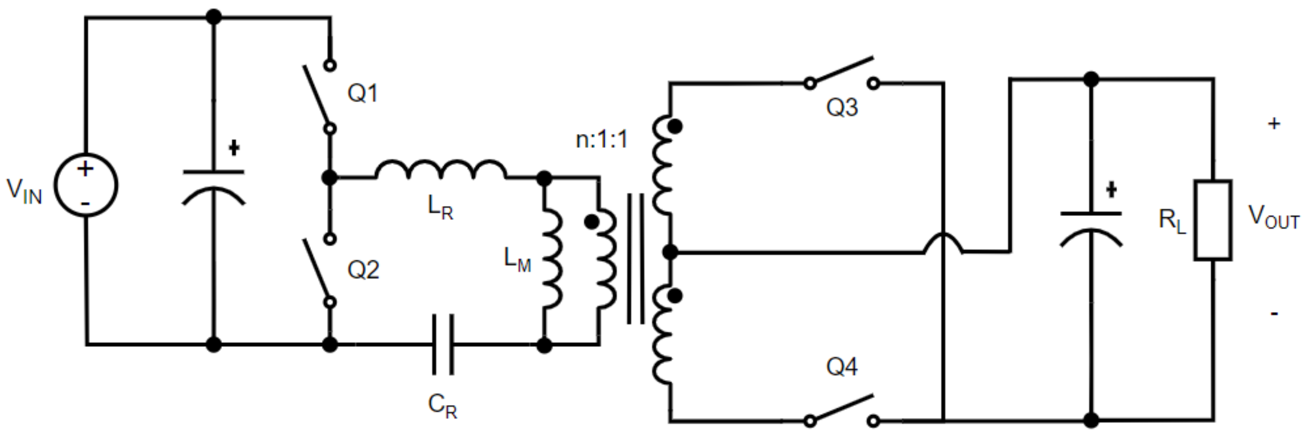

Figure 1: Half-Bridge LLC Resonant Converter with a Center-Tapped Transformer

Figure 2 shows a flowchart of the meticulous step-by-step approach for designing an LLC resonant converter, which is described in further detail in the following sections.

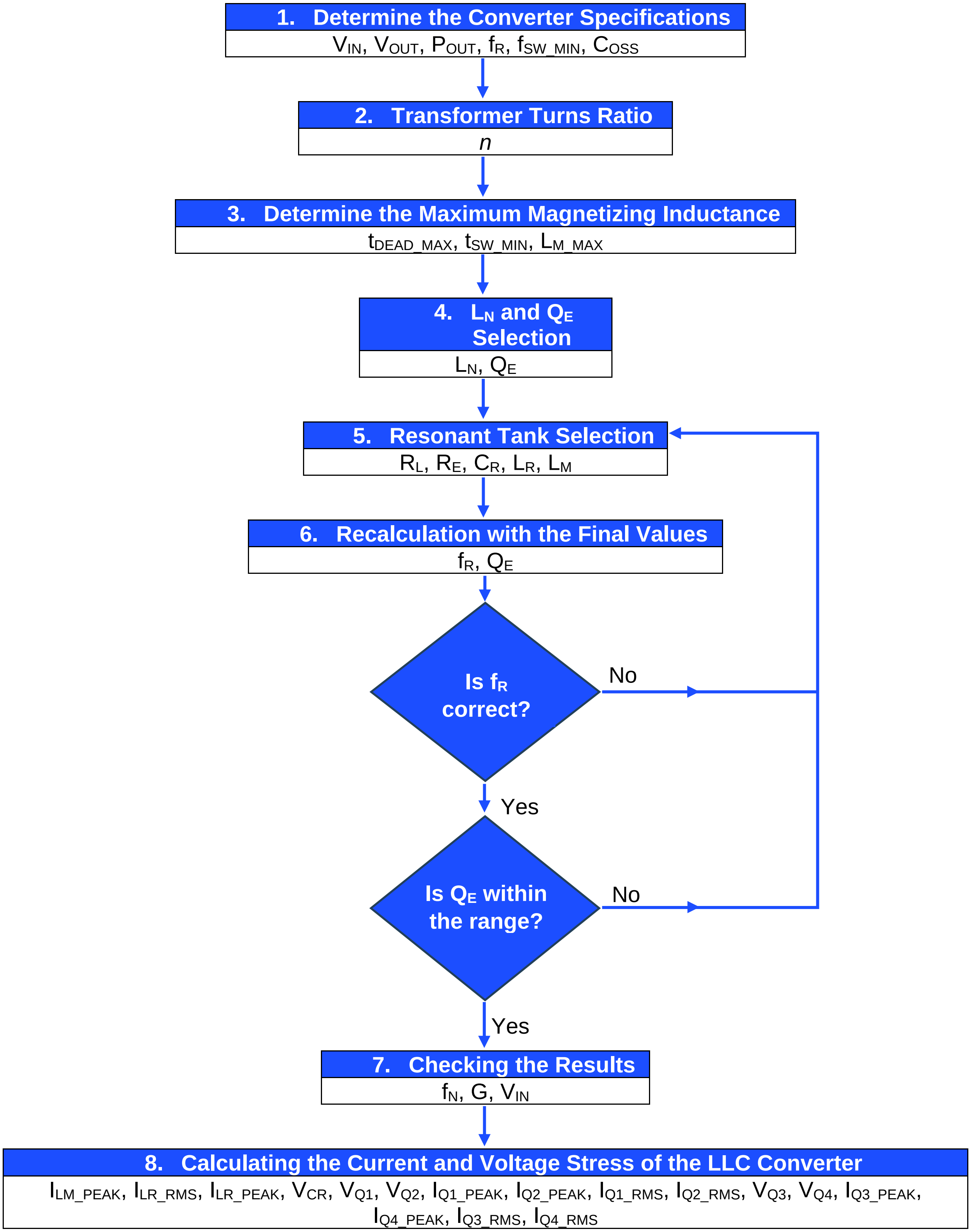

Figure 2: Step-by-Step Flowchart for LLC Resonant Converter Design

Design Considerations

There are two key design considerations that can significantly impact the efficiency and performance of the LLC resonant converter:

1. Optimizing the resonant inductance ratio (L_N): A higher L_N typically improves efficiency under heavy-load conditions. It is recommended to maintain L_N within the 4 to 10 range to balance efficiency and component stress.
2. Selecting an appropriate quality factor (Q_E): To prevent excessive voltage stress on the resonant capacitor and minimize high inrush currents during start-up, Q_E must be maintained within the 0.34 to 0.49 range. This range ensures a good tradeoff between minimizing stress and maintaining overall converter performance.

Step 1: Determine the Converter Specifications

Table 1 shows the specifications of an example LLC resonant converter.

Table 1: Specifications of Example LLC Resonant Converter

Parameters	Values	Units
Input voltage (V_{IN})	400	V_{DC}
Output voltage (V_{OUT})	48	V_{DC}
Output power (P_{OUT})	600	W
Resonant frequency (f_R)	100	kHz
Minimum switching frequency (f_{SW_MIN})	50	kHz
MOSFET output capacitance	80	pF

Step 2: Transformer Turns Ratio

When calculating the transformer turns ratio (*n*), the gain (G) must be equal to 1 to work at the resonant frequency (f_R). *n* can be calculated with Equation (1):

$$n = \frac{N1}{N2} = \frac{V_{IN}}{2 \times V_{OUT}} \times G \Rightarrow n = \frac{400}{2 \times 48} \times 1 \Rightarrow n = 4.17 \quad (1)$$

Where *n* = 4.17 can be rounded to a whole number, so that $n_{LLC} = 4$.

Step 3: Determine the Maximum Magnetizing Inductance

To calculate the maximum magnetizing inductance (L_{M_MAX}), the following parameters must be determined: maximum dead time (t_{DEAD_MAX}), minimum switching period (t_{SW_MIN}), and output capacitance of the primary-side MOSFET (C_{OSS}).

The HR1002A, an enhanced LLC controller, is selected for this design due to its proven reliability under varying operational conditions. Based on the HR1002A datasheet, the controller's t_{DEAD_MAX} is 2µs. The output capacitance of the selected MOSFET (C_{OSS}) is 80pF.

t_{SW_MIN} can be calculated with Equation (2):

$$t_{SW\_MIN} = \frac{1}{f_{START\_UP}} \Rightarrow t_{SW\_MIN} = \frac{1}{3 \times f_{SW}} \Rightarrow t_{SW\_MIN} = \frac{1}{3 \times 100kHz} \Rightarrow t_{SW\_MIN} = 3.33\mu s \quad (2)$$

L_{M_MAX} can be calculated with Equation (3):

$$L_{M\_MAX} = t_{MIN} \times \frac{t_{DEAD\_MAX}}{16 \times C_{OSS}} \Rightarrow L_{M\_MAX} = 3.33\mu s \times \frac{2\mu s}{16 \times 80pF} \Rightarrow L_{M\_MAX} = 5.2mH \quad (3)$$

Step 4: L_N and Q_E Selection

As discussed regarding design considerations, Q_E is recommended to be within the range shown in Equation (4):

$$\frac{1}{3} < Q_E < \frac{1}{2} \Rightarrow 0.33 < Q_E < 0.5 \quad (4)$$

In addition, Q_E is related to the resonant capacitor voltage stress and inrush current during start-up. Therefore, Q_E is selected to be 0.35, which is near the minimum.

Similar to Q_E, the L_N ratio is recommended to be within the range shown in Equation (5):

$$4 \leqslant L_N \leqslant 10 \quad (5)$$

To stabilize efficiency across all the load ranges, it is recommended to use an L_N ratio between 4 and 6. To prioritize efficiency at the maximum output power (P_{OUT}), it is recommended to use an L_N ratio between 6 and 10. In the example LLC resonant converter, L_N is selected to be 9.

Step 5: Resonant Tank Selection

To select the resonant tank, the following parameters must be determined: load resistance (R_L), equivalent load resistance (R_E), resonant capacitor (C_R), resonant inductor (L_R), and the magnetizing inductance (L_M).

R_L can be calculated with Equation (6):

$$R_L = \frac{{V_{OUT}}^2}{P_{OUT}} \Rightarrow R_L = \frac{48^2}{600} \Rightarrow R_L = 3.84\Omega \quad (6)$$

R_E can then be calculated with Equation (7):

$$R_E = \frac{8 \text{ x } {n_{LLC}}^2}{\pi^2} \text{ x } R_L \Rightarrow R_E = \frac{8 \text{ x } 4^2}{\pi^2} \text{x } 3.84 \Rightarrow R_E = 49.8\Omega \quad (7)$$

C_R can be calculated with Equation (8):

$$C_R = \frac{1}{2 \text{ x } \pi \text{ x } f_R \text{ x } R_E \text{ x } Q_E} \Rightarrow C_R = \frac{1}{2 \text{ x } \pi \text{ x } 100\text{kHz x } 49.8 \text{ x } 0.35} \Rightarrow C_R = 91.31\text{nF} \quad (8)$$

It is recommended to round C_R to the nearest standard capacitance or place capacitors in parallel to obtain the nearest value. In this case, two 47nF capacitors are used in parallel for a total capacitance of 94nF.

L_R can be calculated with Equation (9):

$$L_R = \frac{1}{(2 \text{ x } \pi \text{ x } f_R)^2 \text{ x } C_R} \Rightarrow L_R = \frac{1}{(2 \text{ x } \pi \text{ x } 100\text{kHz})^2 \text{ x } 94\text{nF}} \Rightarrow L_R = 26.95\mu\text{H} \quad (9)$$

Where L_R = 26.95µH can be rounded to 27µH.

L_N can be calculated with Equation (10):

$$L_N = \frac{L_M}{L_R} \Rightarrow L_M = L_N \text{ x } L_R \Rightarrow L_M = 9 \text{ x } 27\mu\text{H} \Rightarrow L_M = 243\mu\text{H} \quad (10)$$

L_M can be checked with Equation (11):

$$L_M \leq L_{M\_MAX} \Rightarrow 243\mu\text{H} \leq 5.2\text{mH} \quad (11)$$

Step 6: Recalculation with the Final Values of L_R, C_R, and L_M

The resonant frequency (f_R) can be recalculated with the final values of L_R, C_R, and L_M using Equation (12):

$$L_R = \frac{1}{(2 \times \pi \times f_R)^2 \times C_R} \Rightarrow 2 \times \pi \times f_R = \frac{1}{\sqrt{L_R \times C_R}} \Rightarrow f_R = \frac{1}{2 \times \pi \times \sqrt{L_R \times C_R}} \Rightarrow$$

$$\Rightarrow f_R = \frac{1}{2 \times \pi \times \sqrt{27\mu H \times 94nF}} \Rightarrow f_R = 99.9kHz \quad (12)$$

Q_E can be recalculated with the final values of L_R, C_R, and L_M using Equation (13):

$$C_R = \frac{1}{2 \times \pi \times f_R \times R_E \times Q_E} \Rightarrow Q_E = \frac{1}{2 \times \pi \times f_R \times R_E \times C_R} \Rightarrow Q_E = \frac{1}{2 \times \pi \times 99.9kHz \times 49.8 \times 94nF} \Rightarrow$$

$$\Rightarrow Q_E = 0.34 \quad (13)$$

Where Q_E must be within the recommended range: $0.33 < Q_E < 0.5 \Rightarrow 0.33 < 0.34 < 0.5$.

If Q_E is outside the specified range, adjust C_R and then repeat the calculations for Equation (8) through Equation (13).

Step 7: Checking the Results

To check the results, f_N, G, and V_{IN} are used to obtain the tank resonant voltage transfer function. Then V_{OUT} is validated to ensure the converter's proper operation. The resonant tank and gain can be verified using plots.

Tank Resonant Voltage Transfer Function

To ensure that the converter works in f_R, the following is assumed:

$$f_N = \frac{f_{SW}}{f_R} = 1 \Rightarrow f_{SW} = f_R = 99.9kHz$$

The parameters are then replaced in the tank resonant voltage transfer function, $G(f_N)$, which can be calculated with Equation (14):

$$G(f_N) = \frac{1}{\sqrt{\left[1 + \frac{1}{L_N} - \frac{1}{f_N^2 \times L_N}\right]^2 + Q_E^2 \times \left(\frac{1}{f_N} - f_N\right)^2}} \Rightarrow$$

$$\Rightarrow G(1) = \frac{1}{\sqrt{\left[1 + \frac{1}{9} - \frac{1}{1^2 \times 9}\right]^2 + 0.34^2 \times \left(\frac{1}{1} - 1\right)^2}} \Rightarrow G(1) = 1 \quad (14)$$

Output Voltage

The output voltage (V_{OUT}) can be calculated with Equation (15):

$$V_{OUT} = \frac{V_{IN}}{2 \times n_{LLC}} \times G \Rightarrow V_{OUT} = \frac{400}{2 \times 4} \times 1 \Rightarrow V_{OUT} = 50V \quad (15)$$

With a unity gain, V_{OUT} is 50V instead of 48V.

There are two different methods to adjust V_{OUT}. The first method is to reduce the gain below 1, which can be calculated with Equation (16):

$$V_{OUT} = \frac{V_{IN}}{2 \times n_{LLC}} \times G \Rightarrow G = \frac{V_{OUT} \times 2 \times n_{LLC}}{V_{IN}} \Rightarrow G = \frac{48 \times 2 \times 4}{400} \Rightarrow G = 0.96 \quad (16)$$

The converter works at the normalized switching frequency (f_N), which has a ratio of about 1.2. f_N can be found solving equation (14) or plotting the resonant tank at the 0.96 gain (see Figure 4).

f_{SW} can be calculated with Equation (17):

$$f_N = \frac{f_{SW}}{f_R} \Rightarrow f_{SW} = f_N \times f_R \Rightarrow f_{SW} = 1.2 \times 99.9kHz \Rightarrow f_{SW} = 119.88kHz \quad (17)$$

It is common to work within the f_R range instead of at the exact f_R due to components' tolerances.

The second method to adjust V_{OUT} is by modifying the input voltage (V_{IN}), which can be calculated with Equation (18):

$$V_{OUT} = \frac{V_{IN}}{2 \times n_{LLC}} \times G(f_N) \Rightarrow V_{IN} = \frac{V_{OUT} \times 2 \times n_{LLC}}{G(f_N)} \Rightarrow V_{IN} = \frac{48 \times 2 \times 4}{1} \Rightarrow V_{IN} = 384V \quad (18)$$

By adjusting V_{IN} to 384V, the converter operates at f_R.

Verifying the Resonant Tank and Gain with Plots

The most effective way to validate the calculations is by plotting the tank resonant voltage transfer function using Equation (14) as well as plotting the gain using Equation (16). Consider the following two scenarios for the resonant tank gain.

In the first scenario, V_{IN} = 400V, L_R = 27µH, C_R = 94nF, and L_M = 243µH. Figure 3 shows the resonant tank gain at V_{IN} = 400V with 0.96 gain.

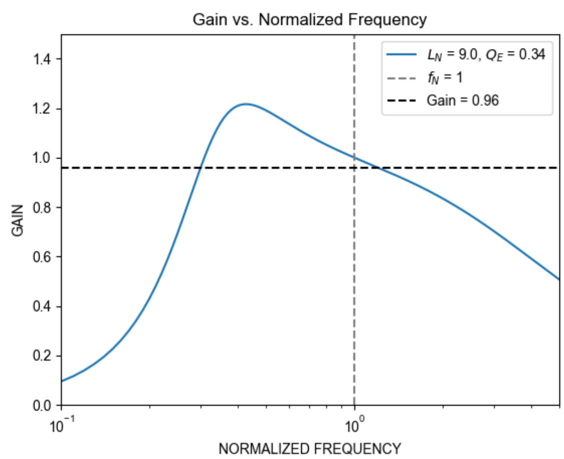

Figure 3: Resonant Tank Gain at V_{IN} = 400V, Gain = 0.96, and f_N = 1

At f_R, the gain is higher than necessary. To lower the gain to 0.96, the normalized frequency (f_N) must be determined.

Figure 4 shows resonant tank gain after adding the calculated gain. The 1.2 ratio of f_N coincides with the 0.96 gain, which are indicated by the grey and black dashed lines.

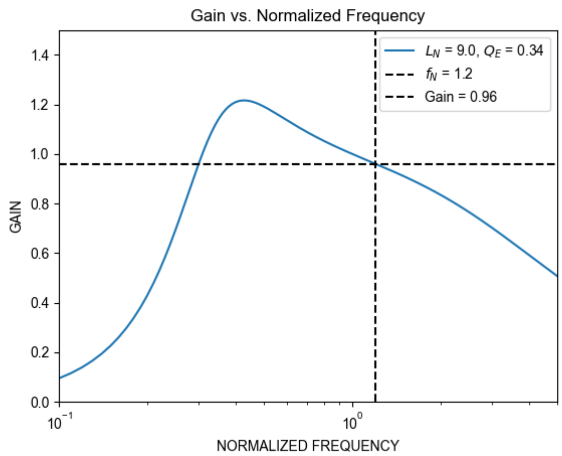

Figure 4: Resonant Tank Gain at V_{IN} = 400V, Gain = 0.96, and f_N = 1.2

In the second scenario, V_{IN} is reduced to 384V, while the other conditions remain the same (L_R= 27µH, C_R = 94nF, and L_M = 243µH). Figure 5 shows the resonant tank gain at V_{IN} = 384V, where the converter operates at f_R with a unity gain.

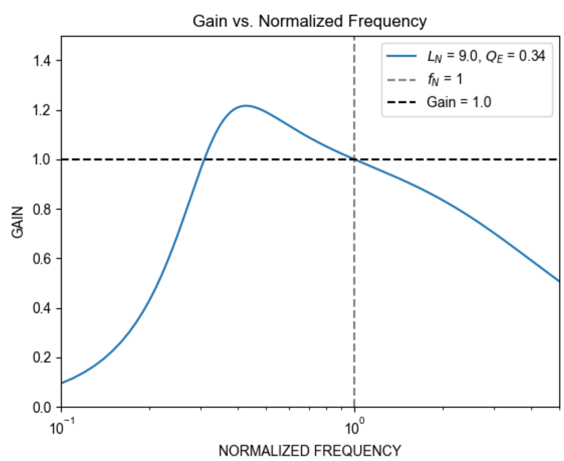

Figure 5: Resonant Tank Gain at V_{IN} = 384V

The second scenario is applied for step 8 and the final design, which are described below.

Step 8: Calculating the Current and Voltage Stress of the LLC Converter

The current and voltage stress of the LLC converter includes the tank resonant stress, the primary-side semiconductor devices' stress, and the secondary-side semiconductor devices' stress.

Tank Resonant Stress

The tank resonant stress is determined by the magnetizing peak inductance current (I_{LM_PEAK}), resonant inductor RMS current (I_{LR_RMS}), resonant peak inductor current (I_{LR_PEAK}), and resonant capacitor voltage (V_{CR}).

I_{LM_PEAK} can be estimated with Equation (19):

$$I_{LM\_PEAK} = \frac{n_{LLC} \times V_{OUT}}{4 \times L_M \times f_R} \Rightarrow I_{LM\_PEAK} = \frac{4 \times 48}{4 \times 243\mu H \times 99.9kHz} \Rightarrow I_{LM\_PEAK} = 1.98A \quad (19)$$

I_{LR_RMS} can be calculated with Equation (20):

$$I_{LR\_RMS} = \frac{V_{OUT} \text{ x } \sqrt{4 \text{ x } \pi^2 + n_{LLC}{}^4 \text{ x } R_L{}^2 \text{ x } \left(\frac{1}{L_M \text{ x } f_R}\right)^2}}{4 \text{ x } \sqrt{2} \text{ x } n_{LLC} \text{ x } R_L} \Rightarrow$$

$$\Rightarrow I_{LR\_RMS} = \frac{48 \text{ x } \sqrt{4 \text{ x } \pi^2 + 4^4 \text{ x } 3.84^2 \text{ x } \left(\frac{1}{243\mu H \text{ x } 99.9kHz}\right)^2}}{4 \text{ x } \sqrt{2} \text{ x } 4 \text{ x } 3.84} \Rightarrow$$

$$\Rightarrow I_{LR\_RMS} = 3.74A \tag{20}$$

I_{LR_PEAK} can be calculated with Equation (21):

$$I_{LR\_PEAK} = \sqrt{2} \text{ x } I_{LR\_RMS} \Rightarrow I_{LR\_PEAK} = \sqrt{2} \text{ x } 3.74 \Rightarrow I_{LR\_PEAK} = 5.29A \tag{21}$$

V_{CR} can be calculated with Equation (22):

$$V_{CR} = \frac{I_{LR\_RMS}}{2 \text{ x } \pi \text{ x } f_R \text{ x } C_R} \Rightarrow V_{CR} = \frac{3.74}{2 \text{ x } \pi \text{ x } 99.9kHz \text{ x } 94nF} \Rightarrow V_{CR} = 63.39V \tag{22}$$

Stress of Primary-Side Semiconductor Devices

The stress of primary-side semiconductor devices is determined by the voltage stress of the primary side (V_{Q1}), peak current of the primary side (I_{Q1_PEAK}), and the RMS current of the primary side (I_{Q1_RMS}).

V_{Q1} can be calculated with Equation (23):

$$V_{Q1} = V_{Q2} = V_{IN} = 384V \tag{23}$$

I_{Q1_PEAK} can be calculated with Equation (24):

$$I_{Q1\_PEAK} = I_{Q2\_PEAK} = I_{LR\_PEAK} = 5.29A \tag{24}$$

I_{Q1_RMS} can be calculated with Equation (25):

$$I_{Q1\_RMS} = I_{Q2\_RMS} = \frac{V_{OUT} \text{ x } \sqrt{4 \text{ x } \pi^2 + n_{LLC}{}^4 \text{ x } R_L{}^2 \text{ x } \left(\frac{1}{L_M \text{ x } f_R}\right)^2}}{8 \text{ x } n_{LLC} \text{ x } R_L} \Rightarrow$$

$$\Rightarrow I_{Q1\_RMS} = I_{Q2\_RMS} = \frac{48 \text{ x } \sqrt{4 \text{ x } \pi^2 + 4^4 \text{ x } 3.84^2 \text{ x } \left(\frac{1}{243\mu H \text{ x } 99.9kHz}\right)^2}}{8 \text{ x } 4 \text{ x } 3.84} \Rightarrow$$

$$\Rightarrow I_{Q1\_RMS} = I_{Q2\_RMS} = 2.65A \tag{25}$$

A high L_N means L_M is high as well, which reduces the RMS current in semiconductor devices.

Stress of Secondary-Side Semiconductor Devices

The stress of secondary-side semiconductor devices is determined by the voltage stress of the secondary side (V_{Q3}), peak current of the secondary side (I_{Q3_PEAK}), and the RMS current of the secondary side (I_{Q3_RMS}).

V_{Q3} can be calculated with Equation (26):

$$V_{Q3} = V_{Q4} = 2 \text{ x } V_{OUT} \Rightarrow V_{Q3} = V_{Q4} = 2 \text{ x } 48 \Rightarrow V_{Q3} = V_{Q4} = 96V \tag{26}$$

I_{Q3_PEAK} can be calculated with Equation (27):

$$I_{Q3\_PEAK} = I_{Q4\_PEAK} = \sqrt{12} \times \frac{V_{OUT} \times \sqrt{12 \times \pi^4 + \frac{5 \times \pi^2 - 48}{L_M^2 \times f_R^2} \times n_{LLC}^4 \times R_L^2}}{24 \times \pi \times R_L} \Rightarrow$$

$$\Rightarrow I_{Q3\_PEAK} = I_{Q4\_PEAK} = \sqrt{12} \times \frac{48 \times \sqrt{12 \times \pi^4 + \frac{5 \times \pi^2 - 48}{(243\mu H)^2 \times (99.9kHz)^2} \times 4^4 \times 3.84^2}}{24 \times \pi \times 3.84} \Rightarrow$$

$$\Rightarrow I_{Q3\_PEAK} = I_{Q4\_PEAK} = 19.71A \tag{27}$$

I_{Q3_RMS} can be calculated with Equation (28):

$$I_{Q3\_RMS} = I_{Q4\_RMS} = \sqrt{3} \times \frac{V_{OUT} \times \sqrt{12 \times \pi^4 + \frac{5 \times \pi^2 - 48}{L_M^2 \times f_R^2} \times n_{LLC}^4 \times R_L^2}}{24 \times \pi \times R_L} \Rightarrow$$

$$\Rightarrow I_{Q3\_RMS} = I_{Q4\_RMS} = \sqrt{3} \times \frac{48 \times \sqrt{12 \times \pi^4 + \frac{5 \times \pi^2 - 48}{(243\mu H)^2 \times (99.9kHz)^2} \times 4^4 \times 3.84^2}}{24 \times \pi \times 3.84} \Rightarrow$$

$$\Rightarrow I_{Q3\_RMS} = I_{Q4\_RMS} = 9.85A \tag{28}$$

Final Design

By calculating the current and voltage stresses on the resonant tank and semiconductor devices, the LLC converter design using the HR1002A can be completed. Table 2 shows the design results.

Table 2: Design Results

Parameters	Values	Units
Input voltage	384	V
Magnetizing inductance	243	µH
Transformer turns ratio	4	-
Resonant inductance	27	µH
Resonant capacitance	94	nF
Peak current (Q1, Q2, and L_R)	5.29	A
RMS current: Q1, Q2, and L_R)	2.65	A
Resonant capacitor voltage	63.39	V
Peak current (Q3 and Q4)	19.71	A
RMS current (Q3 and Q4)	9.85	A

The HR1002A is an enhanced LLC controller that provides robust adaptative dead-time adjustment, (ADTA) as well as several protections, including shoot-through and capacitive mode protection (CMP) to avoid hard switching. There are also two over-current protection (OCP) levels, where one level provides a configurable delay for enhanced surge performance. Brown-in and brownout thresholds set the minimum V_{IN} at which the converter can start working.

Due to the capabilities of the HR1002A, the power converter stage also requires only a few external components to function effectively.

Figure 6 shows the schematic of the half-bridge LLC with a center-tapped transformer using the HR1002A.

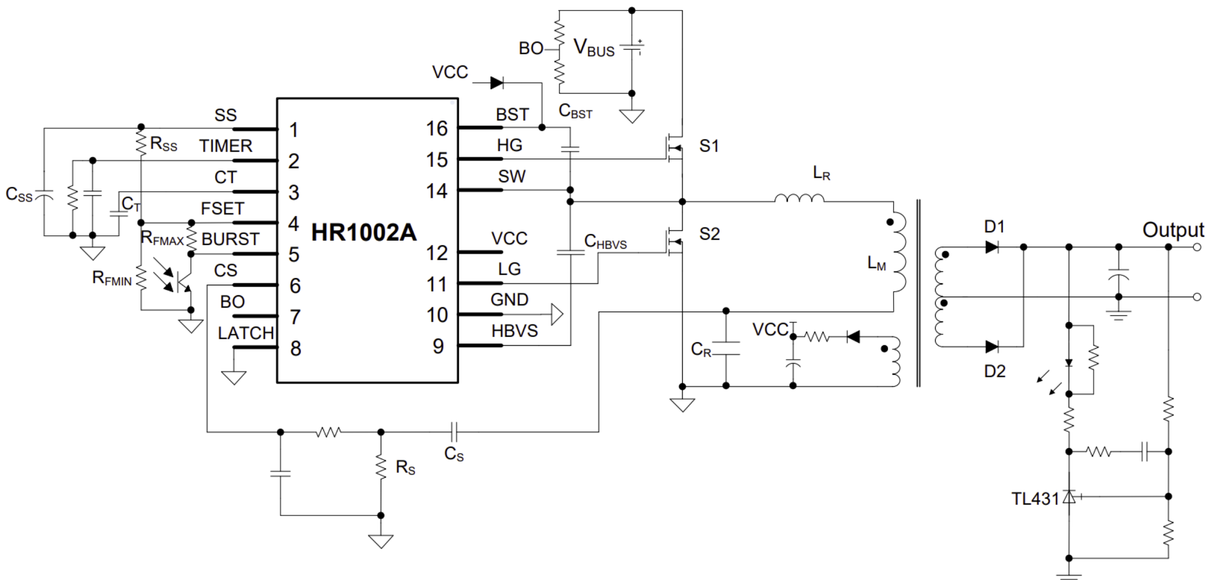

Figure 6: Half-Bridge LLC with a Center-Tapped Transformer Using the HR1002A

Conclusion

Selecting the LLC topology for the primary and secondary sides is critical for optimizing performance across various applications. The half-bridge LLC with a center-tapped transformer is ideal for power levels up to 1kW.

By adhering to the design principles discussed in this article, including optimizing the resonant inductance ratio and quality factor, engineers can ensure that converters operate within the desired parameters while reducing the risk of component failure. Moreover, the HR1002A controller further enhances LLC converter designs with its advanced protection features, ensuring reliability and durability in real-world applications.

For more solution options, explore MPS's selection of integrated, high-reliability LLC controllers.