Technical Article

Tips and tricks for achieving wide operating ranges with LLC resonant converters

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Inductor-inductor-capacitor (LLC) resonant converters have a couple of appealing characteristics for applications requiring an isolated DC/DC converter such as minimal switching losses, no reverse recovery when operating below the resonant frequency and the ability to tolerate large leakage inductance within the transformer.

The challenge

A primary challenge when designing an LLC converter with a wide operating range is the behavior of the gain curve with respect to equivalent load resistance. This is because as the quality factor (Qe), increases, the maximum attainable gain decreases Conversely, the minimum attainable gain increases as Qe decreases. This is shown in Figure 1 below.

$$Q_e = \frac{\sqrt{L_r C_r}}{R_e} \tag{1}$$

$$L_n = \frac{L_m}{L_r} \tag{2}$$

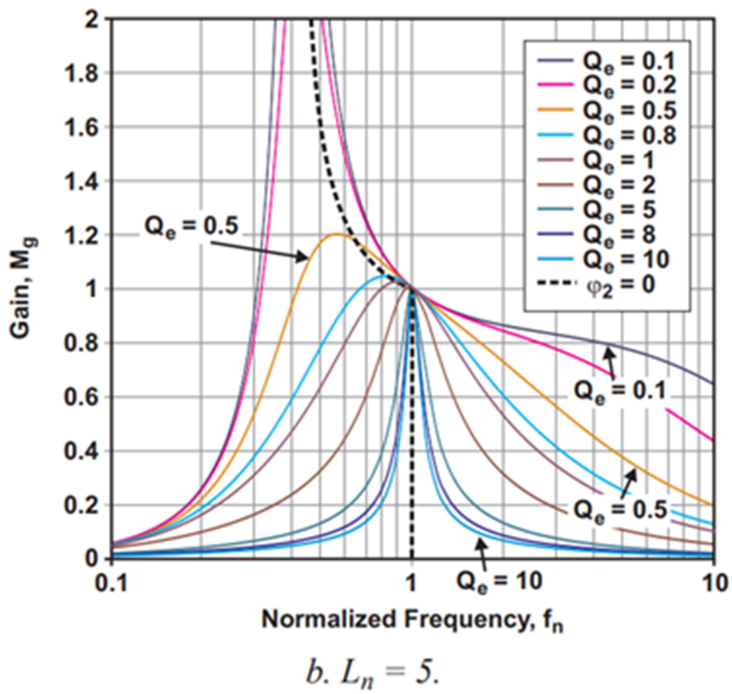

Figure 1. LLC gain curves showing that, as Qe increases, the maximum attainable gain decreases. Source: Texas Instruments

This behavior makes it difficult to maintain reasonable root-mean-square (RMS) currents in the power stage and a reasonable switching frequency range. The inductance ratio (Ln) needs to be reduced to reduce the required frequency range; however, a lower inductance ratio increases the magnetizing current in the power stage. This article will discuss five tips for designing an LLC converter with a wide operating range.

Using a reconfigurable rectifier

One potential way to extend an LLC converter's operating range is to implement a reconfigurable rectifier, as shown in Figure 2.

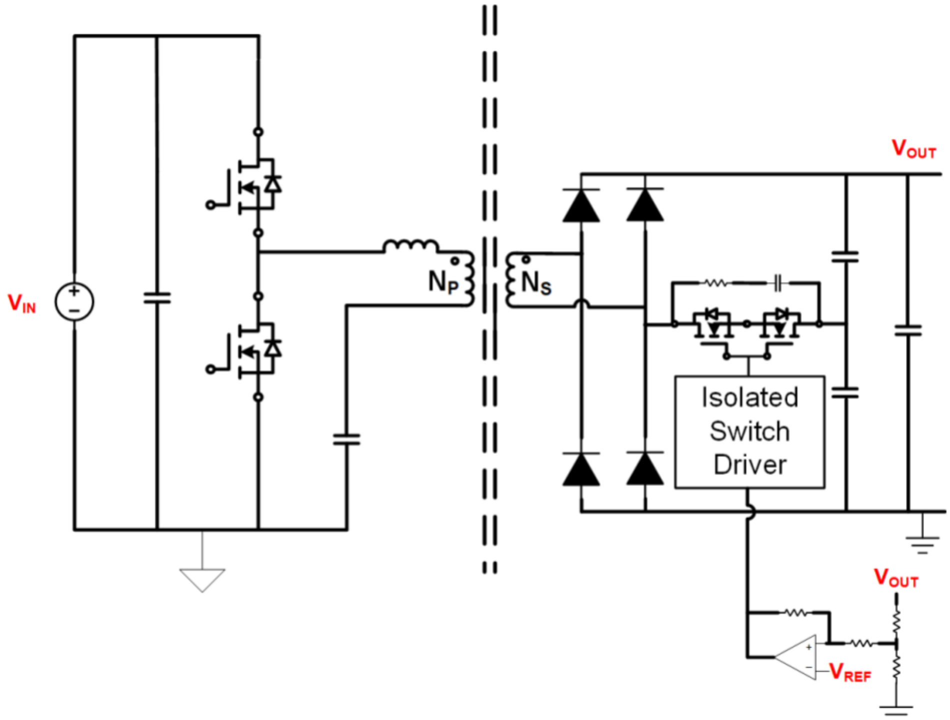

Figure 2. shows an LLC converter with a reconfigurable rectifier, which can be reconfigured as either a full-bridge or a voltage-doubler. Source: Texas Instruments

In this structure, you can configure the rectifier as a full-bridge or a voltage-doubler rectifier by using a comparator to look at the output voltage to decide the mode of operation. When operating as a full-bridge rectifier, Equation 3 calculates the input-to-output transfer function.

$$V_{\text{out}} = M_g(fsw) \times \frac{1}{n} \times \frac{V_{\text{in}}}{2} \quad (3)$$

When operating as a voltage doubler rectifier, the input-to-output transfer function is:

$$V_{\text{out}} = 2 \times M_g(fsw) \times \frac{1}{n} \times \frac{V_{in}}{2} \quad (4)$$

Figure 3 shows the switching frequency versus output voltage for an LLC using the above approach to achieve a 140V to 420V output voltage range from a fixed 450V input. This data is collected with an 800mA load on the output. Notice the jump at 200V where the comparator switches from full-bridge to voltage-doubler mode.

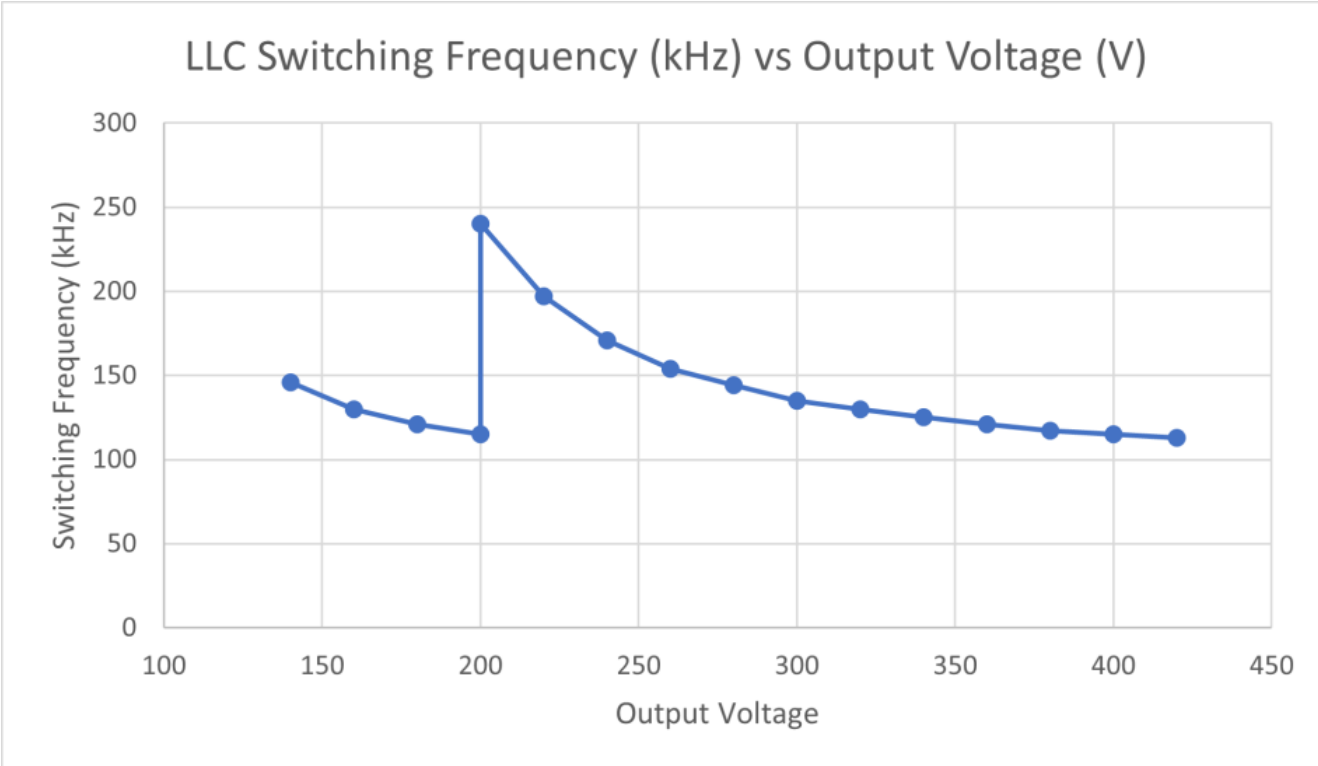

Figure 3. Switching frequency versus output voltage in LED driver reference design. Source: Texas Instruments

Minimizing winding and rectifier capacitance

If the operating point drops below the minimum gain curve, the LLC controller is forced to operate in burst mode to keep the output voltage in regulation. Burst mode results in higher low-frequency output ripple voltage. This is a concern for applications requiring very low output ripple at light load and at the minimum output voltage.

In such cases, the winding capacitance within the transformer and the output capacitance (Coss) or junction capacitance (Cj) of the rectifiers must be minimized. These parasitic capacitances will cause the gain curve to invert when operating above the resonant frequency. Figure 4 shows the traditional first harmonic approximation (FHA) calculation of an LLC gain curve at light load and the same LLC gain curve when accounting for winding the capacitance and Coss of the rectifiers used in the power stage.

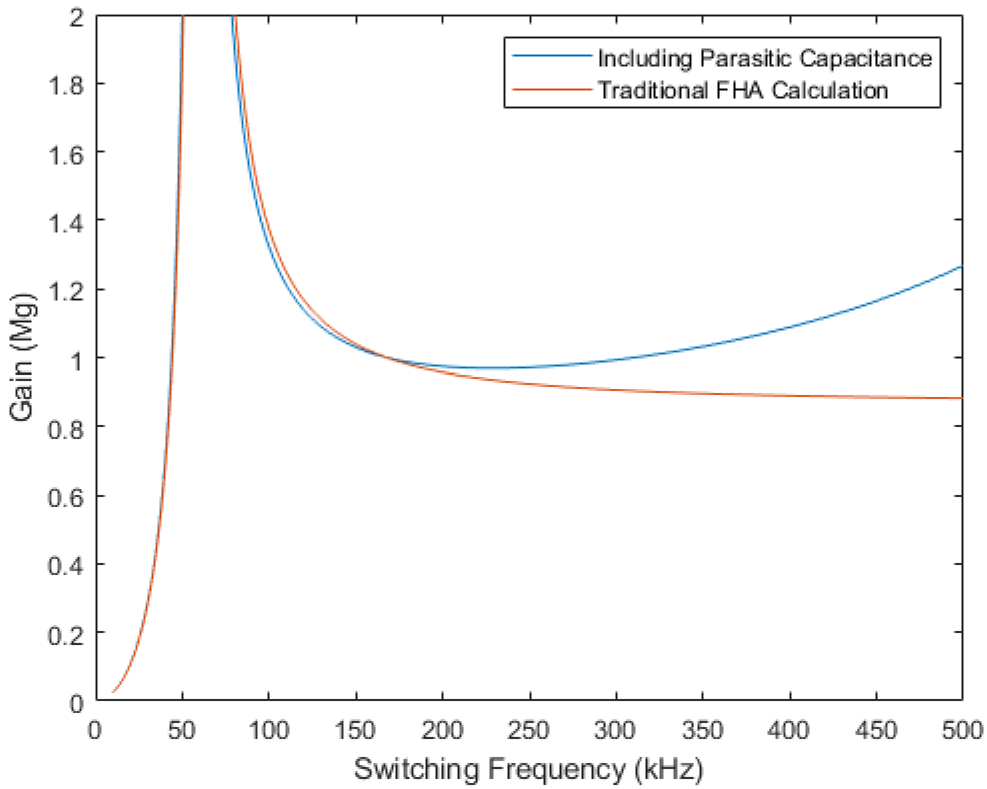

Figure 4. The impact of parasitic capacitance on the LLC gain curve at light load. Source: Texas Instruments

Careful attention to the winding stackup within the transformer and selection of the rectifier components minimizes this gain curve inversion effect. Using wide bandgap devices such as SIC diodes or GaN high electron mobility transistors (HEMTs) as the rectifier can result in considerably lower Coss compared to Si MOSFETs or diodes.

Using LLC controllers with a high-frequency skip mode

A high-frequency skip mode can achieve a lower gain compared to what is achievable with normal switching. Below is an example from a 100W half-bridge LLC converter with an input range of 70V to 450V. In Figure 5, the resonant current is shown in green, and the primary side switch node is shown in blue.

On the right side, the LLC converter is operating in a high-frequency skip mode, omitting every fourth switching cycle. The switching frequency is 260kHz, but it is sub-modulated at a 77kHz burst frequency.

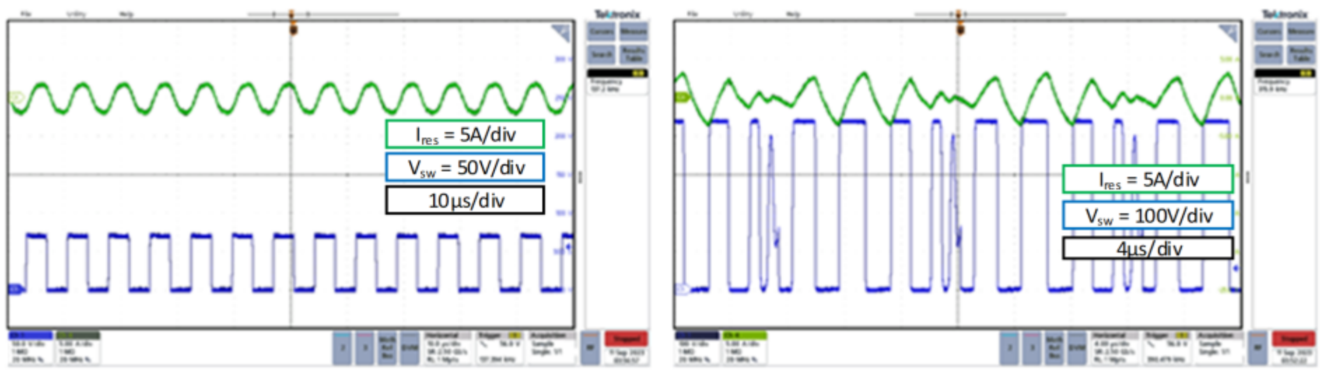

Figure 5. The 100W LLC converter switching behavior at 70V and 450V inputs with resonant current in green and the primary side switch node in blue. Source: Texas Instruments

Managing auxiliary bias voltages

Generating the necessary bias voltages for the primary and secondary sides of the power supply can be done by including auxiliary windings on the LLC transformer. For LLC converters with a variable output voltage, the auxiliary winding voltages will change as the output voltage changes. This is especially true for LLC transformers using sectioned bobbins where the auxiliary windings have poor coupling to the secondary windings. When using a simple low-dropout regulator (LDO) structure to regulate the bias voltage, the efficiency will drop as the output voltage increases. It may require a larger physical package to handle the power dissipation.

In Figure 6, N_{aux1} and N_{aux2} are sized so that at the lowest output voltage, or the VCC bias voltage, is provided through D1, Q1, and D4. As the output voltage increases, the voltage on C2 is limited to the breakdown voltage of Zener D3 minus the gate-source threshold voltage of Q1. As the output voltage is increased further, the voltage generated by N_{aux2} becomes high enough to supply VCC, and Q1 is forced off as the gate-source voltage decreases below the turn-off threshold.

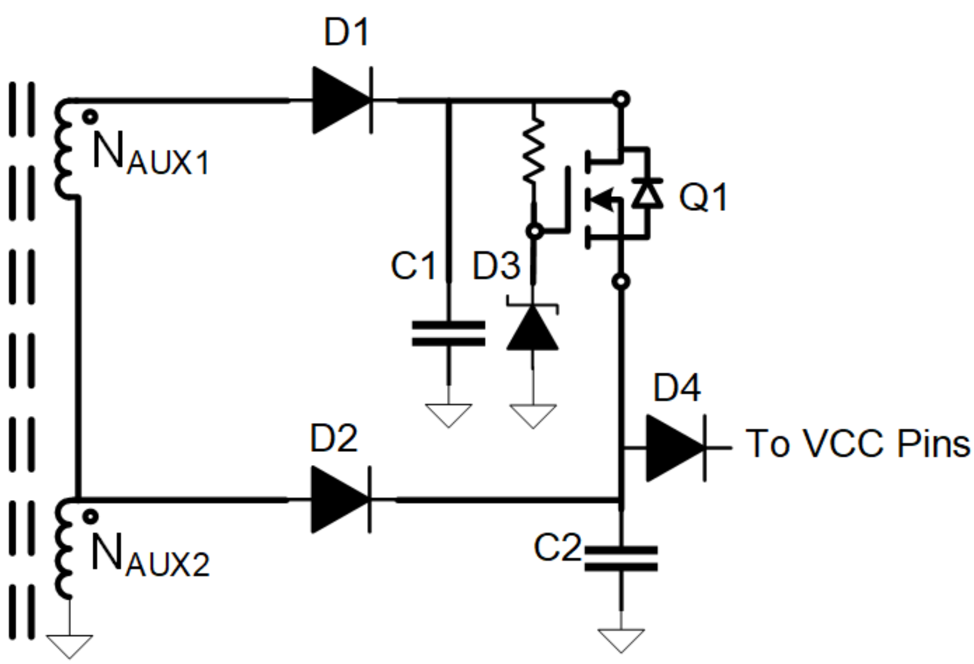

Figure 6. Using auxiliary windings along with an LDO structure to generate the necessary bias voltages for the primary and secondary side of the power supply. Source: Texas Instruments

This approach is more efficient than a single winding + LDO but requires two aux windings. An alternative approach that requires only one aux winding is to use a buck converter or boost converter instead of an LDO.

Managing trickle-charging for deeply discharged batteries

LLC converters used as battery chargers must safely recover deeply discharged batteries by applying a small charging current until the battery pack voltage is high enough to safely take the full charging current. LLCs cannot regulate down to a 0V output with a small output current and therefore struggle to meet this requirement.

This can be managed by including a small constant current circuit with a bypass FET in parallel, as shown in Figure 7. When in trickle-charge mode, the bypass FET turns off, and the output current is supplied by LM317 configured to regulate the output current. This allows the minimum output voltage of the LLC converter to be greater than 0V, even with an output voltage of 0V. This approach allows the LLC transformer to generate the necessary bias voltages on the primary and secondary side and avoid needing a separate bias supply when the output voltage is 0V. Once the battery pack voltage has risen to a high-enough level, a FET with a discrete charge-pump circuit bypasses the constant-current circuit.

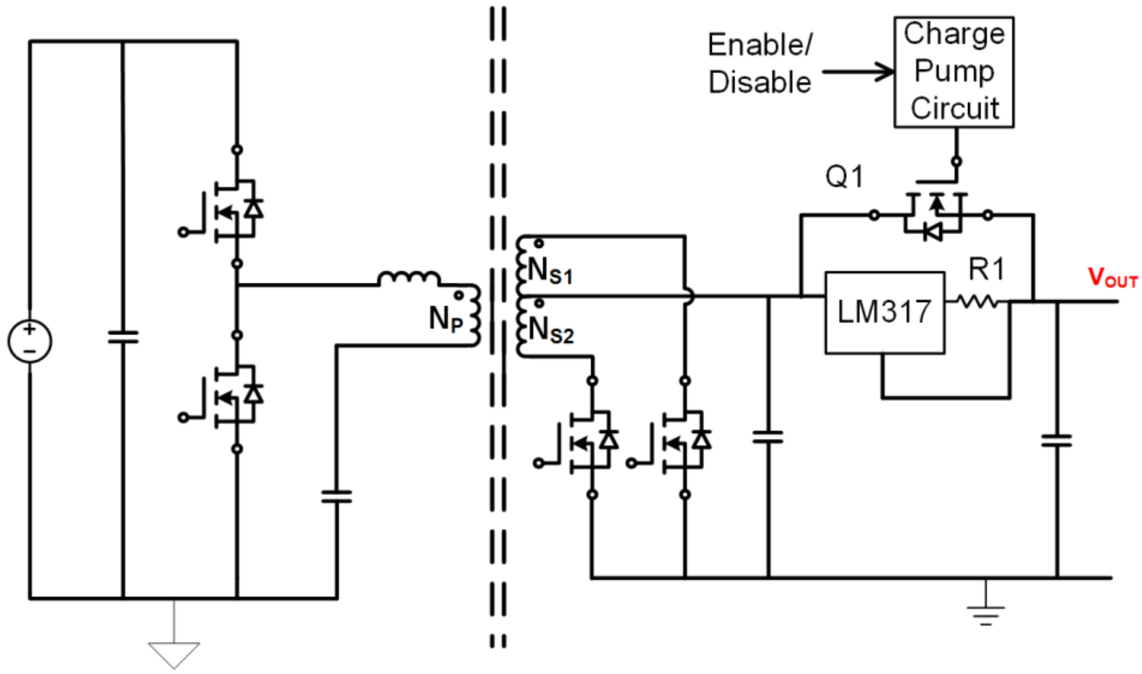

Figure 7. LLC with a trickle charging circuit that can safely recover deeply discharged batteries. Source: Texas Instruments

Wide LLC operation

While achieving a wide operating range with an LLC converter may look difficult due the nature of the LLC topology, several strategies exist for obtaining a wide operating range easier to achieve. The five simple tips and tricks listed here are analog-control friendly and do not require more complex, digital-control implementations.

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