Technical Article

Implementing LLC current-mode control on the secondary side with a digital controller

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Current-mode control LLC considerations

Inductor-inductor-capacitor (LLC) serial resonant circuits, as shown in Figure 1, can achieve both zero voltage switching on the primary side and zero current switching on the secondary side in order to improve efficiency and enable a higher switching frequency. In general, an LLC converter uses direct frequency control, which has only one voltage loop and stabilizes its output voltage by adjusting the switching frequency. An LLC with direct frequency control cannot achieve high bandwidth because there is a double pole in the LLC small-signal transfer function that can vary under different load conditions [1] [2]. When including all of the corner conditions, the compensator design for a direct frequency control LLC becomes tricky and complicated.

Current-mode control can eliminate the double pole with an inner control loop, achieving high bandwidth under all operating conditions with a simple compensator. Hybrid hysteretic control is a method of LLC current-mode control that combines charge control and ramp compensation [3]. This method maintains the good transient performance of charge control, but avoids the related stability issues under no- or light-load conditions by adding slope compensation. The UCC256404 LLC resonant controller from Texas Instruments proves this method's success.

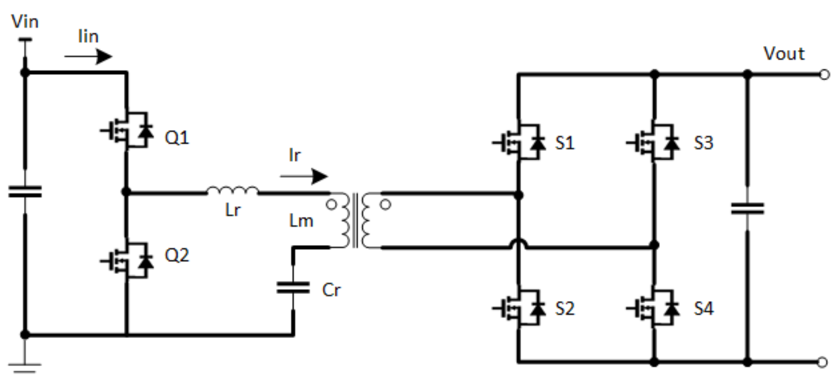


Figure 1. LLC serial resonant circuits that achieve both zero voltage switching on the primary side and zero current switching on the secondary side. Source: Texas Instruments

Principles of LLC current-mode control

Similar to pulse-width modulation (PWM) converters such as buck and boost, peak current-mode control controls the inductor current in each switching cycle and simplifies the inner control loop into a first-order system. Reference [2] proposes LLC charge control with the resonant capacitor voltage.

In an LLC converter, the resonant tank operates like a swing. The high- and low-side switches are pushing and pulling the voltage on the resonant capacitor: when the high-side switch turns on, the voltage on the resonant capacitor will swing up after the resonant current turns positive; conversely, when the low-side switch turns on, the voltage on the resonant capacitor will swing down after the resonant current turns negative.

Energy flows into the resonant converter when the high-side switch turns on. If you remove the input decoupling capacitor, the power delivered into the resonant tank equals the integration of the product of the input voltage and the input current. If you neglect the dead time, Equation 1 expresses the energy in each switching cycle.

$$E_{pos} = \int V_{in} \times i_{in}(t)dt \quad (1)$$

In , Equation 1, the input voltage is constant, and the input current equals the absolute of the resonant current. So, you can modify , Equation 1 into , Equation 2.

$$E_{pos} = V_{in} \times \int |i_r(t)|dt \quad (2)$$

Looking at the resonant capacitor, the integration of the resonant current is proportional to the voltage variation on the resonant capacitor (Equation 3).

$$\int i_r(t)dt = C_{CR} \times \Delta V_{CR} \quad (3)$$

Equation 4 deduces the energy delivered into the resonant tank.

$$E_{pos} = V_{in} \times C_{CR} \times \Delta V_{CR} \quad (4)$$

From Equation 4, it is obvious that the energy delivered in one switching cycle is proportional to the voltage variation on the resonant capacitor when the high-side switch turns on. This is very similar to peak current control in a buck or boost converter, in which the energy is proportional to the peak current of the inductor.

LLC current-mode control controls the energy delivered in each switching cycle by controlling the voltage variation on the resonant capacitor, as shown in Figure 2.

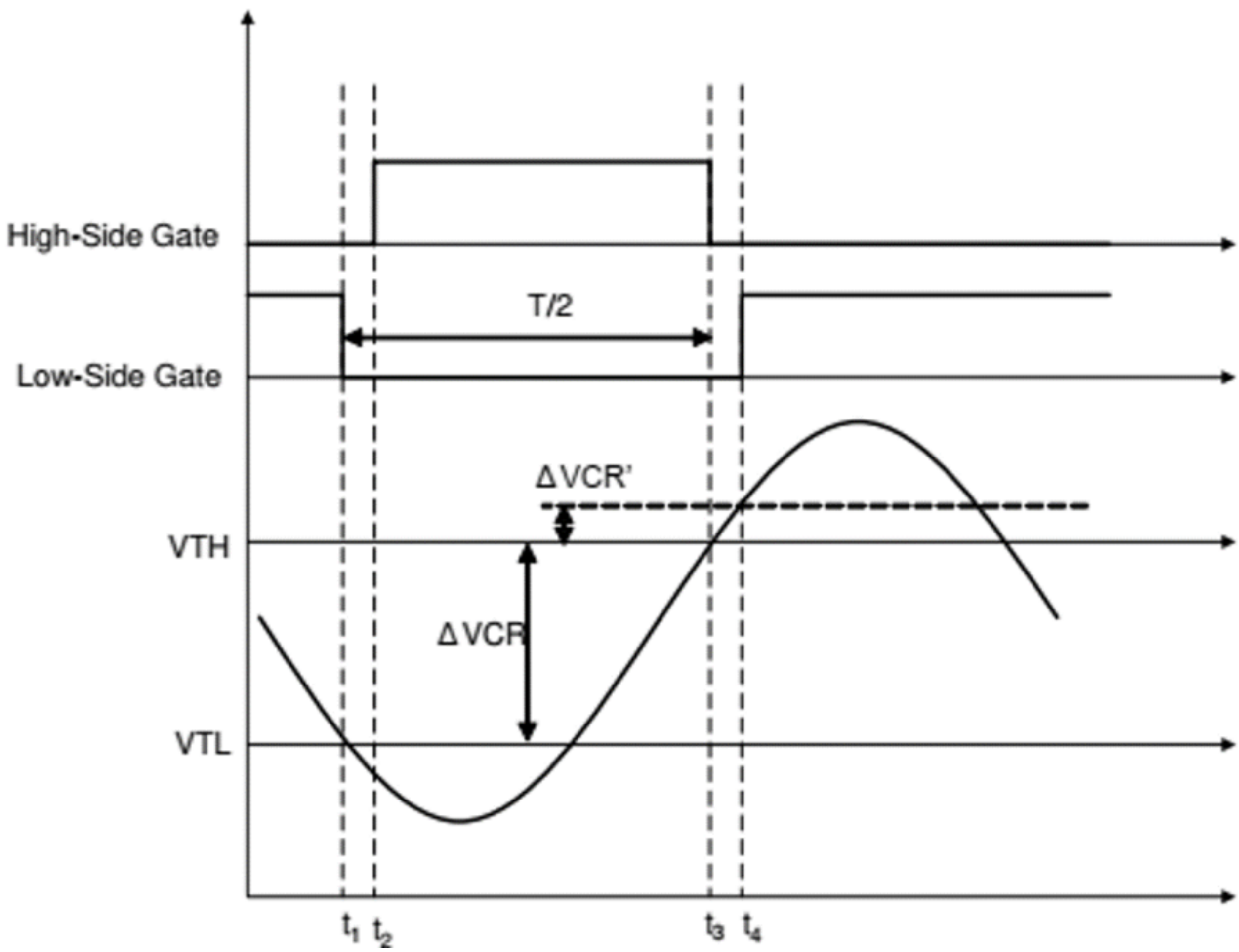


Figure 2. The LLC current-mode control principle that manages the energy delivered in each switching cycle by controlling the voltage variation on the resonant capacitor. Source: Texas Instruments

LLC current-mode control with MCUs

Figure 3 shows the logic of a current-mode LLC implemented with the TMS320F280039C C2000™ 32-bit microcontroller (MCU) from Texas Instruments, which includes a hardware-based delta voltage of resonant capacitor (ΔVCR) comparison, pulse generation and maximum period limitation [4].

In LLC current-mode control, signal Vc comes from the voltage loop compensator, and signal VCR is the voltage sense of the resonant capacitor. A C2000 comparator subsystem module has an internal ramp generator that can automatically provide downsloped compensation to Vc. You just need to set the initial value of the ramp generator; the digital-to-analog converter (DAC) will provide the downsloped VCR limitation (Vc_ramp) based on the slope setting. The comparator subsystem module compares the analog signal of VCR with the sloped limitation, and generates a trigger event (COMPARE_EVT) to trigger enhanced PWM (ePWM) through the ePWM X-bar.

The action qualifier submodule in ePWM receives the compare event from the comparator subsystem and pulls low the high side of PWM (PWMH) in each switching cycle. The configurable logic block then duplicates the same pulse width to the low side of PWM (PWML) after PWMH turns low. After PWML turns low, the configurable logic block generates a synchronous pulse to reset all of the related modules and resets PWMH to high. The process repeats with a new switching cycle.

Besides the compare actions, the time base submodule limits the maximum pulse width of PWMH and PWML, which determines the minimum switching frequency of the LLC converter. If the compare event hasn't appeared until the timer counts to the maximum setting, the time base submodule will reset the AQ submodule and pull down PWMH, replacing the compare event action from the comparator subsystem module.

This hardware logic forms the inner VCR variation control, which controls the energy delivered to the resonant tank in each switching cycle. You can then design the outer voltage loop compensator, using the traditional interrupt service routine to calculate and refresh the setting of the VCR variation amplitude to Vc.

For a more detailed description of the hybrid hysteretic control logic, see Reference [1].

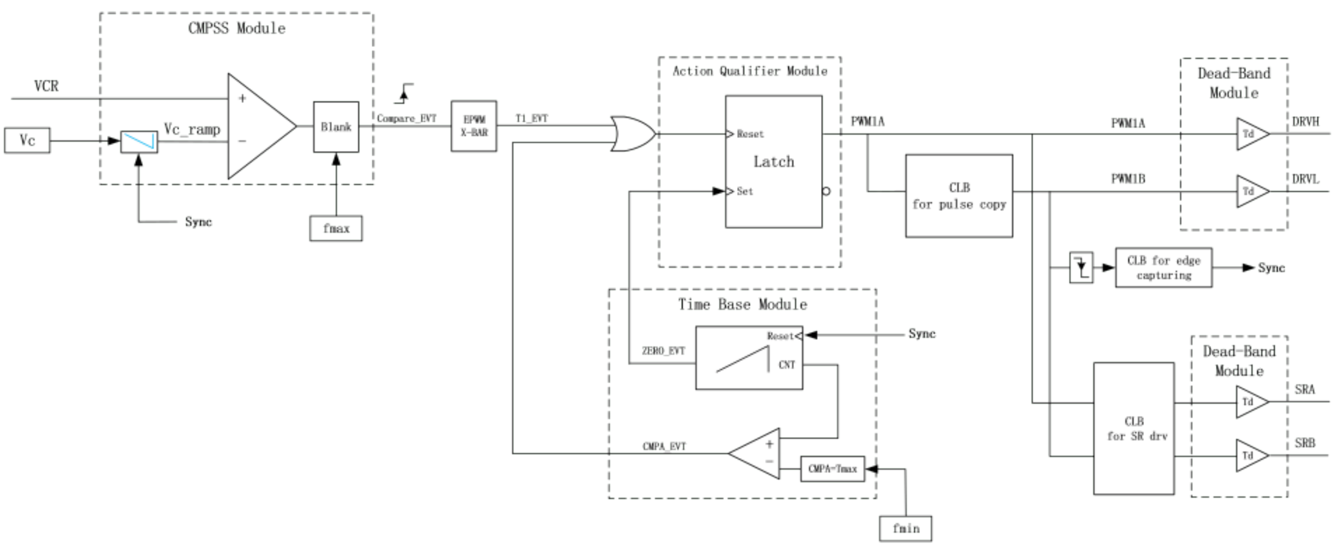


Figure 3. LLC current-mode control logic with a C2000 MCU where the signal Vc comes from the voltage loop compensator, and the signal VCR is the voltage sense of the resonant capacitor. Source: Texas Instruments

Experimental results

I tested the current-mode control method described here on a 1kW half-bridge LLC platform with the TMS320F280039C MCU. Figure 4 shows the Bode plot of the voltage loop under a 400V input and 42A load, proving that the LLC can achieve 6kHz of bandwidth with a 50-degree phase margin.

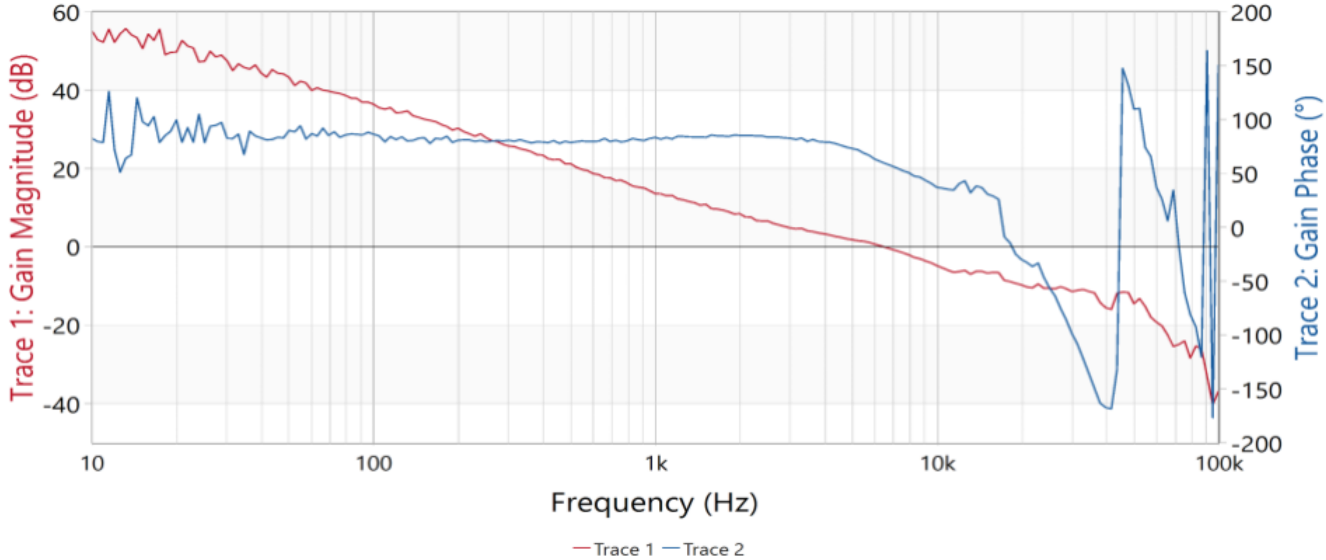
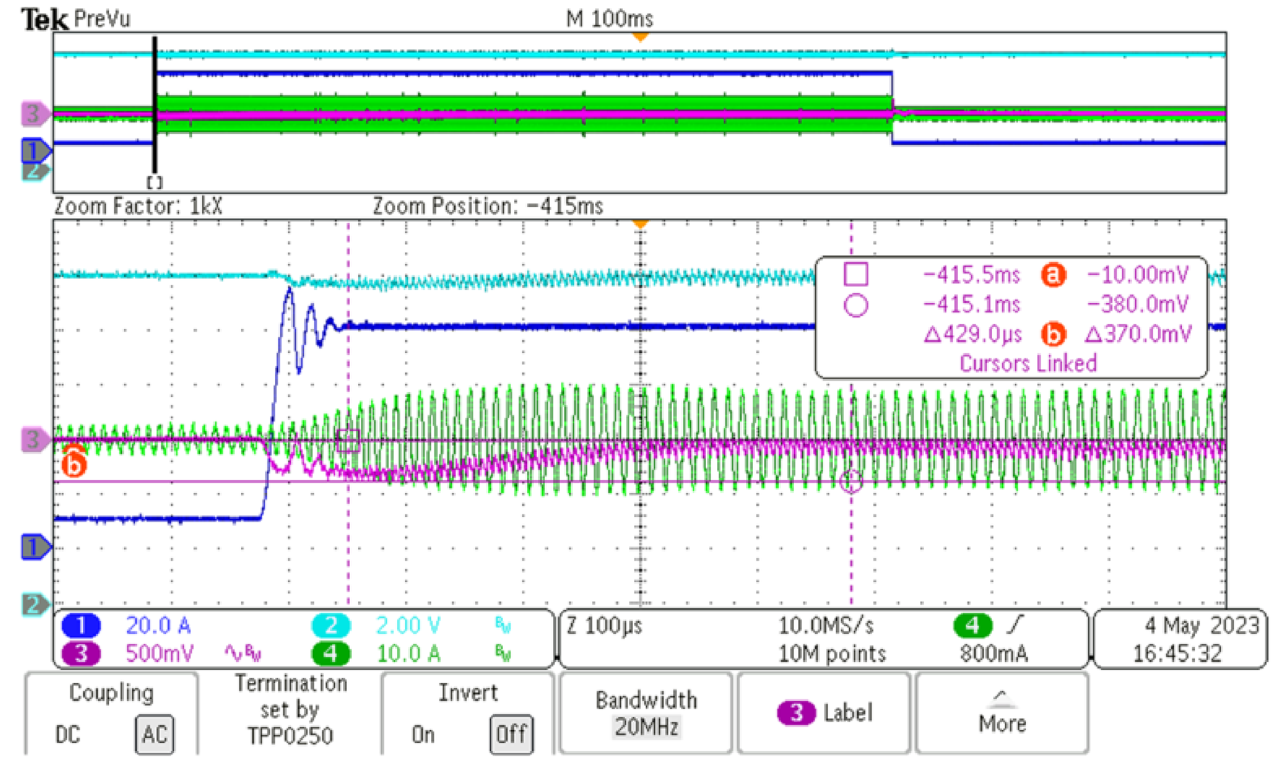


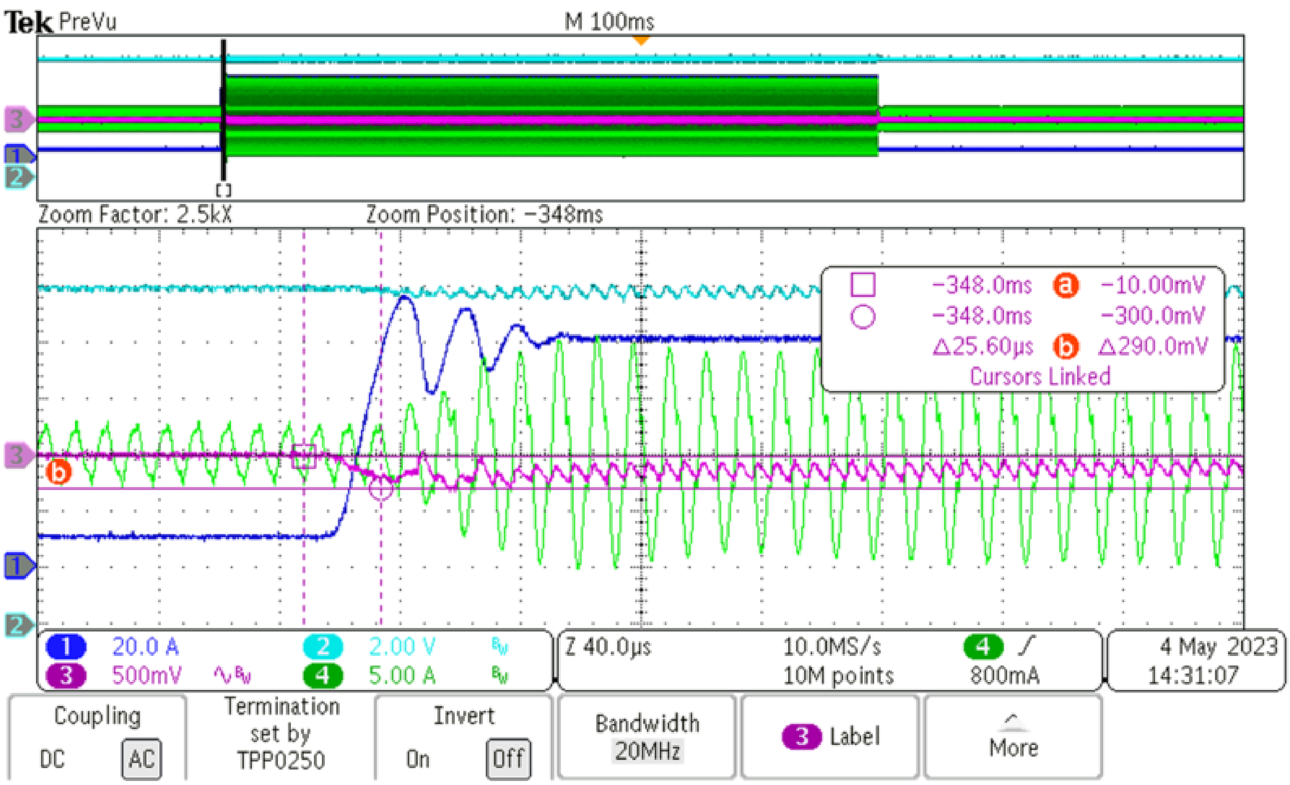
Figure 4. The Bode plot of a current-mode control LLC with a 400V input and 42A load. Source: Texas Instruments

Figure 5 compares the load transient between direct frequency control and hybrid hysteretic control with a 400V input and a load transient from 10A to 80A with a 2.5A/μs slew rate. As you can see, the hybrid hysteretic control current-mode control method can achieve better a load transient response than a traditional direct frequency control LLC.

For more experimental test data and waveforms, see Reference [5].



(a)



(b)

Figure 5. Load transient with direct frequency control (a) and hybrid hysteretic control (b), from 10A to 80A with a 2.5A/μs slew rate under a 400V_{DC} input. Green is the primary current; light blue is the output voltage, with DC coupled; purple is the output voltage, with AC coupled; and dark blue is the output current. Source: Texas Instruments

Digital current-mode controlled LLC

The digital current-mode controlled LLC can achieve higher control bandwidth than direct frequency control and hold very low voltage variation during load transition. In N+1 redundancy and parallel applications, this control method can keep the bus voltage within the regulation range during hot swapping or protecting. So, this control method has been widely adopted in data center power and AI server power with this fast response feature and digital programmable ability.

Related Content

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References

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2. McDonald, Brent, and Yalong Li. “A novel LLC resonant controller with best-in-class transient performance and low standby power consumption.” Published in 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), San Antonio, Texas, March 4-8, 2018, pp. 489-493. doi: 10.1109/APEC.2018.8341056.
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4. Li, Aki, Desheng Guo, Peter Luong, and Chen Jiang. “Digital Control Implementation for Hybrid Hysteretic Control LLC Converter.” Texas Instruments application note, literature No. SPRADJ1A, August 2024.
5. Texas Instruments. n.d. “1-kW, 12-V HHC LLC reference design using C2000™ real-time microcontroller.” Texas Instruments reference design No. PMP41081. Accessed Jan. 16, 2025.

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