Technical Article

Control scheme of a bidirectional CLLLC resonant converter in an ESS

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Introduction

A single-stage isolated converter, such as a bidirectional capacitor-inductor-inductor-inductor-capacitor (CLLLC), is a popular converter type in energy storage systems (ESSs) to save system costs and improve power density. The gain curve of an CLLLC is flatter, however, when the switching frequency (f_s) is higher than the series resonant frequency (f_r) the gain curve will be undesirably flat. The parasitic capacitance of the transformer and MOSFETs would also significantly impact the converter gain [1], which will lead the converter's output voltage out of regulation. In this power tip, I will introduce a CLLLC control algorithm and a synchronous rectifier (SR) control method to eliminate this nonlinearity, using a 3.6kW prototype converter to verify the performance. Figure 1 is a block diagram of a residential ESS.

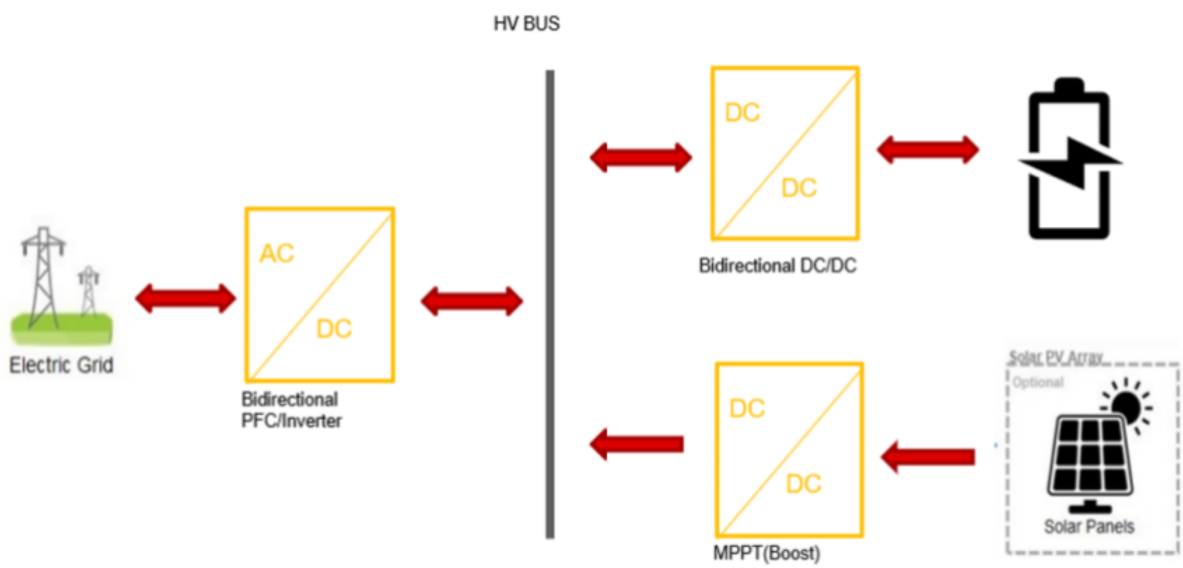

Figure 1. Residential ESS block diagram with bidirectional power factor correction (PFC)/inverter, bidirectional DC/DC converter, and maximum power point tracking (MPPT). Source: Texas Instruments

Design considerations in the control stage

Figure 2 shows the circuit topology of the full-bridge CLLLC resonant converter with the parasitic capacitors. This topology consists of a symmetric resonant tank and full-bridge structure.

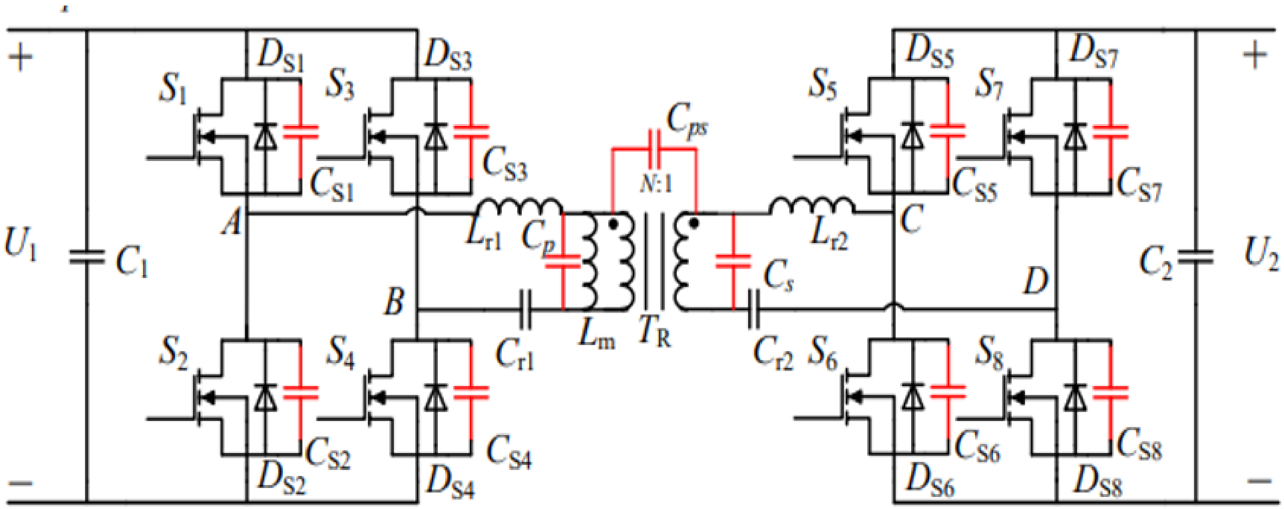

Figure 2. The circuit topology of the full-bridge CLLLC converter with parasitic capacitors. Source: Texas Instruments

Figure 3 shows the ideal gain curve of the CLLLC. Similar to an LLC converter, variable frequency control is a popular control scheme for a CLLLC resonant converter.

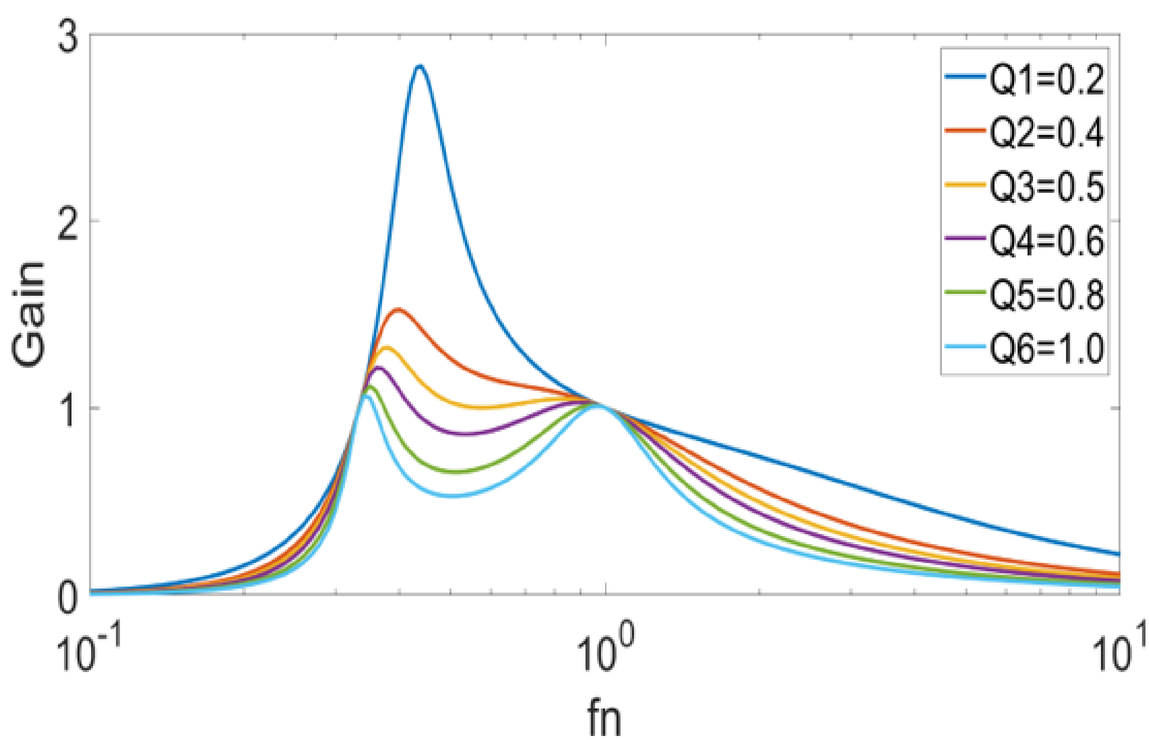

Figure 3. An ideal CLLLC gain curve that uses variable frequency control. Source: Texas Instruments

As mentioned earlier, the gain curve is flat when f_s exceeds f_r. Moreover, with the power level increasing, the converter needs to parallel more FETs on the battery side to handle more current, which means that the output capacitance (C_{OSS}) on the output full-bridge FETs will be extremely large. Considering the parasitic parameters of transformer interwinding capacitance and C_{OSS}, the non-monotonic gain curve at high frequency is serious, which corresponds to a light-load condition, as shown in Figure 4.

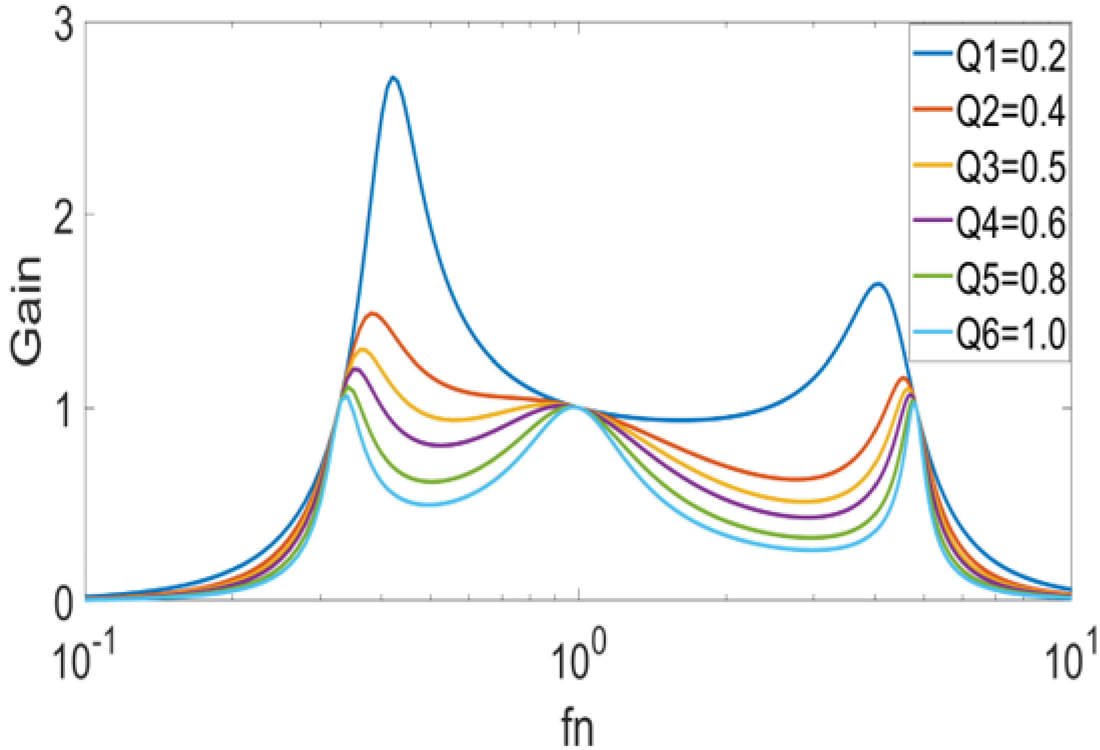

Figure 4. The CLLLC gain curve considering parasitic parameters such as the transformer interwinding capacitance and C_{OSS}. Source: Texas Instruments

In this case, frequency control is useless. Hiccup mode is a popular method for addressing CLLLC resonant converter nonmonotonic features, but this method is not suitable in battery applications because the converter needs to deliver high current when the battery voltage is low. Pulse-width modulation (PWM) and phase-shift control could resolve this issue, but PWM control will make the transistors work at a hard-switching state, which decreases efficiency and limits the operational frequency. Therefore, phase-shift control is a better choice.

Control logic

Figure 5 shows the frequency and phase-shift mixed-control scheme diagram. The battery voltage is low during startup, so the converter needs to soft start with low charging current to limit the high current spike and prolong the battery life. It is a limited effect to soft start from a high frequency if the resonant inductor value or frequency is not high enough. When the battery charges to near full capacity, it will trickle charge with a small current and maintain a constant voltage. Both cases correspond to a light-load condition for the converter. At light load, the output voltage tends to rise because of the parasitic capacitance and could eventually go out of regulation based on previous analysis; phase-shift control can help regulate the output voltage in this state. The controller’s calculation result decides whether the converter needs to enter phase-shift mode or not.

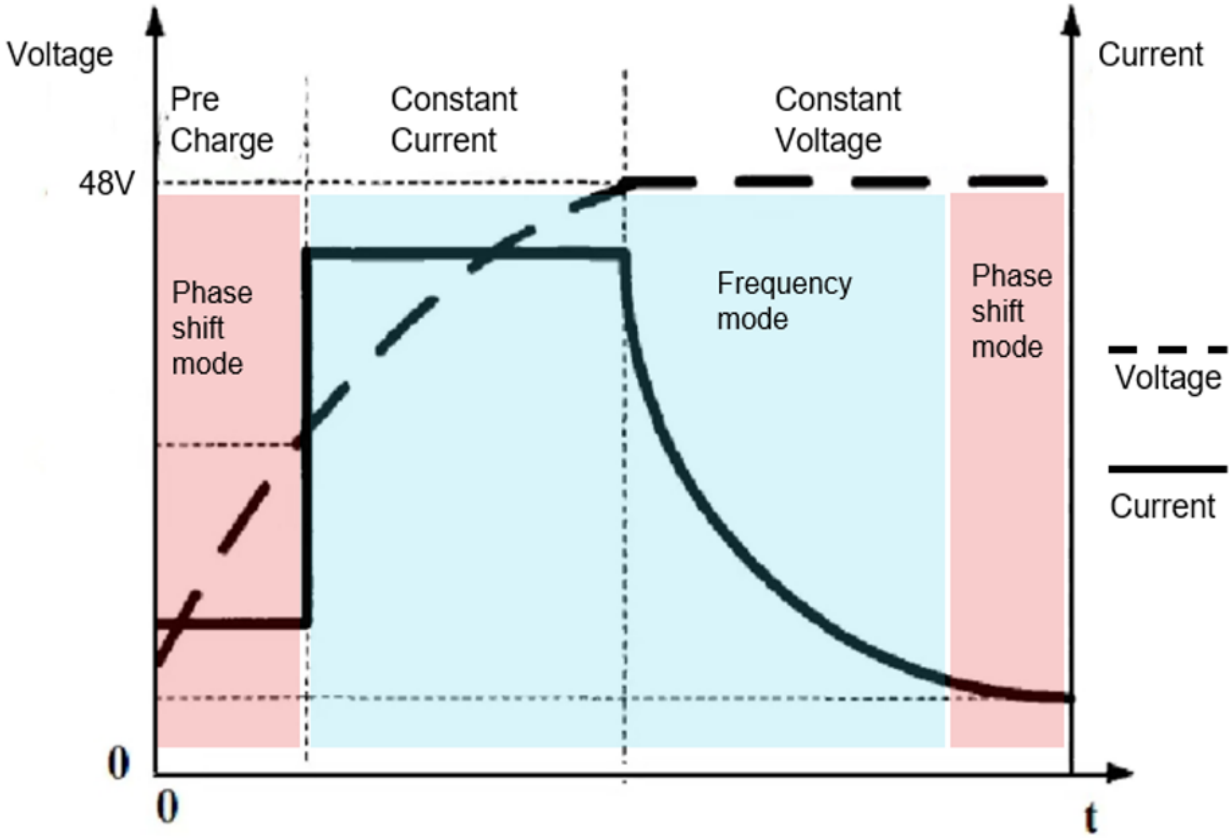

Figure 5. The control scheme in different charge states. Note, the battery voltage is low during startup, so the converter needs to soft start with low charging current to limit the high current spike and prolong the battery life. Source: Texas Instruments

Figure 6 shows the modulation switch between frequency and phase shift. When the load decreases, the frequency will increase to regulate the output voltage. If the calculated maximum frequency is higher than the setting value, the converter will enter phase-shift modulation; then when the load increases, the phase-shift angle will decrease in order to regulate the output voltage. The converter will enter frequency mode again when the phase-shift angle decreases to zero.

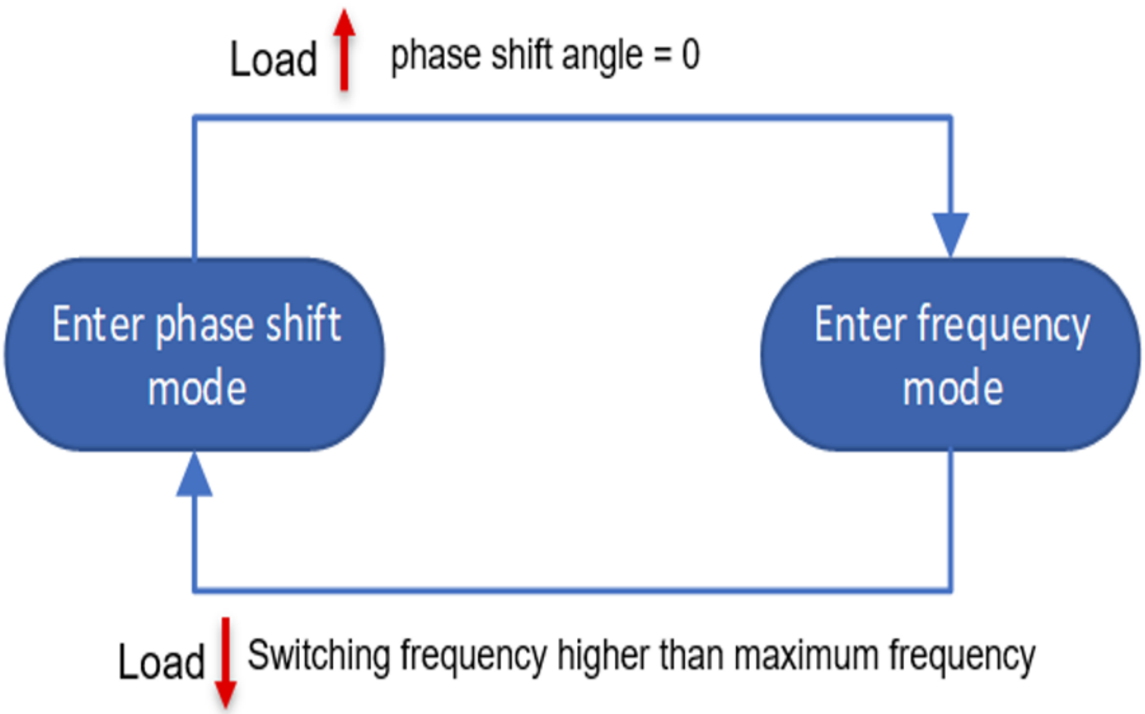

Figure 6. The control scheme between frequency and phase-shift modes. When the load decreases and the phase-shift angle is zero, the frequency will increase to regulate the output voltage (frequency mode). If the maximum frequency is higher than the setting value, the phase shift angle decreases to regulate output voltage (phase shift mode). Source: Texas Instruments

Problems caused by parasitic capacitance

The MOSFETs' C_{oss} also has this effect under phase-shift mode; the tank current will oscillate with these capacitors, as shown in Figure 7.

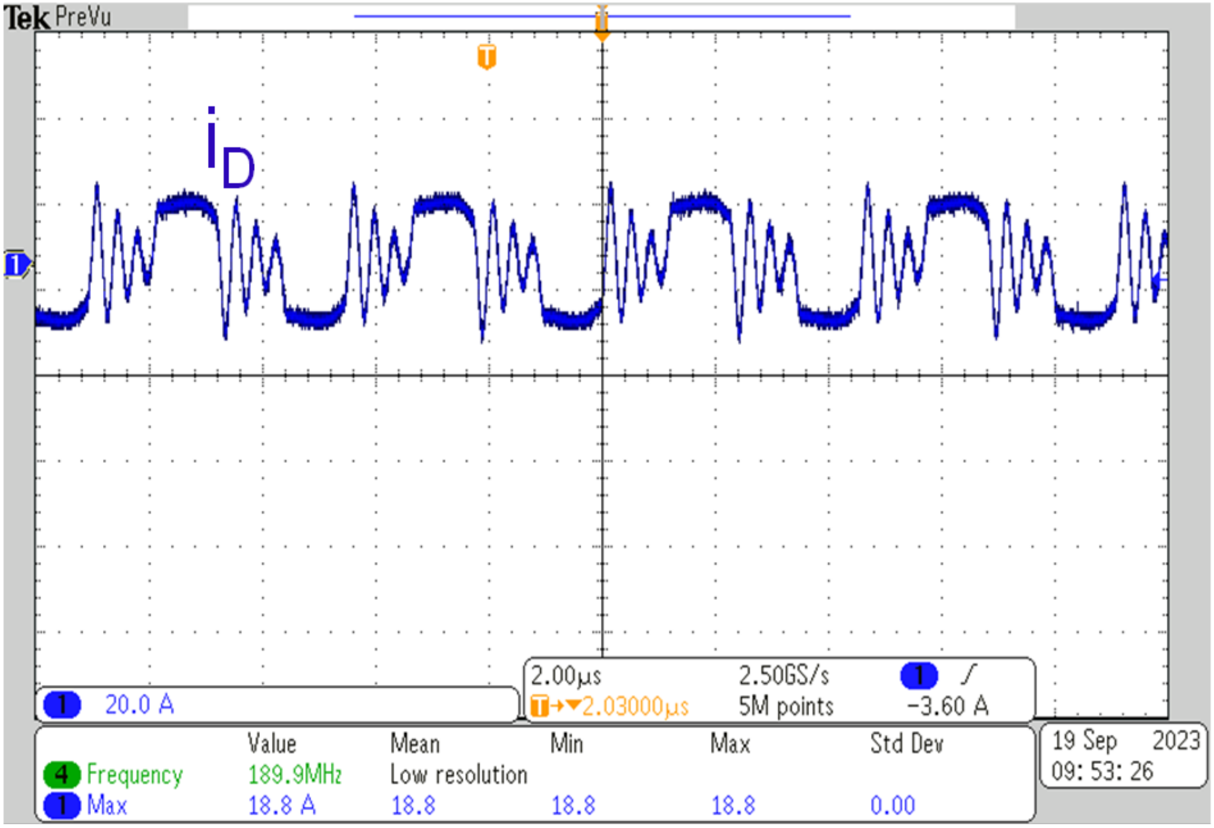

Figure 7. The tank current waveforms under phase-shift mode in open loop. Source: Texas Instruments

Figure 8 plots a gain comparison of a CLLLC converter with and without considering MOSFET C_{oss}. According to the figure, there will be fluctuation in the gain curve. In this case, the controller may adjust the phase-shift angle to the wrong direction under closed-loop control, resulting in a large current spike.

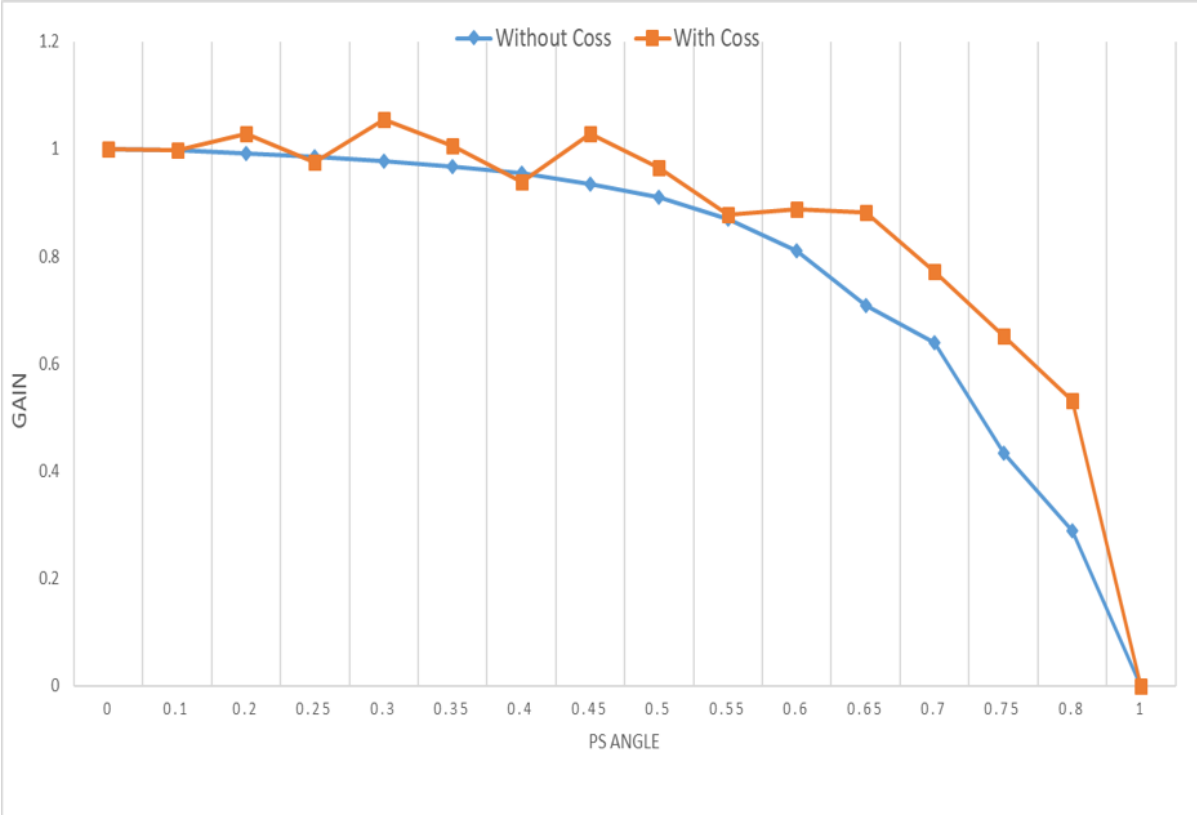

Figure 8. The gain curve under phase-shift mode with and without C_{OSS}. Source: Texas Instruments

Solution for the gain problem

To eliminate the non-monotonic of gain, employing SR control as shown in Figure 9 could resolve this issue. Turning on either two upper or two lower SR switches at the same time during the tank current oscillation period will temporarily short the transformer's secondary-side winding, such that C_{oss} will not involve the resonant.

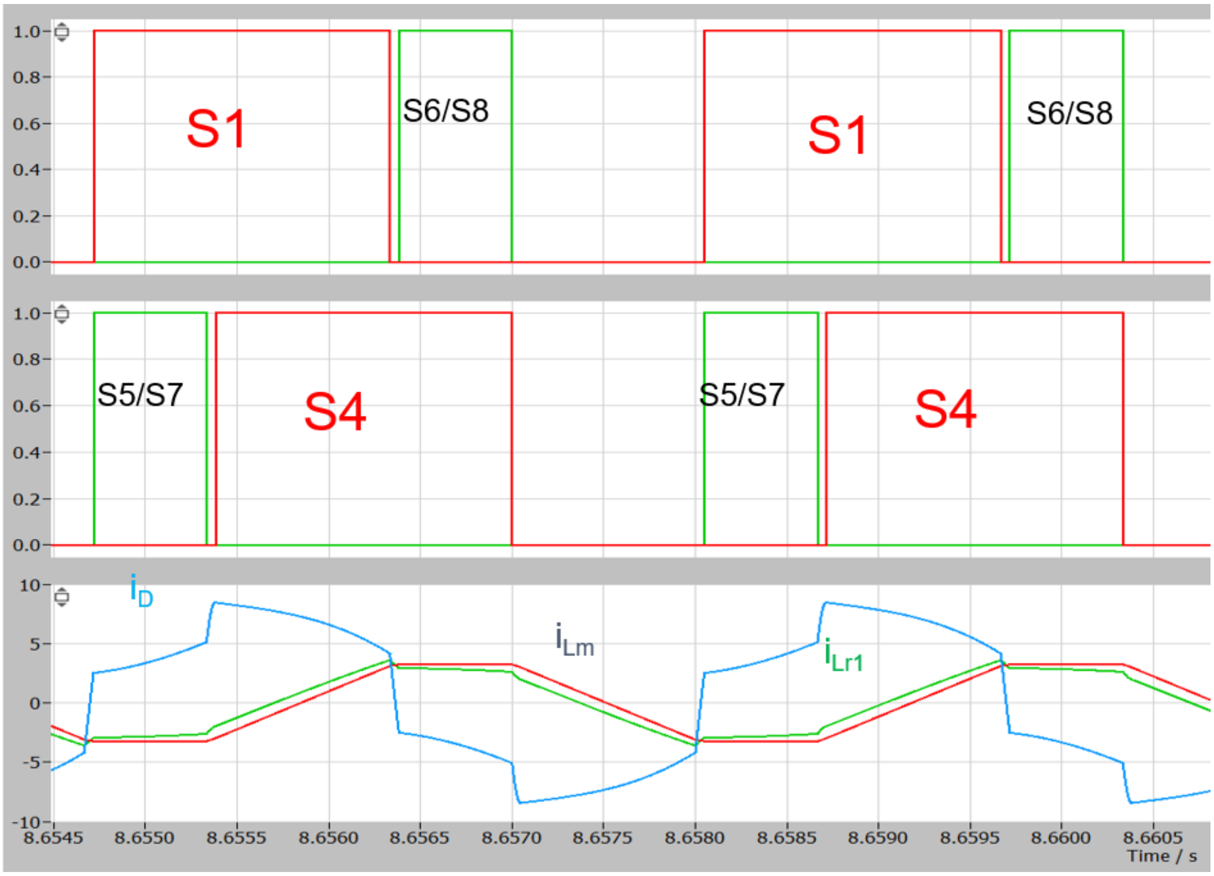

Figure 9. Proposed SR control scheme to eliminate the non-monotonic of gain. Source: Texas Instruments

Figure 10 shows the test result; there is no oscillation compared to Figure 8. For more detailed analysis and test results, see reference [2].

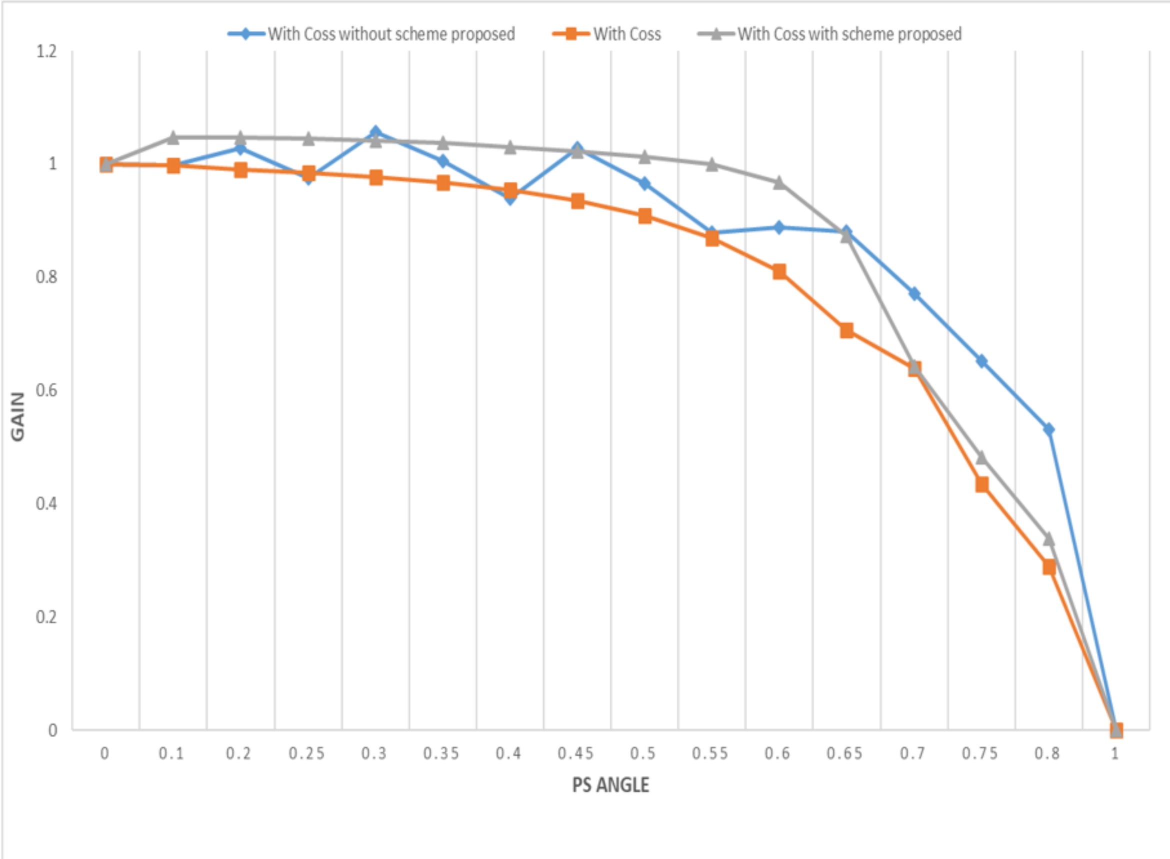

Figure 10. Gain curve under phase-shift mode using the proposed control scheme (grey line). Source: Texas Instruments

Experimental results

A prototype [3] uses this control scheme to verify the performance. Figure 11 shows the soft-start waveform and Figure 12 shows the tank current waveforms under phase-shift mode with the proposed control scheme.

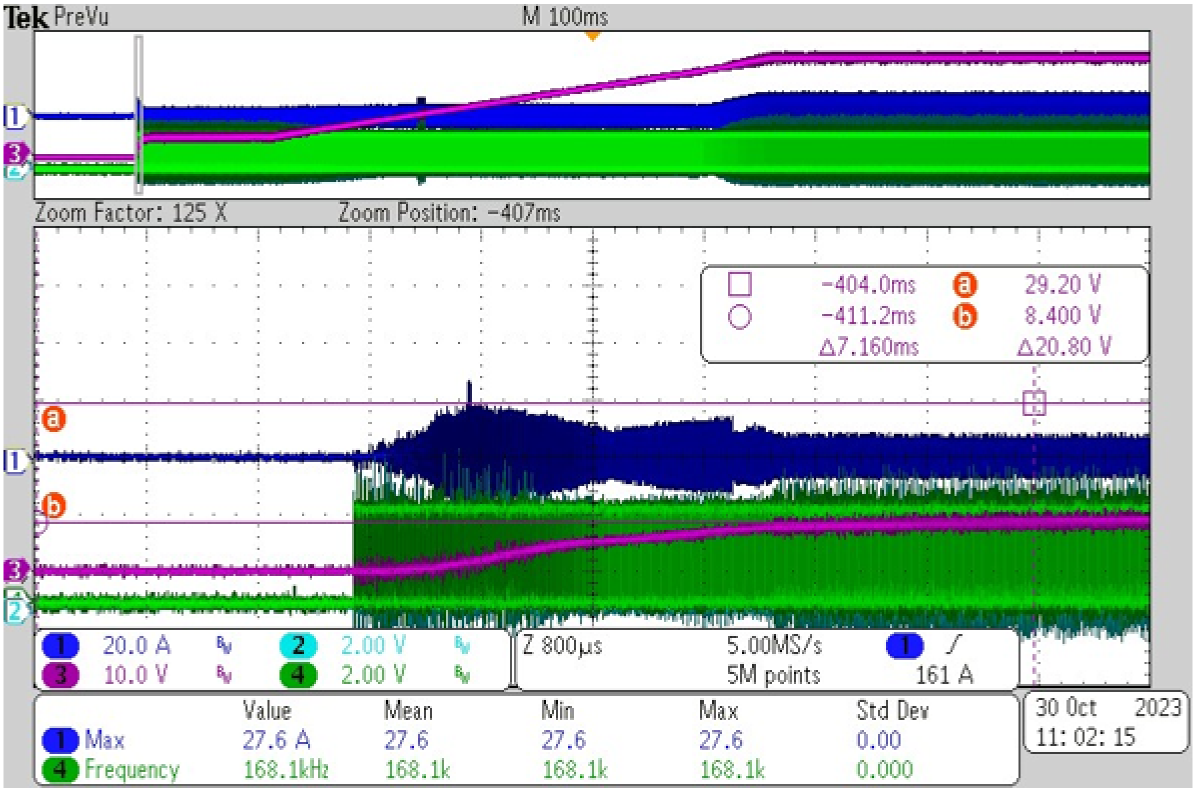

Figure 11. The phase-shift soft start with 750 W of output power. Source: Texas Instruments

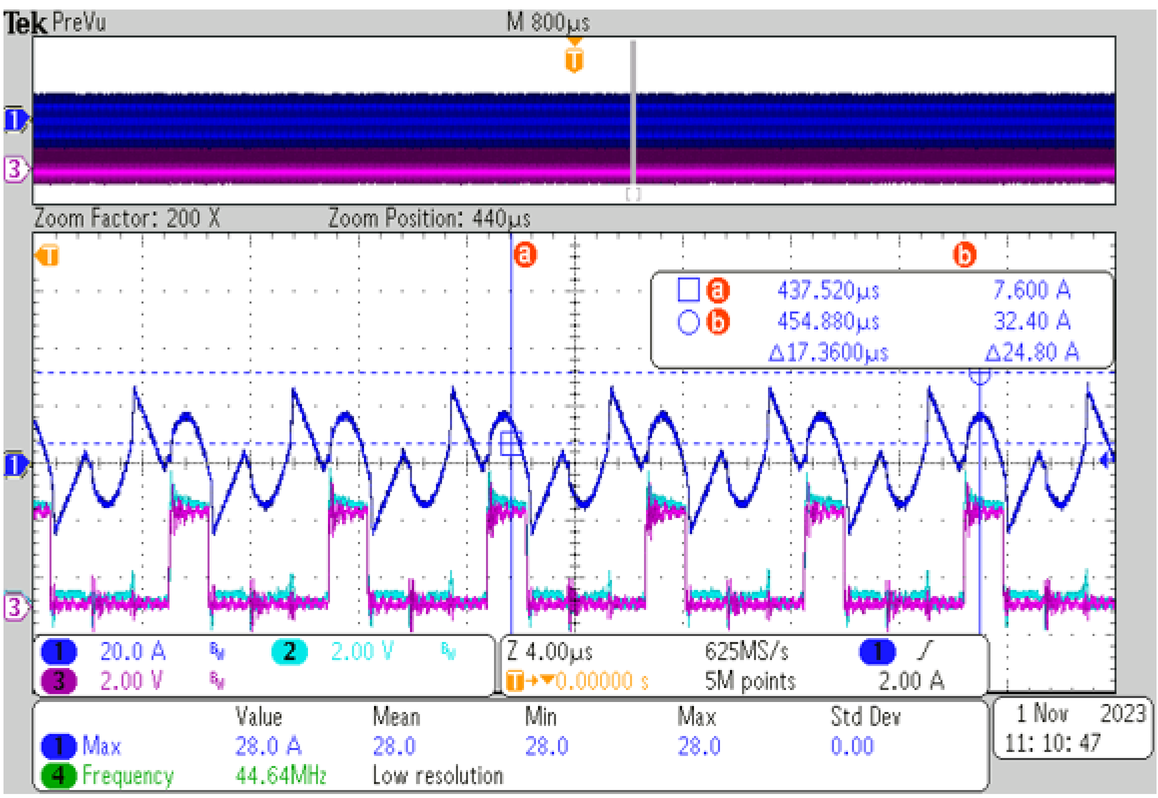

Figure 12. The tank current waveforms under phase-shift mode with the proposed scheme. Source: Texas Instruments

Figure 13 and Figure 14 show the frequency/phase-shift modulation switch test. From the test waveforms, the startup current is limited within 28A with 750W of output power. There is no oscillation in the tank current and the converter could change the modulation smoothly in different working conditions.

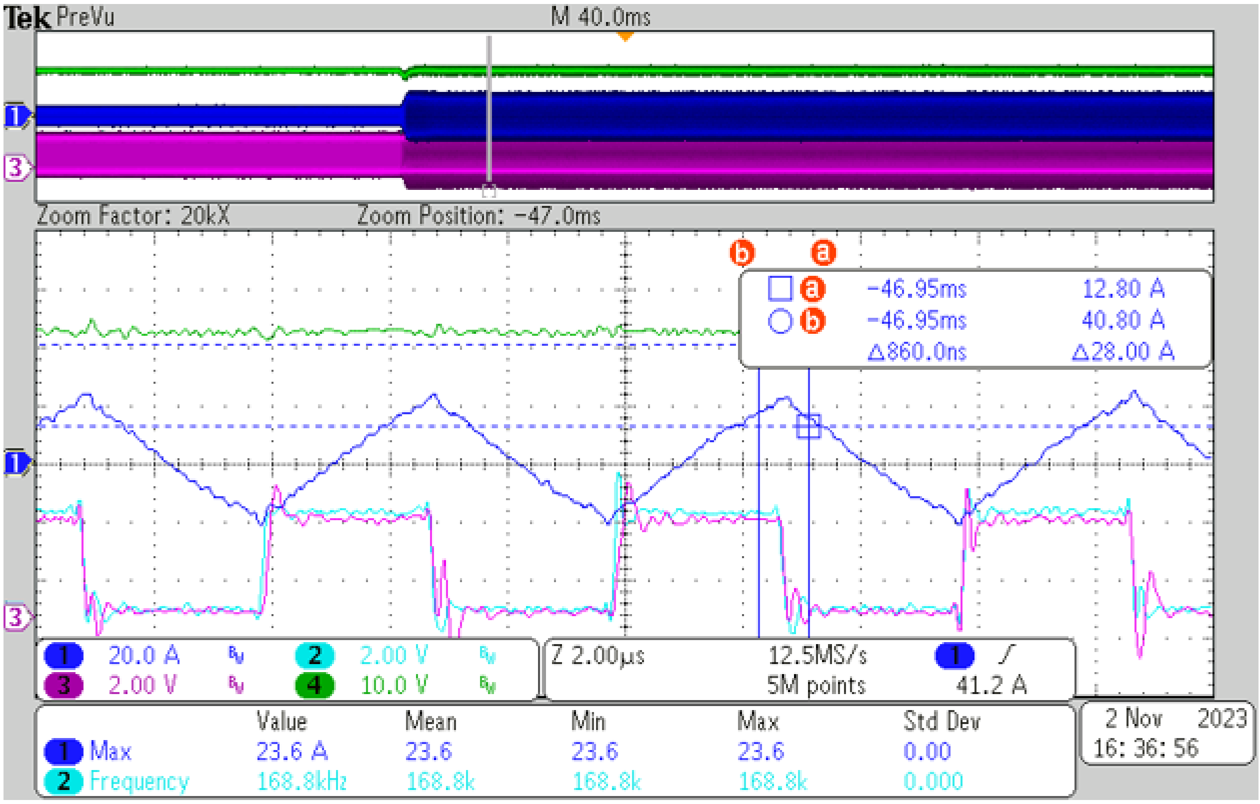

Figure 13. The phase-shift and frequency modulation switch: frequency mode with a 5A load. Source: Texas Instruments

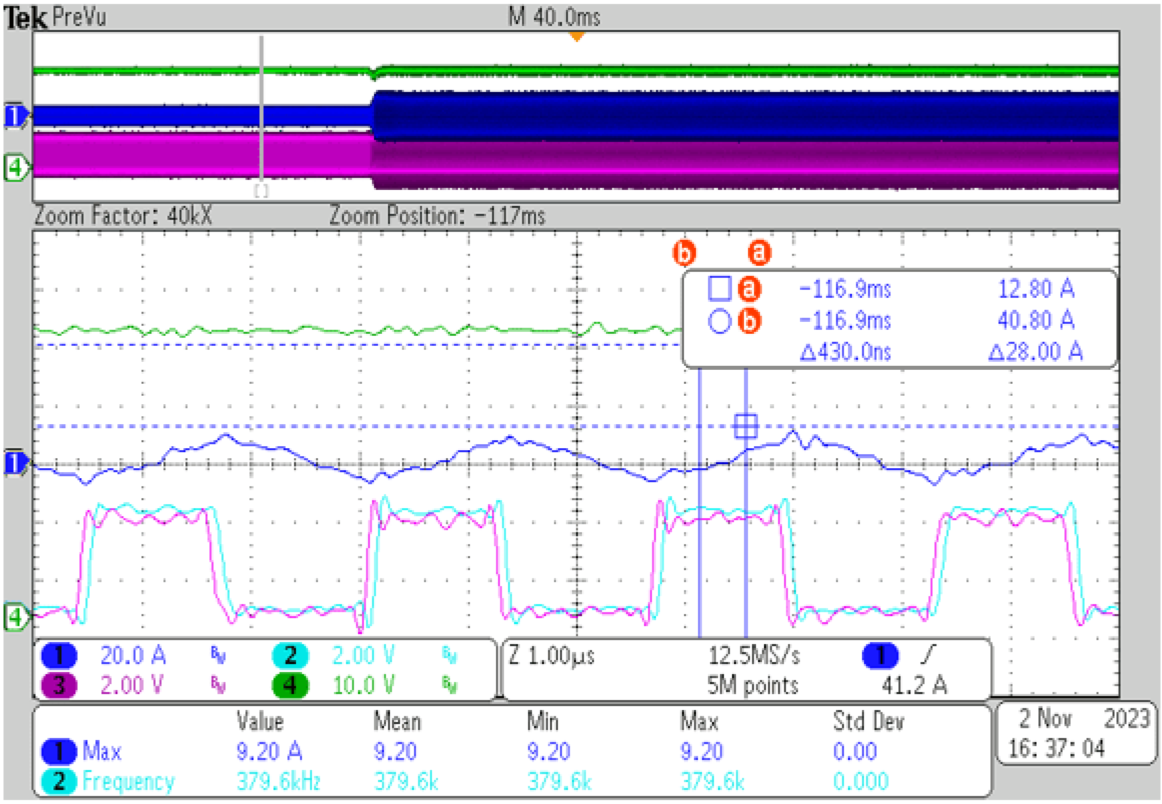

Figure 14. The phase-shift and frequency modulation switch: phase-shift mode with a 1A load. Source: Texas Instruments

Conclusion

The proposed frequency and phase-shift mixed-control scheme limits the inrush current during the startup stage and makes the gain linear at a light load condition. The converter could switch between frequency modulation and phase shift modulation smoothly. Besides, phase-shift control also introduces the non-monotonic gain issue and makes the current oscillate in the designs that have large C_{OSS}. The proposed SR control method can help solve the current oscillation issue and makes the gain monotonic.

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References

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2. Tai, Will, Guangzhi Cui, and Sheng-Yang Yu, "Gain Optimization Control Method for CLLLC Resonant Converters Under Phase Shift Mode." Published in PCIM Europe 2024; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nürnberg, Germany, June 11-13, 2024, pp. 2513-2518.
3. Cui, Guangzhi. n.d. "3.6kW Bidirectional CLLLC Resonant Converter Reference Design." Tex as Instruments reference design No. PMP41042. Accessed Nov. 6, 2024.

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