Application Report

Improving Transient Response in LLC Converters Using Hybrid Hysteretic Control

ABSTRACT

Transient response is a key performance metric in power converter design that describes how a converter responds to a sudden change in load current. This metric is important to satisfy voltage regulation requirements for dynamic loading conditions, and typically requires bulk output capacitance to limit output voltage deviation. Transient response is dependent on the loop response of a converter where the bandwidth and phase margin impacts how quickly the converter responds to a transient event, as well as the settling time behavior of the output voltage. The traditional frequency control method used in LLC converters is difficult to compensate and offers limited bandwidth. An innovative control method, hybrid hysteretic control (HHC), offers superior transient performance by simplifying the LLC power stage into a single pole system, which is easier to compensate and achieves a higher bandwidth. This control strategy offers system benefits by minimizing the amount of necessary bulk output capacitance needed to meet a given voltage regulation requirement, allowing for reduced BOM count and smaller solution size.

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1 Introduction

Transient response is a performance metric in power design that characterizes how a power supply responds to a rapid change in output load current. Ideally, the output of a power converter has little to no change during a load step. In practice however, some variation in the output voltage is encountered. A number of important factors must be considered when analyzing the transient response of a power converter, such as the maximum deviation of the output voltage, the amount of time it takes the output voltage to return to its regulated set point, and the settling behavior of the output voltage. Figure 1 shows a transient response example

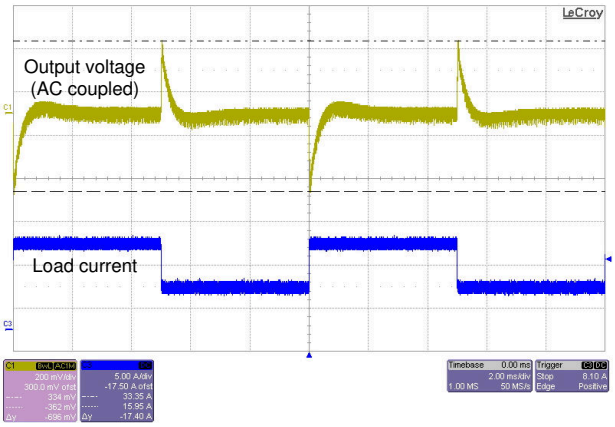

Figure 1-1. Transient Response Example

As shown in Figure 1-1, when a sudden increase in load current occurs, the output voltage droops because the converter control loop is unable to respond to the increased load demand instantaneously. As a result, the output capacitance supplies the extra charge to the load and the output voltage decreases. The control loop eventually responds to this behavior and brings the output voltage back to its regulated set point. A similar behavior is observed when a sharp decrease occurs in load current. As the converter control loop is unable to respond to the decreased load instantaneously, excess charge accumulates on the output capacitance and the output voltage increases. The time it takes for the output voltage to return to its regulated set point is known as the settling time. In addition, returning the output voltage to regulation in a smooth manner with minimal ringing is desirable.

2 Importance of Transient Response

Good transient response is a key component of power design that impacts design choices in a number of ways. Designing the power converter to maintain the output voltage within the required regulation range when subjected to the expected worst case transient load condition is important. Severe output voltage deviation can cause subsequent equipment malfunction or even shutdown.

Transient response is directly correlated to the loop response of a power converter. The bandwidth of the control loop determines how quickly the converter responds to a transient event. Higher bandwidth results in a faster response time. In addition, the settling time behavior is impacted by the control-loop phase margin. Insufficient phase margin results in an underdamped response, and ringing occurs in the output voltage. A minimum of 45° of phase margin is strongly recommended to minimize the possibility of unstable operation because of a transient condition. Bulk output capacitance is also important to limit deviation in the output voltage. More output capacitance can help reduce the output voltage deviation, however, limiting the amount of bulk capacitance required to minimize cost and solution size is desirable.

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3 Direct Frequency Control vs Hybrid Hysteretic Control

The conventional control method for LLC resonant converters is direct frequency control (DFC) where the switching frequency is determined by the voltage loop output directly. Figure 2 shows a simplified block diagram of DFC.

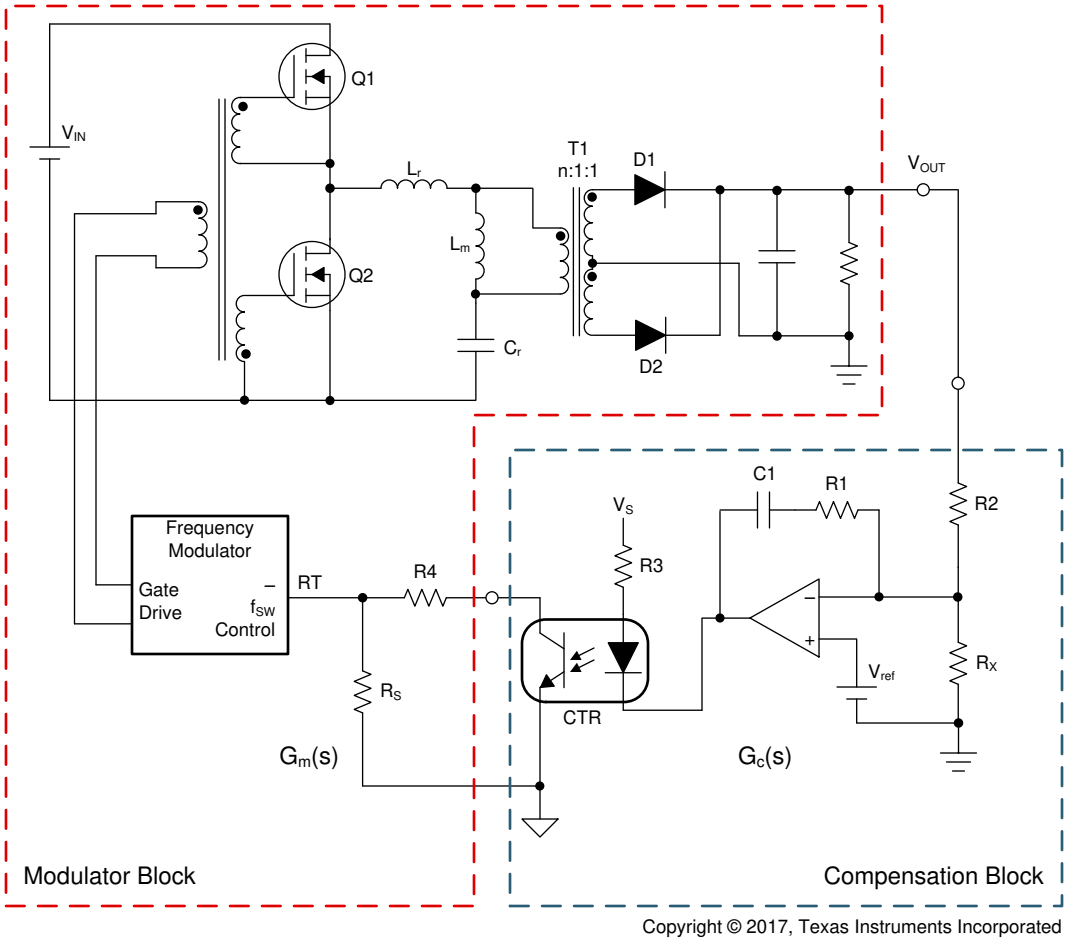

Figure 3-1. DFC Block Diagram

With DFC, feedback from the compensation block is used to determine an appropriate frequency of the gate drive signals. Adjustment of the switching frequency modifies the gain of the modulator block with the goal being to adjust the gain to achieve the desired output voltage. This method has a proven history, but can be difficult to compensate because of complexity of the modulator transfer function and its dependency on the LLC operating point. Optimal compensation can require complex computational modeling and iterative experimentation.

An innovative control method known as hybrid hysteretic control (HHC) is implemented in UCC25640x . HHC uses a combination of frequency control and charge control. Figure 3 shows a simplified block diagram of HHC. The resonant capacitor voltage is sampled through a capacitive divider formed by C1 and C2. This sampled resonant capacitor voltage, V_{CR}, is connected to two current sources that are controlled by the gate drive signals. By sourcing or sinking current at the V_{CR} node, a triangular compensation ramp is added to the sampled resonant capacitor voltage.

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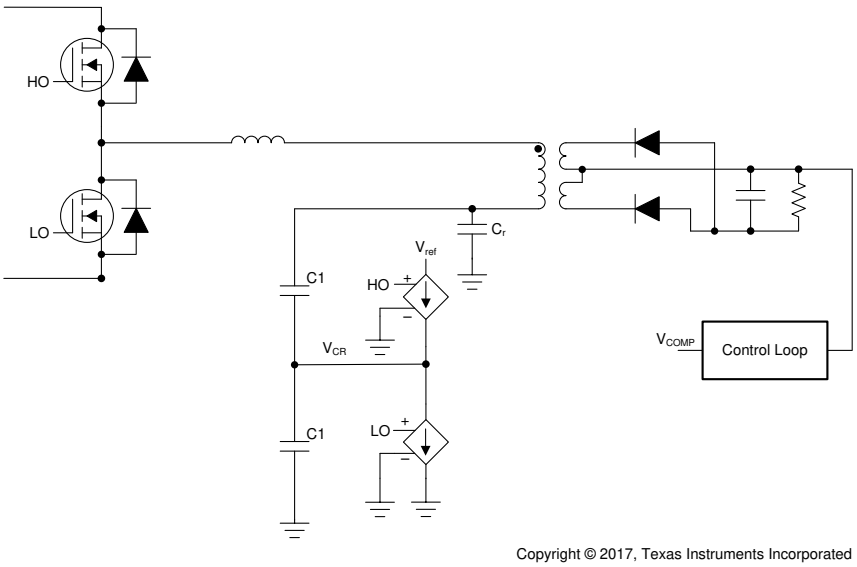

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Figure 3-2. HHC Block Diagram

Switching logic is derived from V_{CR} and loop compensator output, V_{COMP}. The common mode voltage on the V_{CR} pin is V_{CM}. The V_{CM} voltage and the amplitude of the V_{COMP}output are used to generate two logic thresholds, V_{THH} and V_{THL}. Use Equation 1 to calculate V_{THH} and Equation 2 to calculate V_{THL}.

$$V_{THH} = V_{CM} + \frac{V_{COMP}}{2} \quad (1)$$

$$V_{THL} = V_{CM} - \frac{V_{COMP}}{2} \quad (2)$$

The V_{CR} pin voltage is compared to these logic thresholds. When the V_{CR} voltage is greater than the V_{THH} threshold, the high-side switch is turned off. When the V_{CR} voltage is less than the V_{THL} threshold, the low-side switch is turned off. The HO and LO turn-on edges are controlled by the adaptive dead-time circuit.

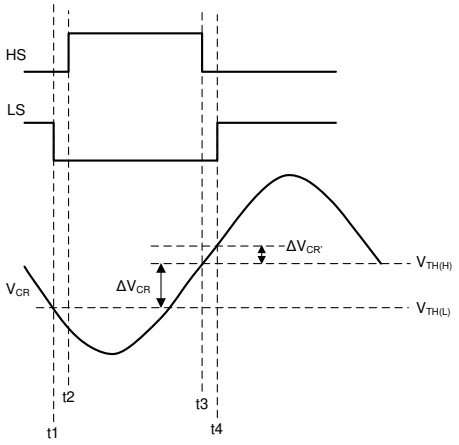

Figure 3-3. HHC Gate Control Principle

Comparing HHC with traditional frequency control, this control method simplifies the power stage into a first-order system, which not only greatly simplifies compensation, but also makes high bandwidth achievable. In addition, the control effort is directly related to input current charged to the resonant tank, it has inherent input feedforward, resulting in excellent input line transient response.

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4 Transient Response Comparison

Figure 5 shows the loop response of a LLC converter using DFC. The bandwidth of this converter is 1.75 kHz with a phase margin of 60°.

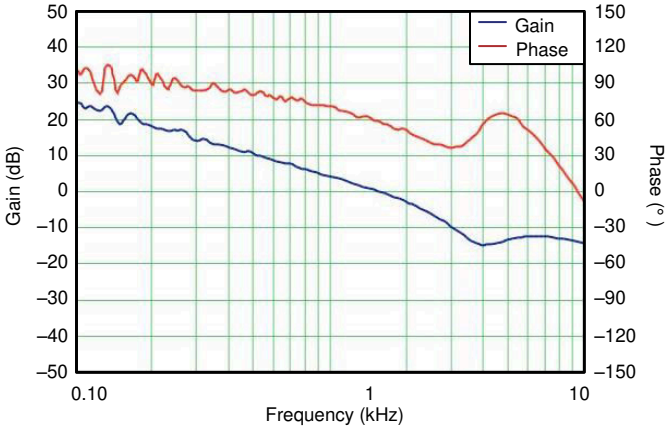

Figure 4-1. DFC Loop Response

While this converter has good phase margin, it has poor bandwidth, indicating the LLC requires a significant amount time to react to a transient event. Figure 6 shows the transient response for this converter where the output current is stepped from no load to full load. As expected, a substantial dip in the output voltage occurs during the transient event. The worst-case output-voltage deviation is more than 20% and requires more than 2 ms for the converter to bring the output voltage back within regulation.

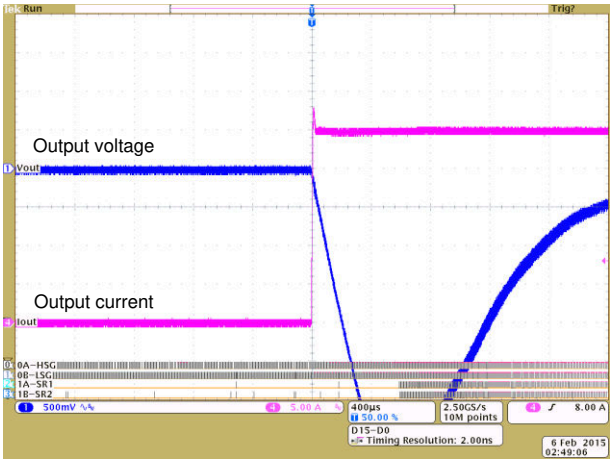

Figure 4-2. DFC Transient Response

For comparison, Figure 7 shows the loop response of an LLC converter using HHC. A bandwidth of 6 kHz and phase margin of 50° is achieved.

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Figure 4-3. HHC Loop Response

The transient response is shown in Figure 8 where the output current is stepped from no load to full load. The greater bandwidth allows the converter to respond significantly faster, limiting the maximum deviation in the output voltage to 1.25%. The output voltage is brought back to regulation within 200 µs.

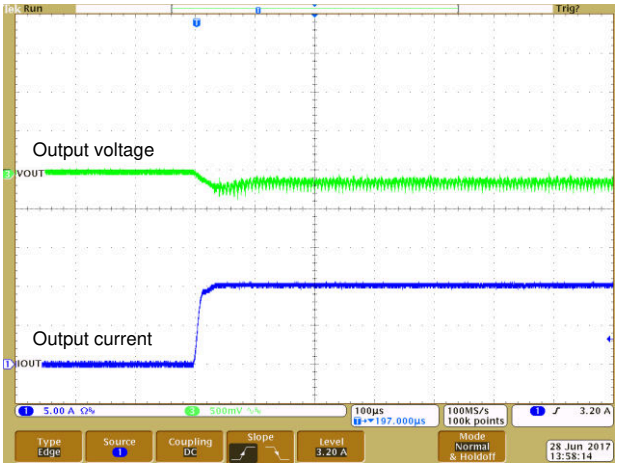

Figure 4-4. HHC Transient Response

The improved transient performance of hybrid hysteretic control enables (HHC) further optimization of LLC design. When the LLC uses HHC, it require less output capacitance to meet a given requirement for output voltage regulation. As such, HHC enables reduction in bill of materials (BOM) count and smaller solution size for applications requiring LLC topology.

5 References

For additional reference, refer to:

- Texas Instruments, *Feedback Loop Design of an LLC Resonant Power Converter* application report
- Texas Instruments, *UCC25640x LLC Resonant Controller with Ultra-Low Audible Noise and Standby Power* data sheet

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6 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision A (October 2019) to Revision B (April 2021)	Page
• Updated the numbering format for tables, figures and cross-references throughout the document	2

Changes from Revision * (August 2017) to Revision A (October 2019)	Page
• Added reference to UCC25640x LLC controller family	3

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