

Boosting LLC Resonant Converter Efficiency by Using UCC24624 Synchronous Rectifier Controller



The LLC converter is a popular topology for PC, server, and TV power supplies, due to its simplicity and high efficiency. The resonant operation achieves soft switching for the entire load range, which makes it a good candidate for high frequency and high power density designs. Besides, LLC converter uses the capacitive filter, eliminating the need of an output filter inductor. The capacitive filter also allows the converter to use lower voltage rating rectifiers and reduce the system cost. Furthermore, the secondary side rectifiers can achieve zero current switching with much less reverse recovery loss. With all the benefits provided by the LLC topology, to further increase its efficiency, the loss on the output rectifiers should be reduced.

Synchronous Rectifier for LLC Resonant Converter

When using the diode rectifiers, as shown in [Figure 1](#) the entire output current flows through the output diodes. For low voltage or high output current applications, there is a significant efficiency loss and thermal stress in these diode rectifiers.

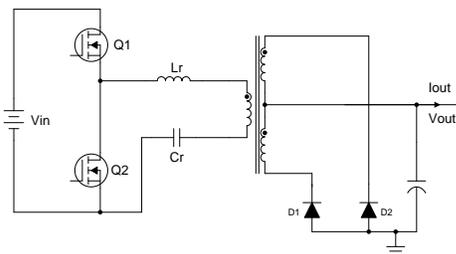


Figure 1. LLC Converter with Diode Rectifier

The loss on each rectifier diode can be estimated based on [Equation 1](#), if the diode is modeled by a fixed forward voltage drop V_F . Using this calculation, for a 12-V, 10-A output design, with 0.5-V forward voltage drop, each diode generates 2.5 W of loss, which translates to about 4% total efficiency loss.

$$P_{Diode} = V_F \times \frac{I_{out}}{2} \tag{1}$$

Using the Synchronous Rectifier (SR) as shown in [Figure 2](#), the voltage drop on the MOSFET could be much lower than a typical diode forward voltage.

For the same design, if the rectifier diodes are replaced with MOSFETs, with proper control, the conduction loss can be calculated using [Equation 2](#), approximating the secondary side current shape as sinusoidal shown in [Figure 3](#). With a 4-mΩ R_{DSon} , each rectifier loss can be reduced to 0.247 W, which translates to total 0.4% efficiency loss.

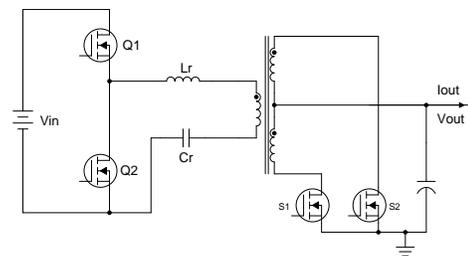


Figure 2. LLC Converter with SR

$$P_{SR} = R_{DSon} \times I_{rms}^2 = R_{DSon} \times \left(\frac{\pi}{4} \times I_{out}\right)^2 \tag{2}$$

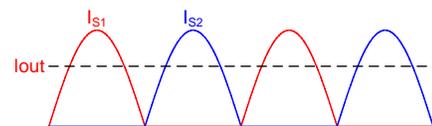


Figure 3. LLC Secondary Side Current

Design Challenges for LLC SR Control

The SRs can be controlled by monitoring its drain-to-source voltage (V_{DS}). Before the SR turns on, the current flows through its body diode. The body diode forward voltage drop can be used to trigger the SR turning on. After the SR is turned on, its on-state resistance becomes a current sensing resistor, the V_{DS} can be used to sense the current to turn off the SR before the current reverses. Even though the control method is quite straightforward, there are several design challenges associated with the LLC resonant converter SR control.

SR Turn off Timing: The biggest challenge of LLC SR control is to turn off the SR at the right timing. Different than the Flyback converters, LLC SRs generally carry much higher current and have higher di/dt. As shown in [Figure 4](#), the sensed voltage V_{SENSE} is used for SR control. It includes the R_{DSon} drop (V_{SR}) and the offset

voltage on the package inductances (L_D , L_S) induced by the di/dt . With high di/dt and package inductances, this offset voltage could be substantial and the SR is often turned off too early, which results in a long body-diode conduction time and large conduction loss.

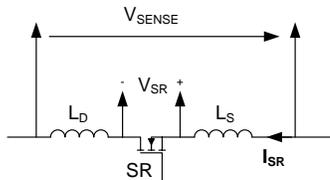


Figure 4. Voltage Sensed by SR Controller

Burst Mode Operation: Another challenge associated with SRs used in LLC converters is the burst mode operation. During the burst mode, both of the primary side switches are turned off. The switch node capacitor resonates with the LLC transformer magnetizing inductor. This low frequency parasitic oscillation can potentially cause the SR to falsely turn on and make the output deliver energy to the primary side, which results in more conduction loss.

Low Standby Power: Even though the SRs save the conduction loss, they add extra loss to the system due to the control circuitry and the gate driver loss. This extra loss is insignificant at a heavier load, due to the large conduction loss savings. However, at no load condition, it is more efficient to disable the SR controller by putting it into a standby mode and use the SR body diode for the rectification.

Reliability Concern: Due to the capacitive filter, if both SRs turn on at the same time, the output is shorted through the transformer and catastrophic failure is expected. It is critical to prevent both SRs from conducting at the same time, even considering the false triggering caused by circuit noises.

UCC24624 Dual SR Controller for LLC Converters

To achieve better LLC resonant converter efficiency, UCC24624 dual SR controller is introduced to work together with LLC controllers such as the UCC25360 series. UCC24624 implements V_{DS} sensing for the SR control, together with various features addressing the LLC SR control challenges, making it an ideal solution for high efficiency LLC designs.

To address the **SR early turn off challenge**, UCC24624 implements proportional gate drive, together with an adjustable +10.5-mV turn-off threshold. The proportional gate drive reduces the SR gate voltage during the current falling edge. The reduced gate drive voltage increases the SR MOSFET $R_{DS(on)}$, resulting in higher voltage drop across the SR. This increased voltage drop overwhelms the offset voltage induced by the package inductance. Together with the positive turn-off threshold, UCC24624 keeps the body diode conduction time to a minimum. To operate better with higher parasitic inductance

packages, such as TO-220, UCC24624 allows the designer to further increase its turn-off threshold by using an external offset resistor from VSS pin to SR MOSFET source pin. This makes the controller less sensitive to the MOSFET package selections.

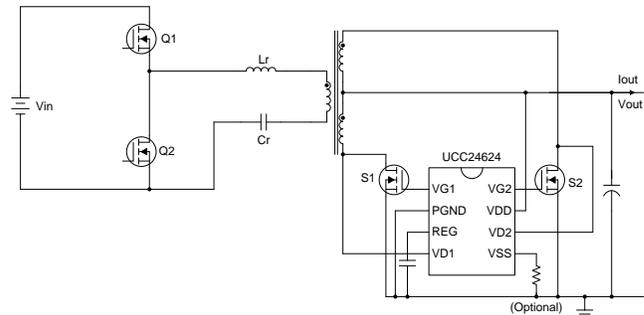


Figure 5. UCC24624 Dual SR Controller for LLC Converter

To improve the **burst mode operation**, besides the traditional off-time blanking, adaptive turn-on delay time is adopted in UCC24624. During normal operation, the turn-on delay is kept short to minimize the body diode conduction time and improve the efficiency. During burst mode operation, the SR operation changes from complimentary fashion to no switching. UCC24624 uses this as the indicator to detect the LLC has entered burst mode operation. It increases its turn-on delay time to help reject the parasitic oscillation. The turn-on delay is also increased at light load conditions to provide extra noise rejection. This adaptive turn-on delay time helps to maintain noise rejection without sacrificing efficiency performance.

UCC24624 also has a built-in **automatic standby mode** detection circuit, without using external components. For the LLC converters at the no load, the converter operates in burst mode to regulate the output voltage. The LLC SR conduction time in each switching cycle could still be long, while the average switching frequency of the converter is quite low. UCC24624 detects the light load condition based on the converter average switching frequency. It allows the controller to enter standby mode at no load and helps to achieve low standby power.

To **enhance the reliability**, and prevent both SRs turning on at the same time, interlock logic is applied to both channels of the SR controls. During one channel SR conduction time, the other channel SR conduction is prohibited. This added logic provides more robust operation despite system noises.

Summary

With all the built-in intelligence, together with TI UCC25630 series LLC controllers, UCC24624 provides a high efficiency, cost effective solution for SR control in LLC converter designs.

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