Application Brief

LLC-Resonant Controller in Battery Charging Applications: Achieving High Efficiency Across a Wide Output Voltage Range

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Recent advancements in charging technology – including power tool, vehicle on-board, and industrial chargers – are yielding increasingly compact designs with high power density and consistent efficiency across all load levels. These designs are also engineered for robust performance in demanding environments, withstanding wide temperature fluctuations and extended operational use.

The half-bridge LLC topology serves as a practical fit for charging designs in the <1.3kW power range. Beyond this power level, designers typically shift to full-bridge LLC and phase-shifted full-bridge (PSFB) topology to minimize conduction losses and increase efficiency. The UCC25661x is TI's latest LLC controller that provides better regulation and integrated protection compared to previous generations and traditional PWM controllers.

The UCC25661x is TI’s latest discrete LLC controller packed with features like the controller’s ability to resonate up to 750kHz, which enables the small form factor and high-power density. The implementation of two burst modes at low load enables high standby efficiency while eliminating audible noise. The input power proportional control (IPPC) mechanism makes a significant difference in the device when used in charging applications. Unlike traditional control mechanisms like charge control or hybrid hysteresis control, IPPC enables a better wide input voltage (Vin) and wide output voltage (Vout) operation in an LLC converter design. This wide Vin/Vout is enabled because, in simple terms, the controller looks at the input power rather than the input current or frequency during regulation. These benefits are further elaborated below.

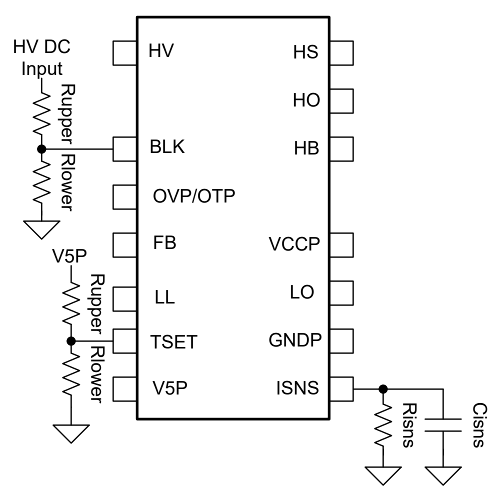


Figure 1. IPPC Pin Specific Connections

IPPC-aided features in UCC25661x make the device practical for battery charging applications. The following pins are associated with IPPC:

1. FB pin: FBReplica is dependent on the current sourced in the FB pin, enabling wide Vout.
2. ISNS pin: This pin is used to provide cycle-by-cycle OCP protection to the circuit, attached directly to the resonant tank. The pin generates an internal resonant capacitor voltage using a voltage coefficient of resistance (VCR) synthesizer.

3. BLK pin: This pin is used to determine the gain of the controller. The pin additionally functions as brown-in/brownout (BI/BO) threshold settings and is used to turn the controller on and off.
4. TSET pin: This pin is used to set the minimum frequency operation of the controller and set the integrator time constant for the controller. Different TSET options set different minimum frequencies.

Table 1. Advantages of IPPC in a Battery Charging Application

Feature	System benefit	System impact
Internal VCR synthesizer	The VCR signal is synthesized internally by adding a compensation ramp with feed-forward gain to the signal sensed from the ISNS pin. The external VCR timing capacitors are eliminated here.	BoM reduction in a system-level design by reduction of two VCR capacitors
Wide input voltage capability	Since the feedback signal here is proportional to the output power, the FB signal has less variation with varying Vin and Fsw.	High efficiency across an input voltage range while maintaining low ripple
No hard switching	The V_{TL} and V_{TH} FET turn-off times (adaptive dead time) are determined by the previous cycle output on the FB pin, allowing hard switching to be prevented.	High efficiency across load range with good thermals
Minimal variation in OLP trigger point	The OLP trigger point is maintained nearly constant with changes in output voltage while maintaining a constant power level	Enhanced protection, prevents sharp increases of power
Prevents unwanted burst mode operation	Even when the battery voltage is low, the controller does not enter faulty burst mode due to IPPC. IPPC removes the impact of switching frequency on the control voltage, so the battery voltage does not determine the operating frequency of the controller or vice versa.	Shorter battery charging time and improved efficiency
Pre-biased start-up	No external circuitry is required to protect the controller or the battery when the battery already has a load at start-up. Typically, when there is some load already present during start-up, ACDC PSUs go into hard switching and losses are high. UCC25661x prevents this mode switch and loss.	No hard switching and minimized losses

Typically, battery charging customers implement a constant-current constant-voltage (CC-CV) loop with feedback in a closed loop DC-DC topology. This implementation delivers high efficiency, safety, and cell balancing for multiple combination of cells (for instance, 6S and 12S battery packs). The system operates in either CC mode or CV mode depending on the battery load resistance.

1. CC mode: In the CC mode of operation, the battery voltage gradually increases from a lower value to the desired maximum voltage value. The battery charging current value is constant.
2. CV mode: In the CV mode of operation, the battery voltage is constant in the desired value, whereas the current drops drastically to near zero values. Thus, the charging power also reduces to lower values.
3. Trickle charge: To prevent the battery from draining itself, the system gives approximately 0A of current in small burst charge packets. This phenomenon occurs when the system detects a small decrease in load resistance.

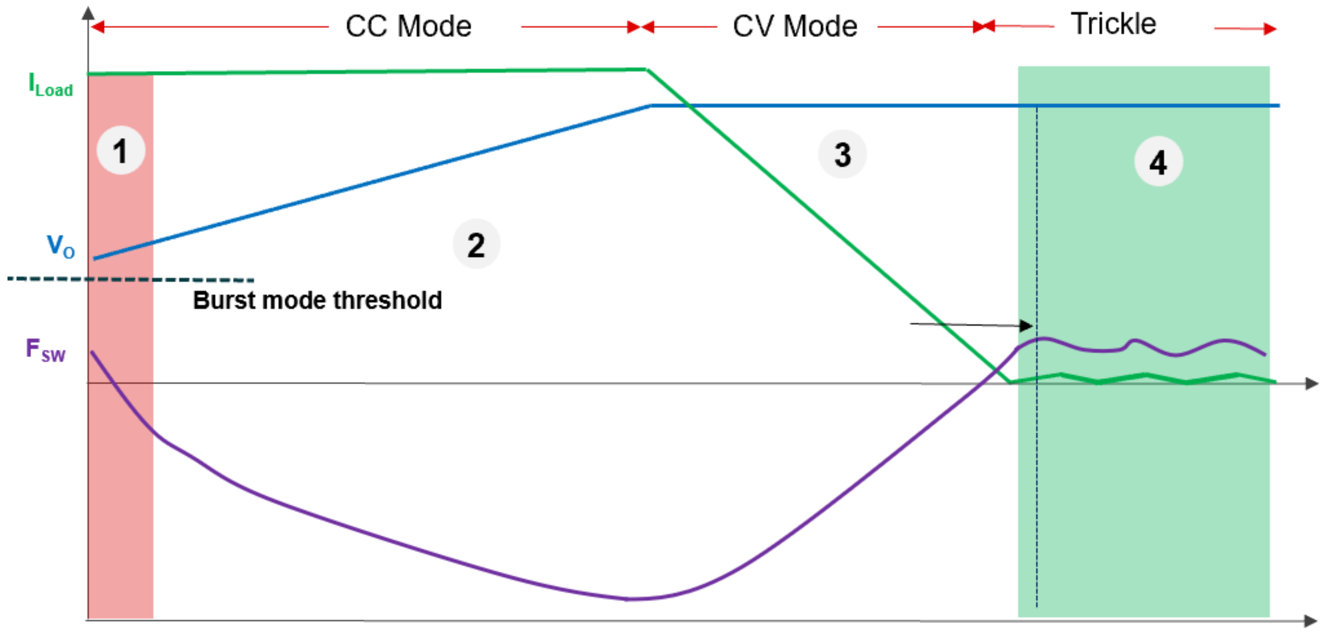
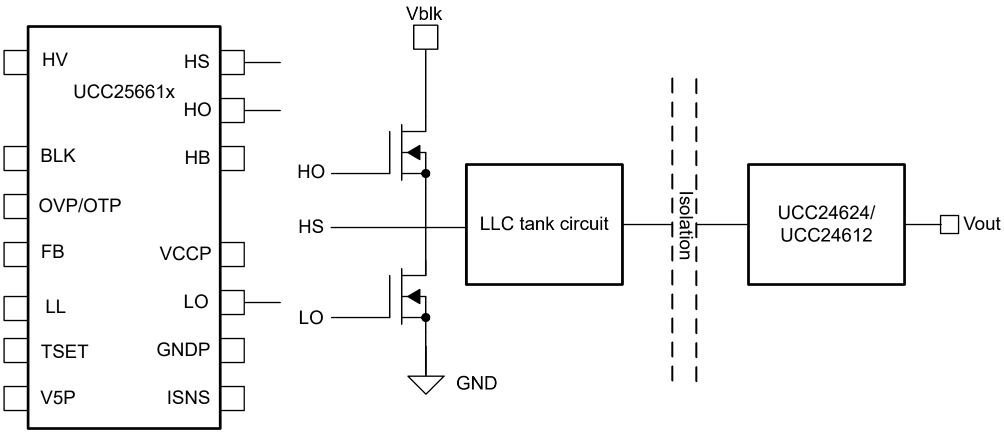


Figure 2. Different Regions of Operation in a CC-CV Loop Setting

Figure 2 shows the variation of V_O, load current, and switching frequency during different modes of operation:

1. Region 1: The battery voltage is very low. Traditional LLC controls operate in burst mode, but IPPC prevents the controller from entering unwanted burst mode operation. The switching frequency is also high during this region.
2. Region 2: Peak current is delivered until the battery voltage reaches the desired value. Power produced is also high and switching frequency gradually reduces in the constant current mode . If the battery voltage here is very low, for example, when just exiting Region 1, then traditional LLC controller-based designs can still operate in burst mode, introducing huge ripple in the battery charging current and unwanted audible noise.
3. Region 3: The current gradually reduces to near zero values during this period. Power delivered also gradually reduces, hence switching frequency increases during the constant voltage mode.
4. Region 4: Trickle charge is present to keep the battery in fully charged mode. The controller produces small burst of charge to avoid the discharge of battery.



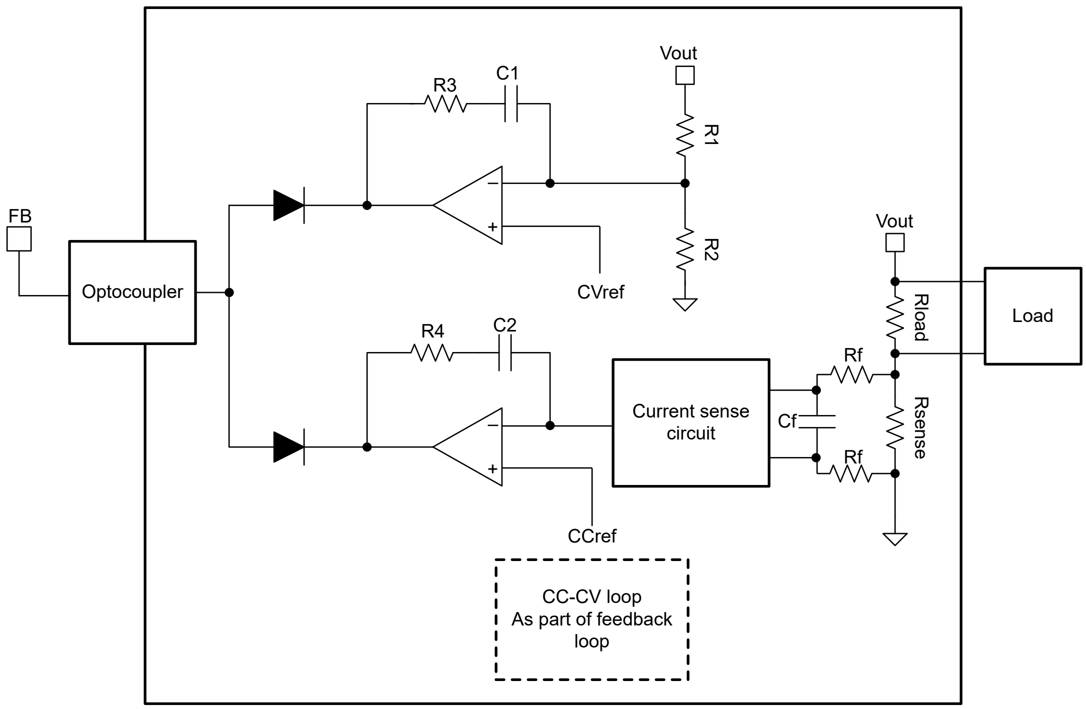


Figure 3. Implementation of Typical CC-CV Loop with UCC25661x

The block diagram in Figure 3 represents how the UCC25661x is designed in a CC-CV reference loop. Two references, CCref and CVref, are set from the 5V input through a resistor divider according to Equation 1 and Equation 2, where H = current amplifier gain:

$$CC_{ref} = \left(\frac{V_{out}}{R_{load}}\right) \times R_{sense} \times H \quad (1)$$

$$CV_{ref} = \left(\frac{R2}{R1 + R2}\right) \times V_{out} \quad (2)$$

This reference point determines whether the battery chargers operates in current control or voltage control. Since, in case of battery chargers, the output voltage increases with increase in output resistance, we need to make sure that the voltage gains are met. Hence, we take a range of Vout (maximum, minimum, typical) and try to fit the LLC gain with the Mg curves. Since UCC25661x has a wide Vout, we can provide a good margin in the gain curves with the variation in Vout. You can check out the UCC25661x design calculator by inserting the Vout values, tank parameters and see the gain curves for these values.

In conclusion, the UCC25661x from Texas Instruments delivers a significant advancement in battery charging technology, offering a uniquely optimized and streamlined design for demanding applications. This controller fundamentally simplifies the design and implementation of CC-CV charging loops, using the IPPC mechanism and wide input/output voltage operating range. Unlike traditional LLC resonant controllers which often require complex tuning and optimization, the UCC25661x inherently maximizes power transfer efficiency and maintains tight voltage regulation across a broad spectrum of input voltages and load conditions. For detailed design guidelines and application-specific recommendations, please refer to the UCC25661x datasheet and associated application notes available on the Texas Instruments website.

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