*Technical White Paper*

# *High Efficiency by Leveraging GaN FET in an LLC Resonant Converter Design*

TEXAS INSTRUMENTS

*John Cummings, Anders Svensson, Roberto Scibilia*

**ABSTRACT**

This technical white paper provides insight on a 5S battery charger application using TIs new LLC resonant controller and GaN FETs.

## Table of Contents



## List of Figures

## List of Tables



## Trademarks

All trademarks are the property of their respective owners.

## 1 Introduction

Power supply designed for outdoor use need to excel in their thermal performance to give headroom enough to handle high environment temperatures. Outdoor power supplies operate often in higher temperatures than normal indoor 25°C. One way to design for high thermal performance is to aim for the highest possible efficiency. Small size is an important factor to minimize the environmental foot print in package size and weight. It is also a selling factor that appeals the customers. TIs new GaN FETs is a new technology that help designers to reach higher efficiency in their AC/DC converter designs.

LLC resonant controllers have become more and more popular in power electronics because this topology can meet the demanding performance requirements that modern power supply designs have. LLC resonant controllers reduce switching loss through zero-voltage switching (ZVS)

LLC controller traditionally are optimized to run at approximately 100kHz with the limitation being able to detect the switch node slew rate. TI's recent series of LLC controllers the UCC2566x family breaks the speed barrier and allows resonant operation up to 750kHz allowing applications to utilize GaN FETs fast switching capacity and support ha larger output voltage range.

LLC resonant controllers used in charging applications is extra challenging due to the required dynamic output voltage range. The broad output voltage regulation impacts the switching frequency of the LLC stage.

## 2 Benefits of GaN In LLC Resonant Converter

In LLC resonant converter, the thermal benefits of GaN (Gallium Nitride) FETs compared to MOSFETs are significant, especially in high-power applications. Below we breakdown and explain the advantages of GaN FETs in terms of thermal performance / high efficiency.

### 2.1 Higher Efficiency

For a given breakdown voltage and die size GaN FETs has lower conduction losses due to their significant lower $R_{DS(on)}$ compared to silicon MOSFETs. This is due to superior material properties in GaN. This leads to less power dissipation when current is flowing through the device, reducing overall heat generation. This is especially noticeable at high switching frequencies, which are typical in LLC resonant converters.

MOSFETs are also efficient but suffer from higher conduction losses as their $R_{DS(on)}$ increase faster with temperature and voltage.

### 2.2 Faster Switching Speeds

GaN FETs can switch much faster than MOSFETs, which leads to shorter transition times during switching (both turn-on and turn-off). This results in lower switching losses, further reducing the amount of heat generated in the converter.

In contrast, MOSFETs are slower and generate more heat during transitions due to longer switching times, especially at high frequencies.

### 2.3 Reduced Parasitic Capacitances

GaN FETs typically have lower parasitic capacitances, meaning there is less energy loss associated with charging and discharging these capacitances during switching transitions. This reduces the overall thermal load (higher efficiency) on the power converter.

MOSFETs have higher parasitic capacitances, which leads to higher switching losses and thus more heat.

The LLC resonant controllers enable us to achieve Zero-Voltage Switching and the principle of ZVS is to turn on the switching element when the drain-to-source voltage ($V_{DS}$) is zero. With this knowledge we can assume that during transition in the LLC power stage ($V_{DS}$ = 0V) the parasitic capacitance $C_{GS}$ and $C_{GD}$ can be considered as zero. Then, the total input capacitance $C_{ISS}$ ($C_{GS}$ + $C_{GD}$) is considered as zero.

→The parasitic capacitance impacting the switch performance in a topology using ZVS is then total output capacitance $C_{OSS}$.

$$C_{OSS} = C_{DS} + C_{GD} \tag{1}$$

$$(V_{DS} = 0V \rightarrow C_{GD} = 0)\ C_{OSS} = C_{DS} \tag{2}$$

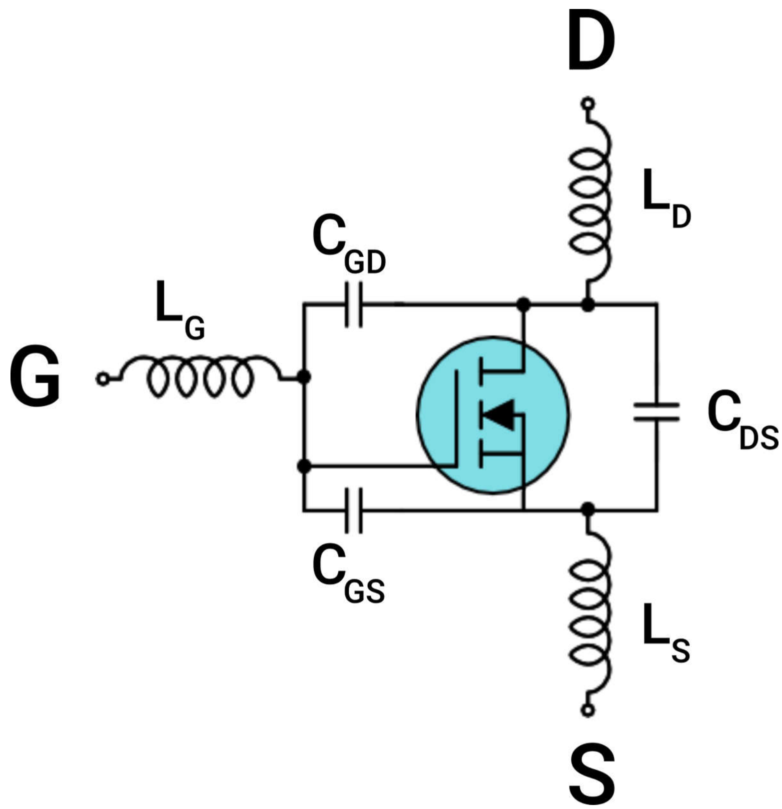


**Figure 2-1. GaN FET Parasitic Model**

In ZVS topologies running with high frequency switching, it is crucial to use a switching element that have low and stable $C_{OSS}$ values to achieve high efficiency. In Figure 2-2 and Figure 2-3, the examples show how $C_{OSS}$ varies with $V_{DS}$ during switching transitions and the differences in $C_{OSS}$ value on a typical 650V MOSFET and GaN FET.

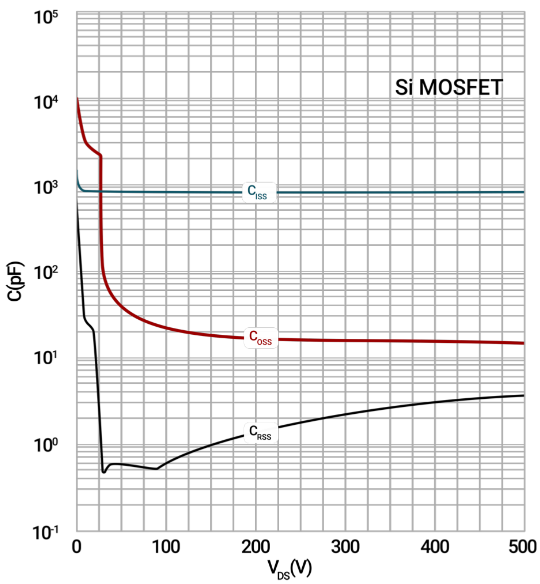


**Figure 2-2. 650V MOSFET 230mΩ (typ)**

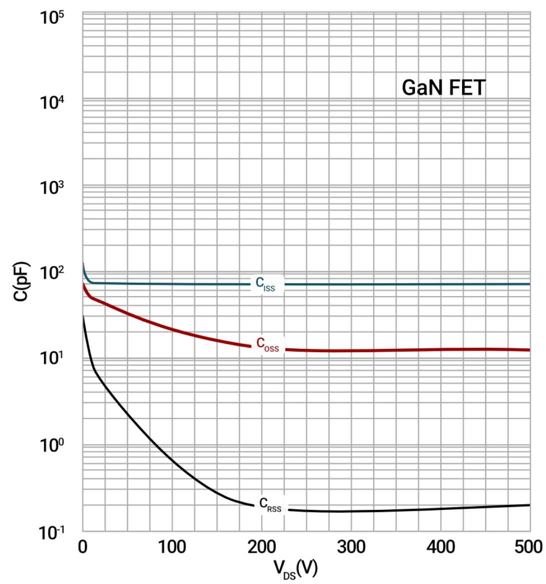


**Figure 2-3. 650V GaN FET 270mΩ (typ)**

### 2.4 Improved Power Density

GaN FETs allow for smaller, more compact designs with higher power density. Because of the improved efficiency and better thermal performance, converters using GaN can operate at higher power levels while maintaining manageable thermal conditions.

MOSFET-based converters need to be larger or require more complex cooling systems to handle the same power levels due to the higher heat dissipation.

### 2.5 High Thermal Conductivity

GaN materials (Gallium Nitride) have a higher thermal conductivity than silicon (used in MOSFETs), which allows them to dissipate heat more efficiently. This helps keep the operating temperature lower and potentially reduces the need for cooling solutions.

In contrast, MOSFETs have lower thermal conductivity, which means heat dissipation is less efficient and lead to worse thermal performance.

### 2.6 Lower Junction Temperatures

Due to better efficiency and lower losses, the junction temperature ($T_j$) of GaN FETs is generally lower than that of MOSFETs in similar applications. This can significantly extend the lifespan of the components and improve reliability, especially in thermally constrained environments like outdoor equipment.

## 3 LLC Resonant Converter

An LLC resonant converter is a frequency-controlled topology (see Figure 3-1). The output voltage is regulated by varying the switching frequency of the inverter stage. The converter uses a resonant tank (series inductor ($L_R$) resonant capacitor ($C_R$) and a magnetizing inductance ($L_M$) ) that filters the switching waveform and transfer energy to the output.

In this section, a 5S battery charger that support wide Output Voltage ($V_{OUT}$) = 15,0 – 28,0V is used to explain how the switching frequency changes with $V_{OUT}$ and why GaN FETs are a good alternative to use in this application to reach high efficiency.

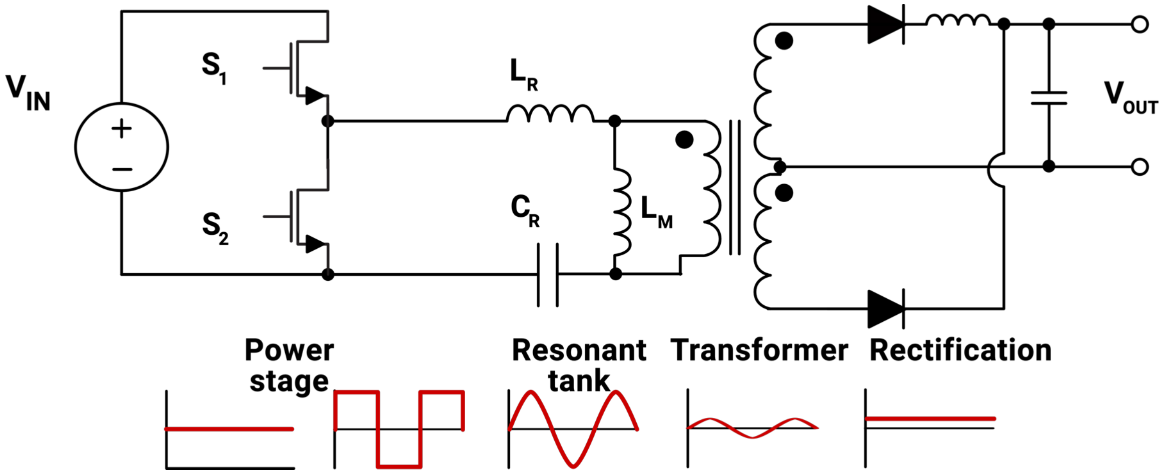


**Figure 3-1. LLC Converter Circuit**

## 3.1 The Relationship Between Output Voltage (VOUT) and Switching Frequency ($f_S$) in an LLC Resonant Controller

- To maintain resonance, the LLC topology has a 50% duty cycle, which leaves frequency modulation (FM) as the only tool to regulate output voltage.
- The voltage gain of the Resonant Tank depends on the switching frequency.
- The controller adjusts the switching frequency ($f_S$) to maintain required output voltage despite load or input variations.

**Nominal** Output Voltage ($V_O$) →The resonant tank operates at its resonant frequency ($f_R$)

$$f_R = \frac{1}{2\pi\sqrt{L_R \times C_R}} \tag{3}$$

At resonance ($f_S$ = $f_R$) → voltage gain is close to 1, ZVS is maintained, highest efficiency point

**Higher** Output Voltage ($V_{OUT}$) → Decrease Switching Frequency ($f_S$)

To boost the output voltage, the controller decreases switching frequency (operate closer to or just below resonant frequency ($f_R$)) to increase voltage gain of the resonant tank. More power is transferred to the output, raising the voltage.

Below resonance ($f_S < f_R$) → voltage gain > 1, useful for boost mode.

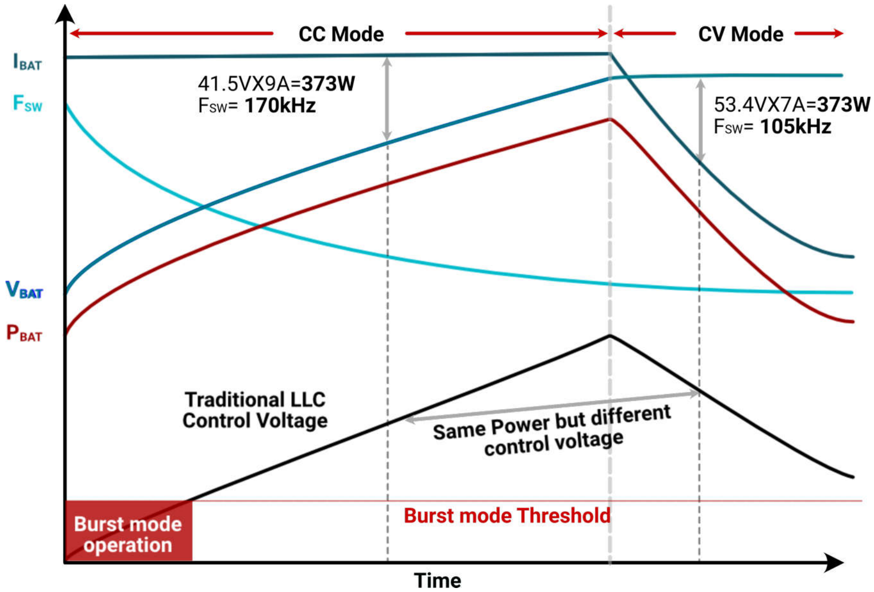


**Figure 3-2. Battery Charging CC-CV Profile for Traditional LLC**

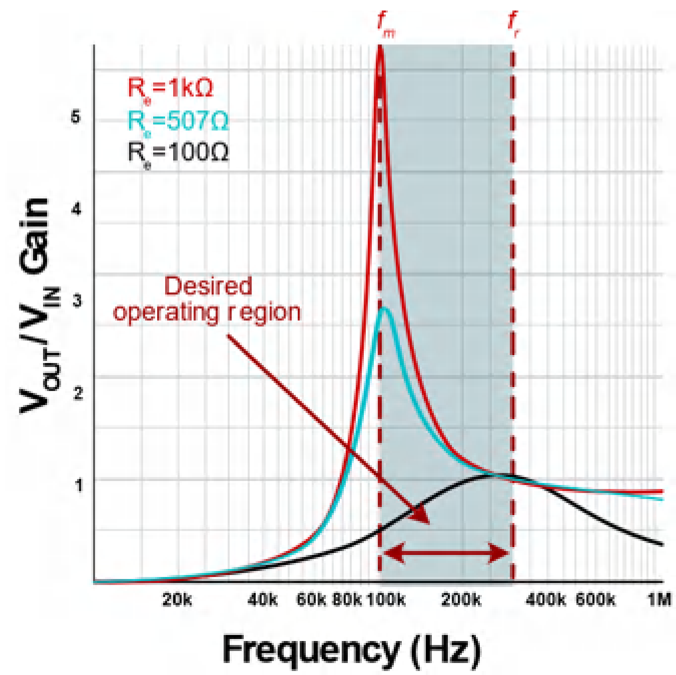


**Figure 3-3. LLC Resonant Operating Frequency Range**

**Lower** Output Voltage ($V_{OUT}$) → Increase Switching Frequency($f_S$)

To reduce output voltage, the controller increases switching frequency to lower voltage gain of the resonant tank. Less power is transferred, lowering the output voltage.

Above resonance ($f_S > f_R$) → voltage gain < 1, converter regulates lower output voltages. but ZVS may be lost (can happen if the magnetizing current is not sufficient)

**Table 3-1. Switching Frequency vs Output Voltage**

| Output Voltage Change | Switching Frequency Change | Reason |
|---|---|---|
| Output ↓ | Frequency ↑ | Increase gain |
| Output ↑ | Frequency ↓ | Decrease gain |

### 3.1.1 The LLC Charging Challenge

To support the wide output voltage required for battery charging, the LLC resonant tank and burst mode threshold must be tuned perfectly as a low battery voltage charging in the constant current phase could go in and out of burst mode which could potentially damage the cells.

One way the LLC has been used to support the wider output voltage requirements of a battery was to use it in the LCC configuration. The LCC is a modification to the resonant tank which has two capacitive elements and one inductive element.

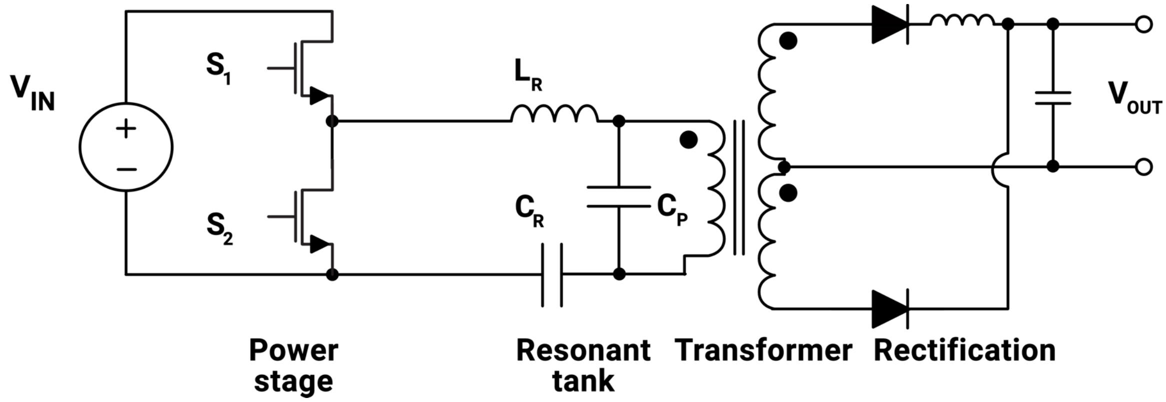


**Figure 3-4. LCC Converter Circuit**

The LCC is setup to operate at a minimum resonant frequency and has a much wider range of operation.

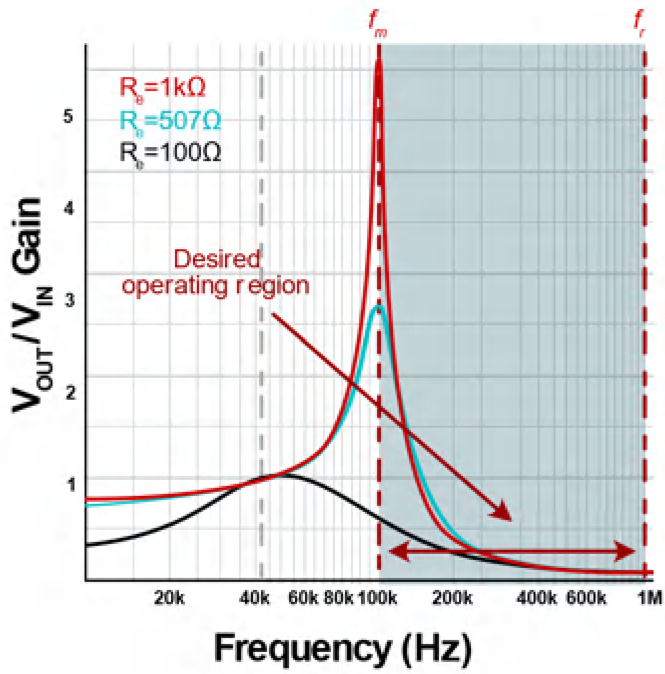


**Figure 3-5. LCC Resonant Operating Frequency Range**

By supporting a wider range, the LCC approach is much more suitable to battery charging and LED lighting applications where the output voltage can vary. The downside of the LCC approach is that it is less efficient as the input RMS currents are higher than the LLC at the same power level.

Table 3-2 shows a quick comparison of the primary current and switching frequency.

**Table 3-2. LLC vs LCC Primary Current and Switching Frequency Comparison**

| $V_{OUT}$ | $I_{OUT}$ | $LLCI_{PRI\ (ARMS)}$ | $LCCI_{PRI\ (ARMS)}$ | $LLC_{fSW}$ (kHz) | $LCC_{fSW}$ (kHz) |
|---|---|---|---|---|---|
| 200 | 1 | 1.73 | 2.69 | 131 | 122 |
| 100 | 1 | 0.775 | 1.65 | 196 | 130 |

Looking at the switching frequencies, the LCC barely moves when VOUT changes from 100 to 200V. Whereas the LLC sees almost a 33% reduction in switching frequency. The real impact if the LCC topology is the higher input currents.

So the LLC topology is more desirable from an overall efficiency perspective but the potential to enter burst mode when the battery voltage is low was a difficult design hurdle. Until now.

### *3.1.2 A Wide $V_{IN}$/$V_{OUT}$ Capable LLC*

To simplify designs for wide input/output voltage applications, IPPC or Input Power Proportional control was introduced at the end of 2023. The real power of IPPC is that it removes the switching frequency from the feedback loop which means for the same power level, you have the same control point.

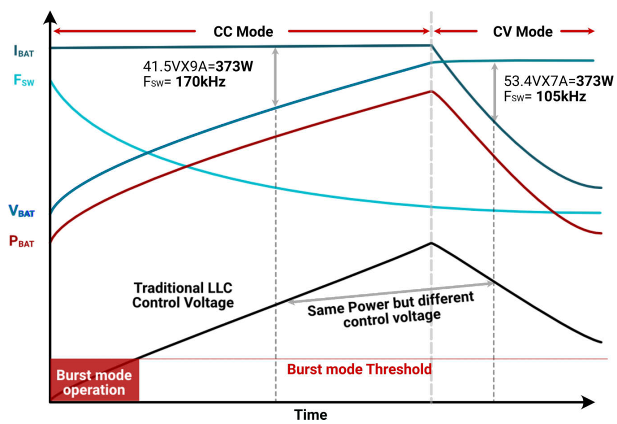


**Figure 3-6. No IPPC**

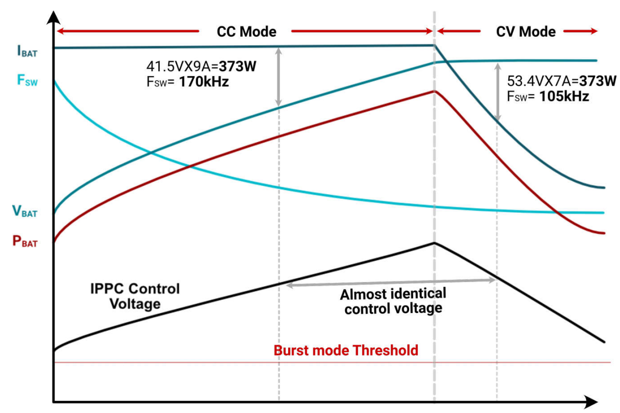


**Figure 3-7. With IPPC**

Here you can see with and without IPPC, when in the constant current (CC) phase the switching frequency is 170kHz when the charging power is 373W, but in the constant voltage (CV) phase the switching frequency is 105kHz. What is different is that without IPPC the switching control feedback control voltage is a function of both input power and the switching frequency.

$$FB = f_n(P_{IN}, f_{SW}) \tag{4}$$

IPPC removes the impact of the switching frequency leaving it as only a function of input power or

$$FB = f_n(P_{IN}) \tag{5}$$

# 4 Practical Application of LLC Converters for a Battery Charger Leveraging GaN Switches

## 4.1 Requirements and Scope

- Charge current, 1A – 8A
- Wide $V_{OUT}$ regulation, 14V – 28V
- Max component temperature < 60°C @ 25°C ambient
- No ventilation, no heat sink
- Low standby power
  - Target to fulfill CoC Tier 2 standard (200W rating)

**Table 4-1. COC Tier 2 Single-Voltage External AC-DC Power Supply, Basic Voltage**

| Nameplate Output Power ($P_{OUT}$) | Minimum Average Efficiency in Active Mode (expressed as a decimal) | 10% Load Average Efficiency in Active Mode (expressed as a decimal) | Maximum Power in No-Load Mode (W) |
|---|---|---|---|
| 0.3W≤$P_{OUT}$ ≤ 1W | ≥ 0.50×$P_{OUT}$ + 0.169 | ≥0.50×$P_{OUT}$ + 0.160 | ≤0.075 |
| 1W≤$P_{OUT}$ ≤49W | ≥ 0.071×in($P_{OUT}$)" 0.00115x$P_{OUT}$ + 0.670 | ≥ 0.071×in($P_{OUT}$)" 0.00115x$P_{OUT}$ + 0.570 | ≤0.075 |
| 49W≤$P_{OUT}$ ≤250W | ≥0.890 | ≥0.790 | ≤0.150 |
| $P_{OUT}$ > 250W | N/A | N/A | N/A |

## 4.2 Charging Curve for Lithium-Ion Battery

Lithium-ion batteries are charged using a specific algorithm to ensure safety, efficiency and longevity. The most common mode is called Constant Current /Constant Voltage (CC/CV) charging. This design incorporates the CC/CV algorithm.

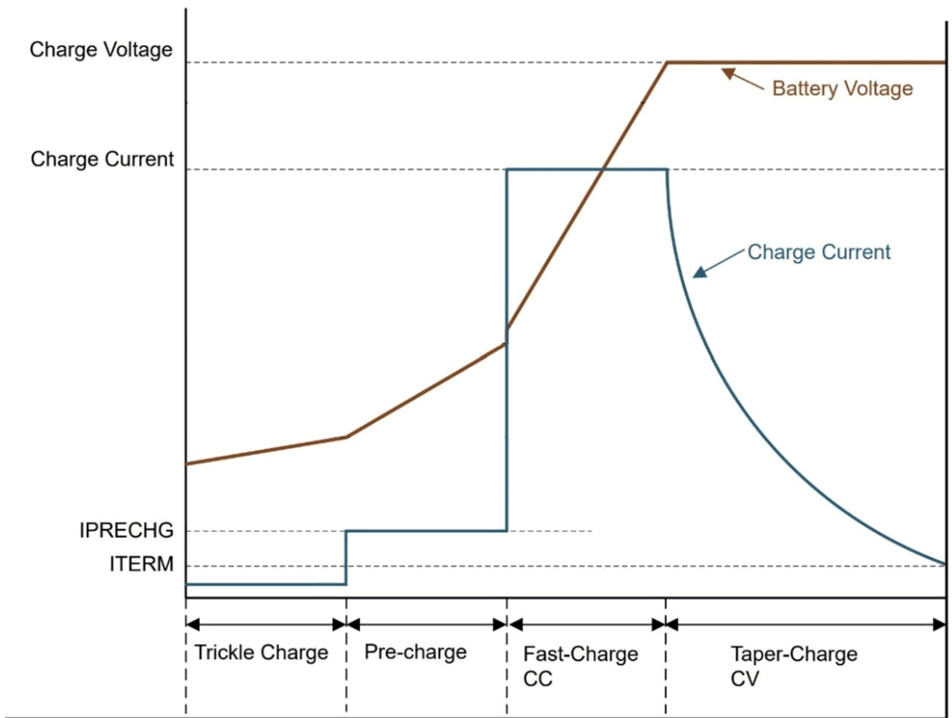


**Figure 4-1. Typical Li-Ion Battery Charging Profile**

- Trickle charge: Very low constant current phase, only used with deeply discharger battery (typically below 2.5-2.9V per cell). This phase secure the battery cells not are damaged.
- Pre-charge: Low constant current phase brings the battery up to a safe level (current often 1/10th of normal $I_{CHARGE}$).
- Constant Current (CC): This is high current phase that rapidly deliver the bulk of the energy to the battery.
- Constant Voltage (CV): Voltage is held constant when maximum battery voltage is reached (typically 4.2V per cell). When the battery is fully charger the internal resistance increases and lower $I_{CHARGE}$ to a defined termination level ($I_{TERM}$ , often around 2-5% of CC).

## 4.3 How to Support Wide $V_{OUT}$ Range in an LLC Design for Battery Chargers

The first point is to achieve ZVS in the whole Vin / Vout / Iout range, then regulate $V_{OUT}$ in a wide range, suitable for battery chargers.

The challenge is that the magnetizing current changes a lot versus switching frequency, output voltage and input voltage; all these three parameters are connected between each other through the gain – frequency relationship as shown below. Here we highlighted two main areas where the converter works far away from resonance. As explained at the beginning, at $f_S > f_R$ the gain of the LLC tends to zero only if enough load current is present, typically in overload condition or close to short. For all other conditions (light or mid load) the gain is slightly less than 1. For battery charger it's more challenging because the battery voltage level is requiring gain variation to achieve values well below 1. In this regard the controller, with a combination of low and high-frequency burst mode, is adapting the equivalent gain to be way lower than 1, without any particular penalty and achieving high efficiency without the need to shift the switching frequency to very high values. The main disadvantage of shifting $F_{sw}$ to the range of MHz is that all of the parasitic components (which are difficult to manage in production) have more and more impact on the functionality and efficiency to the power stage.

On the other side, the second area where $f_S < f_R$ add the challenge to have enough gain to allow the LLC converter covering low $V_{IN}$ and high $V_{OUT}$. High gain of the power stage can be obtained by designing properly the transformer with appropriate value of Ln (Lm / Lr) because this defines the maximum attainable gain. If the integrated leakage inductance of the transformer is not sufficient to get the right Ln value, then it is possible to add an extra inductor.

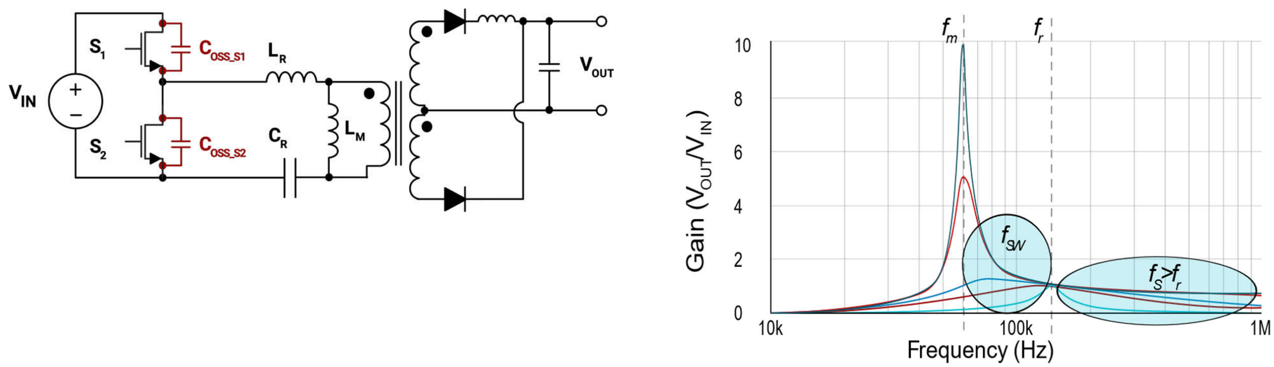


**Figure 4-2. LLC Gain In and Out of Resonance**

$$L \times I_L^2 > C_{TOTAL} \times V_{SW}^2 = 2C_{OSS} \times V_{SW}^2 \quad (6)$$

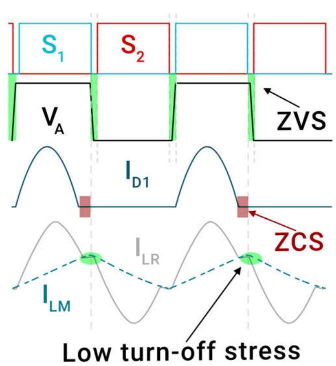


**Figure 4-3. Low Turn-Off Stress**

- Necessary and sufficient soft-switching conditions:
  – Inductive input impedance
  – Sufficient energy inside resonant tank for discharging or charging output capacitor of switches in switching network
  – Enough dead-time between switches inside switch network

By leveraging TI GaN, we can achieve:

**Optimizing internal GaN architecture by integrating drivers:**

- Improves reliability by reducing overshoot and ringing on drain-source voltage

**Taking advantage of low Input and Output Capacitance:**

- Reduces switching losses in hard-switched converters
- Allows faster switching frequency in hard-switched and soft-switched converters
- Reduces circulating currents in soft-switched converters

**Zero Reverse Recovery Charge:**

- No reverse-recovery losses in hard-switched, half-bridge converters
- Enables new bridge-oriented topologies

**Greatly-reduced switching loss:**

- Lower gate-drain capacitance ($C_{OSS}$) reduces transition period
- Allows faster switching speeds
- Reduced or eliminated heat sinking

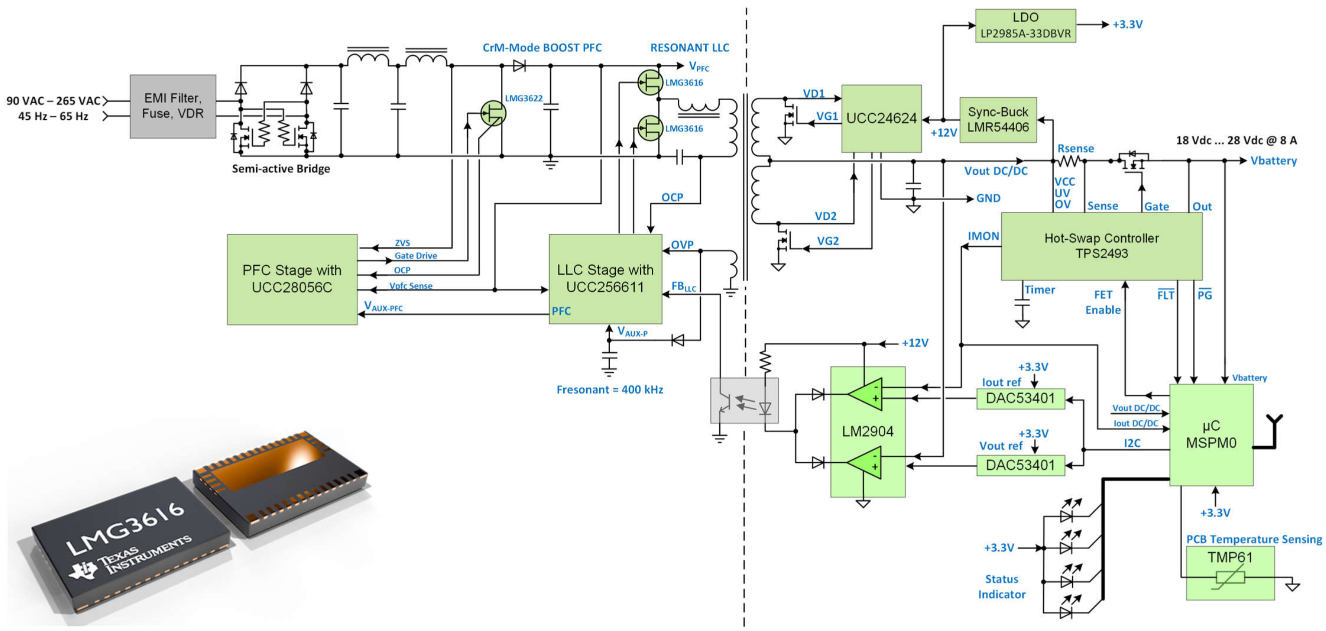


**Figure 4-4. Block Diagram of the Complete Solution**

The power conversion architecture employs a multi-stage approach, engineered for high efficiency and compact form factors.

The two-stage EMI filter is composed of two stages, employing two common mode chokes and two x-capacitors. This is followed by a self-driven semi-active bridge rectifier, which almost eliminate the conduction losses on the two low side diodes of the bridge, but the high side diodes remain standard diodes. This method reduces the total loss in the bridge, and allows the use of only SMD components, avoiding expensive and bulky heat sinks.

The main PFC Boost stage, driven by UCC28056 controller is leveraging GaN to achieve enhanced efficiency by keeping high switching frequency and facilitating the use of a small inductor.

The second conversion stage is the LLC resonant converter, driven by the latest controller UCC256611.

A synchronous rectifier section is added to improve efficiency and keep losses and dissipation under control.

The system control and communication are handled by a MSPM0 microcontroller, sending $V_{OUT}$ and $I_{OUT}$ reference set points by means of I2C communication to two DACs.

Finally, an extra hot-swap function has been added to limit the worst case load current and managing load connections dynamically. This feature is crucial for robust operation in scenarios involving real battery connections or when a battery management system (BMS) oversees charging and discharging parameters.

## 4.4 The Prototype Hardware

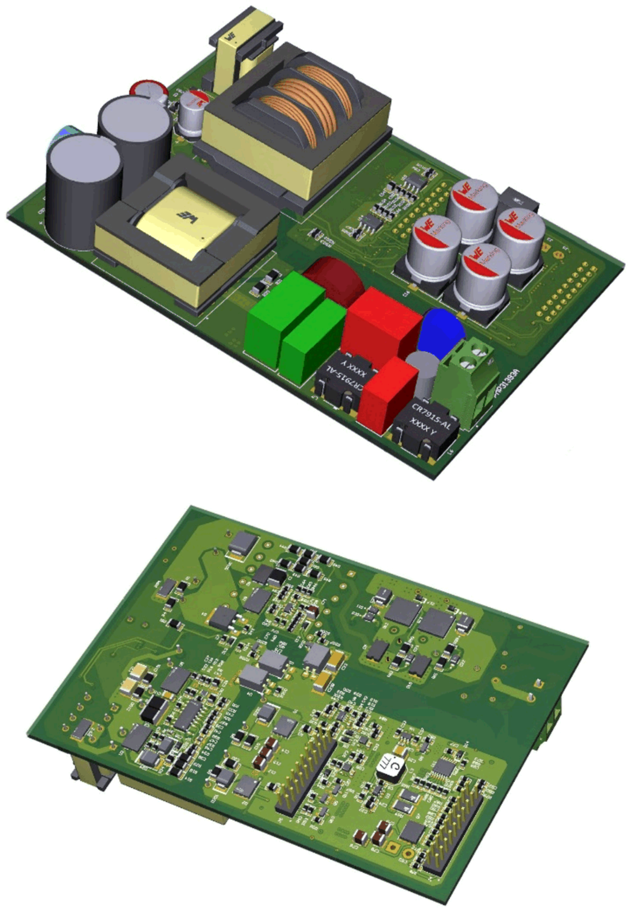

**Figure 4-5. 3D View of Complete Charger Design**

Test results from 200W charger with PFC, LLC and GaN on both stages:

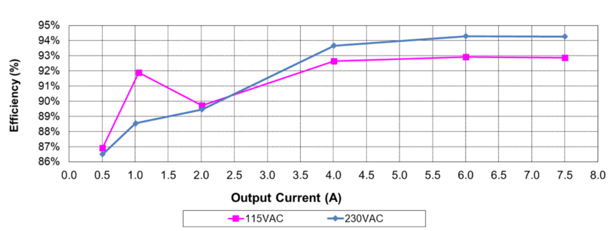


**Figure 4-6. Efficiency Versus VAC**

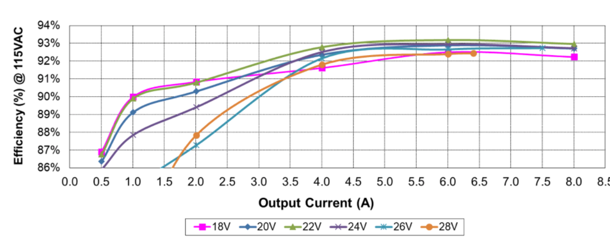


**Figure 4-7. Efficiency Versus $V_{OUT}$**

Since in this design LF burst mode is impacting the peak-peak charging current ripple, we measured at what conditions LF burst mode stops and the converter runs continuously or with HF bursts. Below are some graphs showing the thresholds (when the curve collapses, then at this point LF bursts are off).

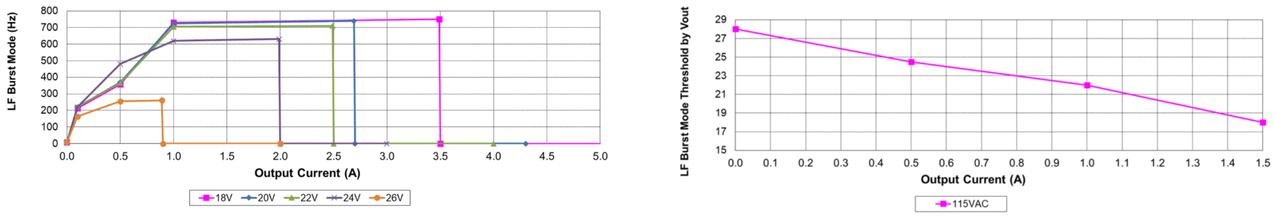


**Figure 4-8. Entry Level and Frequency Versus $V_{OUT}$ and $I_{OUT}$**

The waveforms below describing the main characteristics of switch node and resonant current, in continuous mode and burst mode. In all possible working modes and points, versus $V_{IN}$, $V_{OUT}$ and $I_{OUT}$.

The switching frequency is shifting from 170 kHz up to 380 kHz in normal operation, therefore it is a critical factor to select a controller and switching elements that can operate in this frequencies and deliver high efficiency and low loss. During burst mode, as well as soft start, the controller can even reach 1 MHz frequency, shown in Figure 4-9. With TI new controller UCC256611 and GaN extremely high-speed capability this is not a problem.

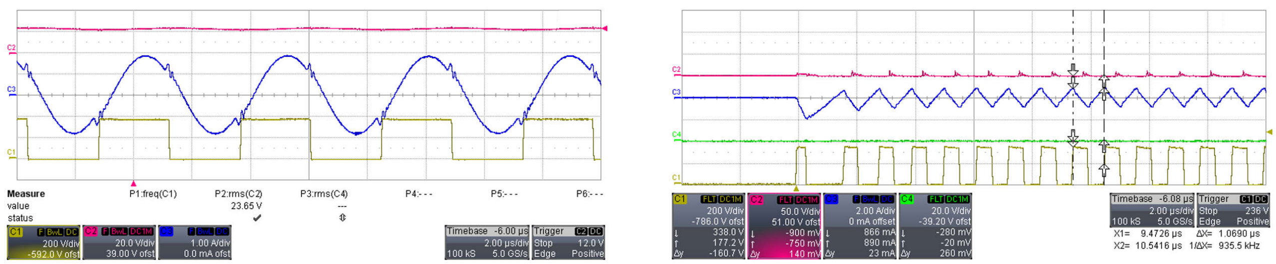

**Figure 4-9. Steady State Operation vs Startup**

A more detailed description of the behavior during burst start is better shown and explained in the *ZCS Prevention During Startup* figure in the *UCC25661x Family 750kHz Wide VIN/VOUT Range LLC Controller Optimized for Light-Load Efficiency Data Sheet*, where $T_{ON}$ extensions are used to wait until the current in resonant inductor has the right polarity.

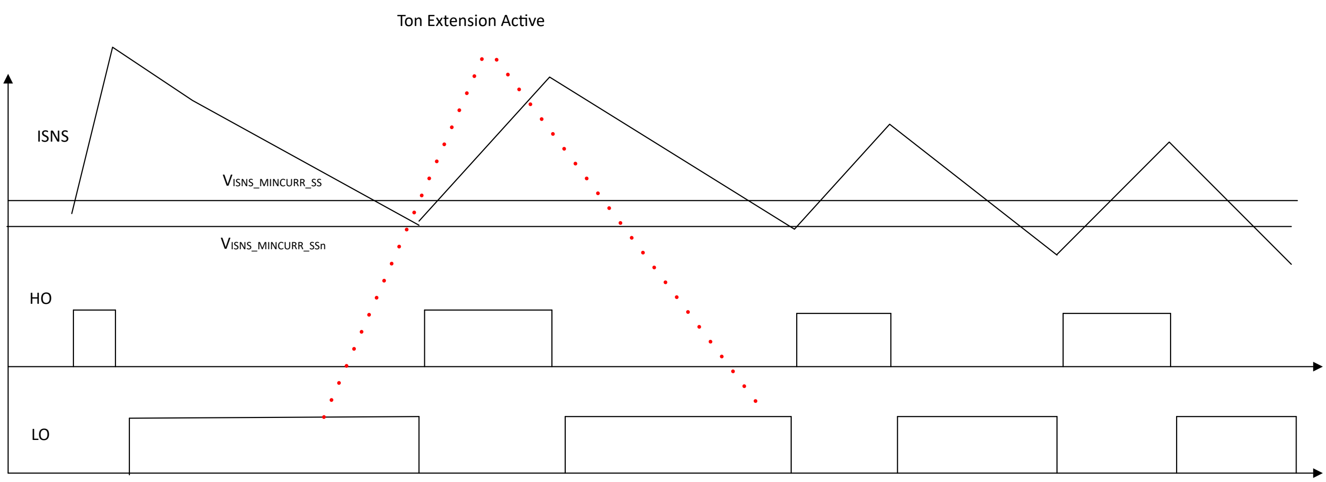


**Figure 4-10. ZCS Prevention During Startup**

## 5 Summary

The LLC resonant topology is known as a highly efficiency topology. For battery charging applications, IPPC enabled LLC controllers like the new family UCC25661 coupled with TI GaN FETs can achieve the highest efficiency and the best overall power density for battery charging applications. UCC25661 is a family of five versions: UCC256610, UCC256611, UCC256612, UCC256613, and UCC256614.

With the new reference design (PMP31393), built with UCC256611 and TI GaN FETs, a design with very low switching and conduction losses is presented. The LLC controller combined with GaN FETs deliver high thermal conductivity, allowing for more compact designs with high power density and low operating temperature. There is no need for advanced cooling, and offer an improved overall system reliability. This is critical parameter to fulfill for battery chargers that will operate in high environment temperatures.