

# Shape an LLC-SRC gain curve to meet battery charger needs



John Dorosa

A growing trend in many household appliances is the replacement of the traditional AC plug with a rechargeable battery. Instead of being tethered to a wall outlet while vacuuming, for example, consumers have the freedom to be more mobile, and not worry about managing clumsy cables.

Every battery used to power an appliance needs a power supply to recharge that battery. As rechargeable batteries become more common in appliances, consumers also want them to last longer before recharging. The simple solution is to use a larger battery pack; however, larger battery packs require much more power than what a flyback converter can charge in a reasonable amount of time. The inductor-inductor-capacitor-series resonant converter (LLC-SRC) provides a higher-power alternative that is versatile enough to work for mobile household appliances.

Traditionally, an LLC-SRC is optimized to operate close to the resonant frequency and maximize efficiency for applications with a narrow input voltage range and a fixed output voltage, as explored in the technical article, [Designing an LLC resonant half-bridge power converter](#). Even so, it is possible to carefully tune a resonant tank design to enable efficient operation along the changing voltage of a battery charging cycle. If fed by power factor correction (PFC) for a narrow input voltage, the LLC-SRC shown in [Figure 1](#) can be a great topology choice for a battery charger.

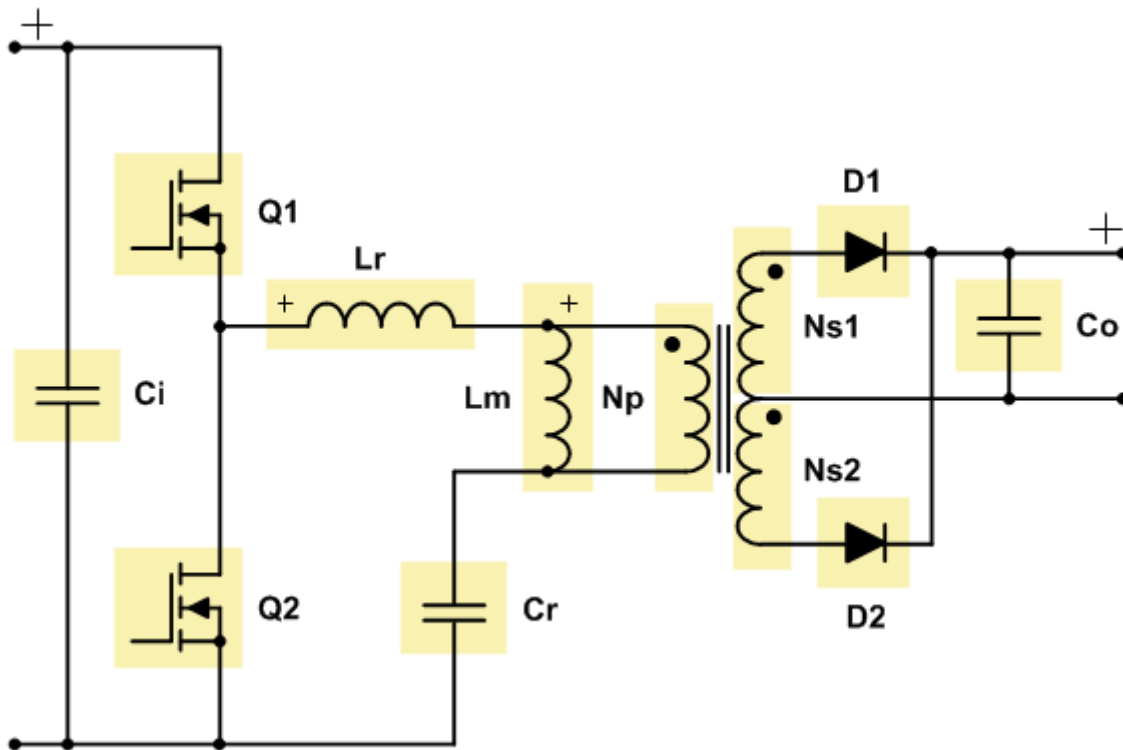
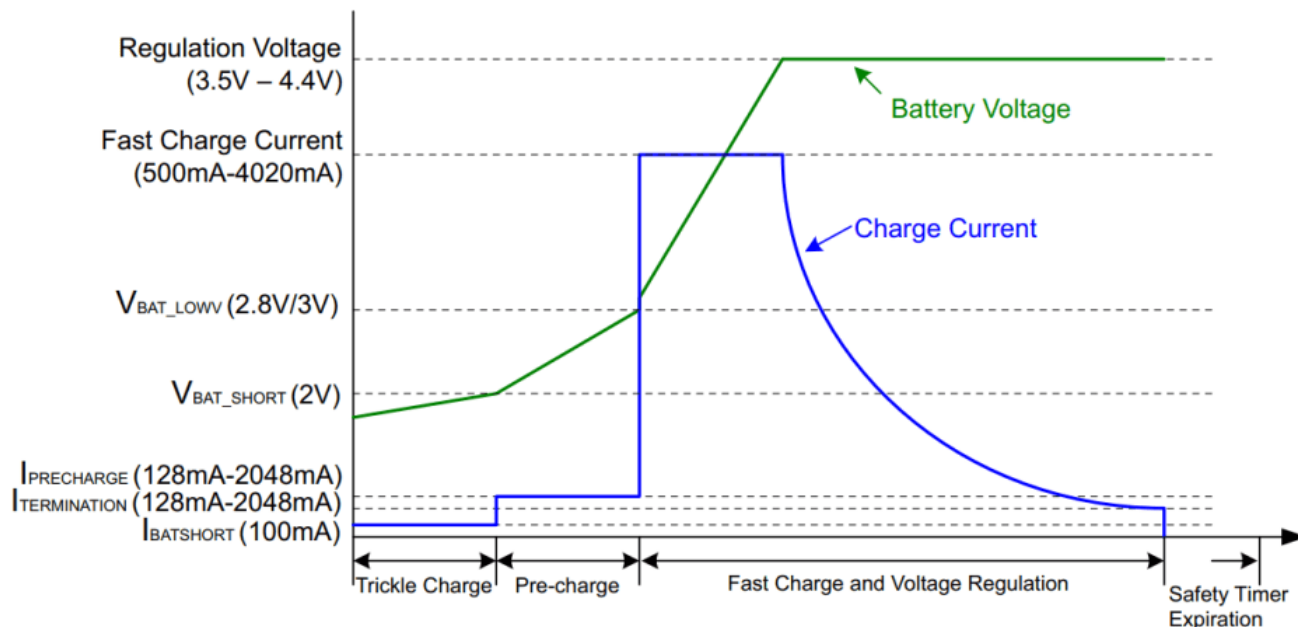


Figure 1. The half-bridge LLC-SRC with  $L_r$ ,  $L_m$ , and  $C_r$  as its resonant elements can serve as a battery charger when used with a PFC front end.

A battery charger has two main operating modes: constant current and constant voltage. When the battery voltage is low, the charger delivers a constant current to the battery. As the battery pack charges, the pack's voltage increases. Once the voltage reaches a desired point, the charger's control loop switches to a constant voltage mode, during which the current backs off while the charger maintains the maximum battery voltage.

This mode ensures that the battery reaches full capacity before terminating the charge. Figure 2 shows an example charging profile versus time for a single cell lithium-ion battery. In more complicated systems there are additional features, like a trickle-charge setting for severely discharged batteries or programmable charging currents and maximum voltages. But in general, the power delivery to a battery can be simplified as either constant voltage or constant current.



**Figure 2. The charging cycle of a single lithium-ion battery charges the cell to 3.5 – 4.4V. Multiple cells can be used in series to achieve higher battery pack voltages.**

The key to an LLC-SRC converter's operation is the shape of its gain curve. The half-bridge FETs switch at a fixed 50% duty cycle and vary in switching frequency to keep the output in regulation. The operating point where the voltage level intersects the gain curve determines the frequency for a given output voltage. Ideally, the operating point is in the curve's inductive region. The equation below calculates the input-to-output voltage gain as:

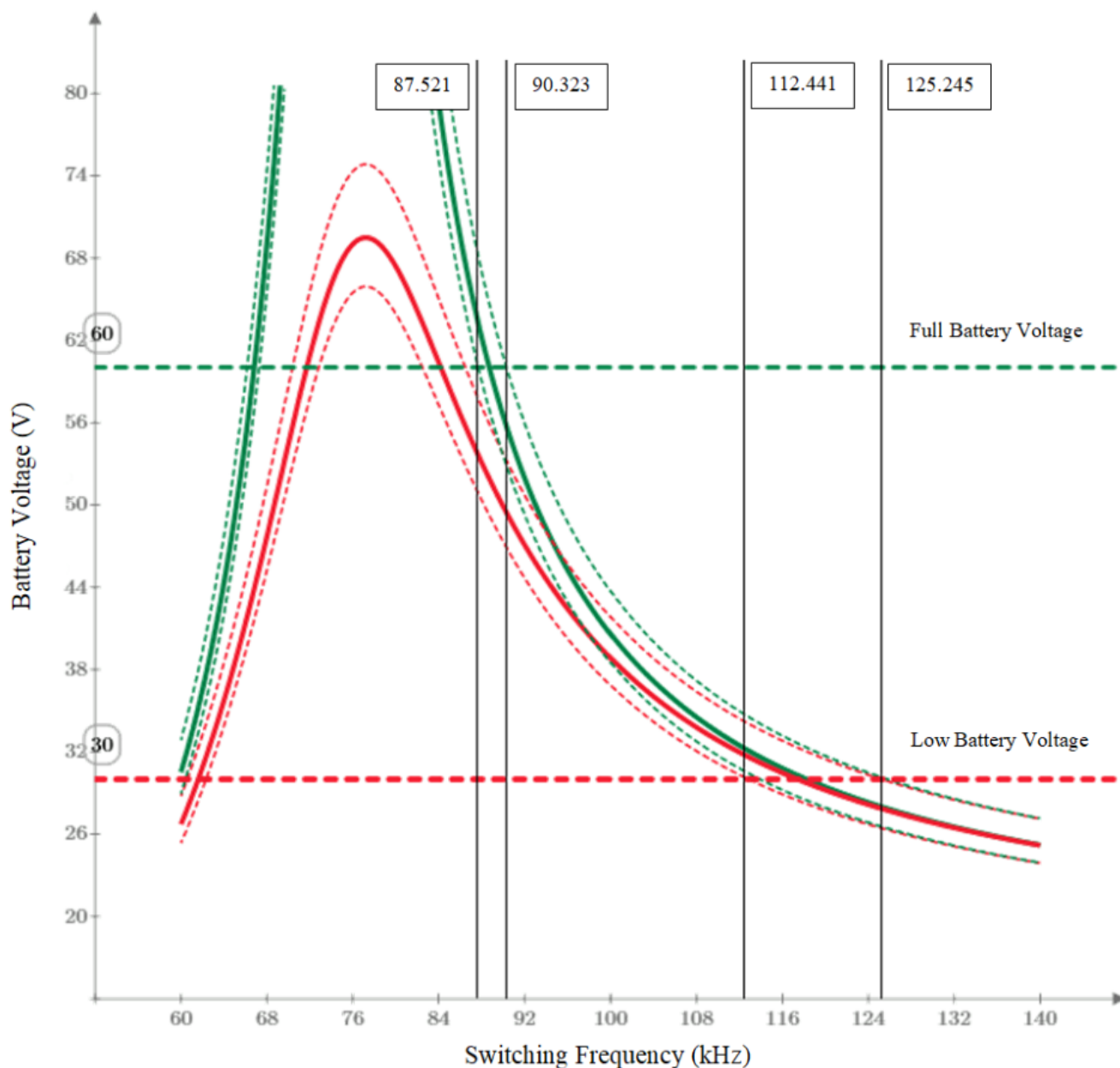
$$V_{out}(R_e, f, V_{in}) = \frac{V_{in}}{2 \cdot n} \cdot \frac{L_m \cdot C_r \cdot R_e}{\sqrt{\left(L_p \cdot C_r \cdot R_e - \frac{R_e}{4 \cdot \pi^2 \cdot f^2}\right)^2 + \left(4 \cdot \pi^2 \cdot f^2\right) \cdot \left(\left(L_r \cdot C_r - \frac{1}{4 \cdot \pi^2 \cdot f^2}\right) \cdot L_p + L_m \cdot L_r \cdot C_r\right)^2}} \quad (1)$$

This shows that the series resonant elements ( $L_m$ ,  $L_r$ , and  $C_r$ ), and the output resistance ( $R_e$ ), determine the gain curve's shape. The load resistor's impact is critical in a battery charger design because the output current and voltage specifications vary across operation.

When determining values for the resonant elements, it is critical to account for the converter's performance across all operating points. In the charging cycle's constant-current portion, the operating point will move up and to the left along the gain curve. While the operating point is moving, however, the load resistor is also changing, which leads to the gain curve shifting up.

Figure 3 is an example gain curve for a battery charger. To account for the variance in load resistor, the figure shows separate curves for a battery at low charge (red) and a battery close to full charge (green). The dotted

red lines show how the regulation on the PFC output voltage ( $\pm 5\%$ ) will change the LLC's operating point. This variance is not as noticeable in the full battery case because the operating point is higher up on the gain curve.



**Figure 3. The output voltage versus switching frequency gain curves for an LLC-SRC resonant tank used for a battery charger shows the variance in operating points.**

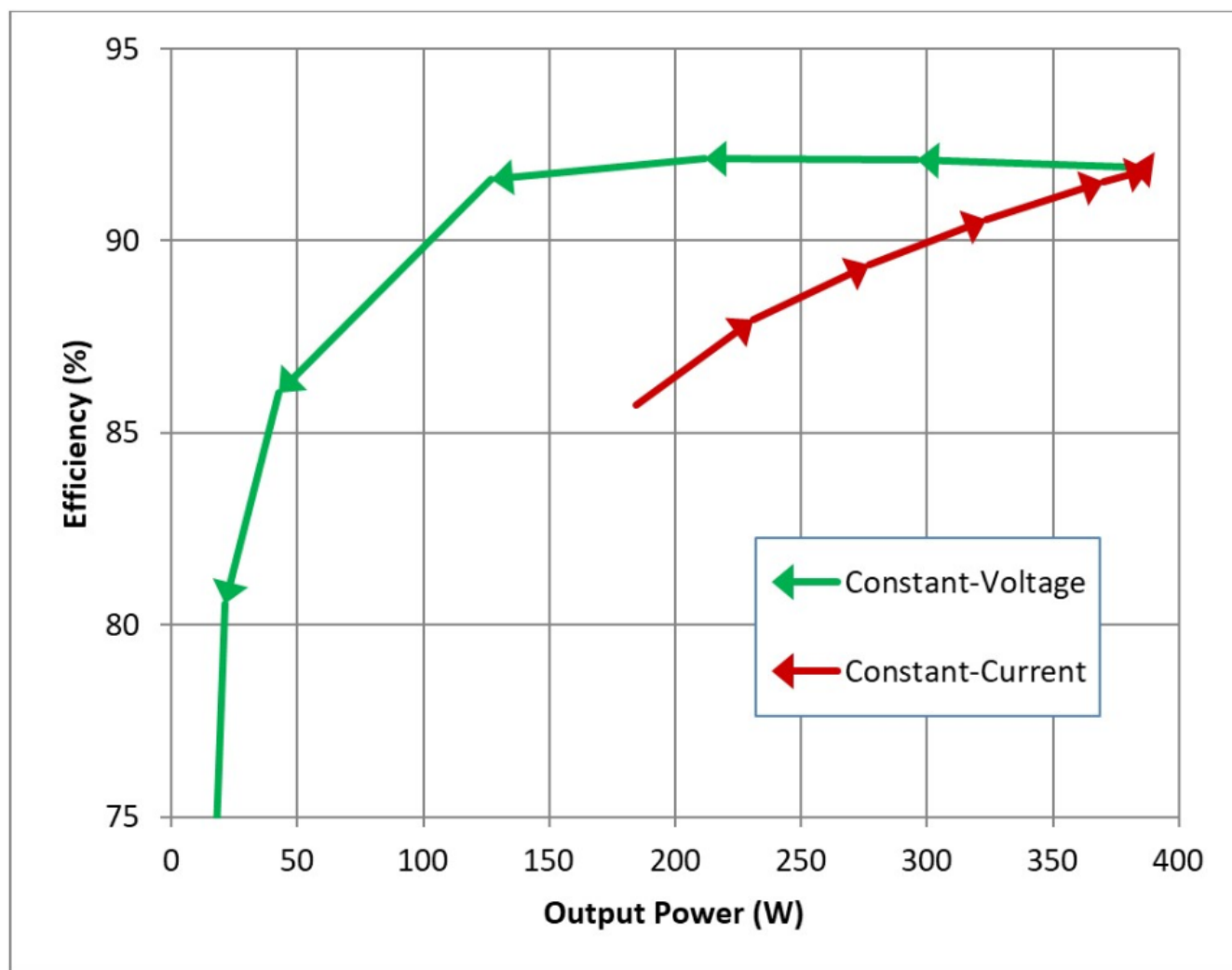
Horizontal markers for 30V and 60V outputs correlate to the battery chemistry for which this charger was designed. As the battery is charging, the operating point will go from where the red curve intersects the 30V line to where the green curve intersects the 60V line.

When shaping a gain curve there are many attributes to consider. First, the curve must be tall enough to regulate the output voltage at the amplitudes the battery pack requires. Next, the operating frequency should be as narrow as possible to create a design that has good performance at all operating points in the charging cycle. A tighter switching frequency enables optimization of the transformer's AC losses. Additionally, a narrower range of operating frequencies will reduce the magnetizing inductor current's ( $I_{Lm}$ ) variance. For an LLC-SRC, having  $I_{Lm}$  too large will increase the conduction losses. If  $I_{Lm}$  is allowed to drop too low, however, an LLC-SRC will lose

zero-voltage switching. Thus, a trade-off must be made in the design. In a battery charger application, the  $I_{Lm}$  will be lower during the higher frequency operation when the battery is at its lowest charge.

Choosing the turns ratio will have a large determination on the possible operating voltage range. To start, I choose a turns ratio optimized for the minimum battery pack voltage (This parameter can be varied in later iterations of the design). Choosing the series resonant elements will determine the converter's general operating frequency as well as the slope of its gain curve. Selecting the  $L_r$  and  $C_r$  values will determine the resonant frequency (The actual switching frequency will be less than the resonant frequency). Decreasing the  $L_m$ -to- $L_r$  ratio will make the curve taller. As the gain curve becomes taller the frequency deviation reduces.

Choosing the series resonant elements is an iterative process that may take time, but a well-designed resonant tank can provide an efficient solution for a battery charger application. Figure 4 shows an efficiency curve for a battery charger using an LLC-SRC topology. Note that the total end-to-end efficiency is shown, which includes the losses associated with the PFC front end. The curve's x-axis is the converter's total output power. As the output voltage and current vary across the charging cycle, the total output power first increases as the battery voltage increases, then decreases as the charging current decreases.



**Figure 4. Efficiency data curves show both operating modes in a PFC to LLC-SRC battery charger design.**

The LLC-SRC is thus a topology that can achieve high efficiencies and is capable of higher power levels than traditional battery chargers that use flyback converters, allowing designers to create compact and efficient supplies that do not sacrifice overall charging performance. The converter's gain curve must be shaped to fit a

battery charging application, but the benefits are well worth the design time required to optimize the resonant tank.

**Related articles:**

- [Power Tips #84: Think outside the LLC series resonant converter box](#)
- [Power Tips #89: High-frequency resonant converter design considerations](#)
- [Fast-charging a supercapacitor from energy harvesters](#)
- [Keeping it safe: The lithium-ion battery](#)
- [Charging batteries rapidly and safely](#)
- [Introduction to lithium-ion rechargeable battery design](#)

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