MICHAEL O'LOUGHLIN, Applications Engineer,
Texas Instruments, Dallas, Texas

Choosing Between Semi-Bridgeless or Interleaved PFC Pre-Regulators

Designers have a choice between semi-bridgeless and interleaved PFC pre-regulators. The semi-bridgeless removes half the bridge-rectifier losses, whereas the interleaved PFC can reduce I²R losses up to 50%.

To help conserve energy some utility companies and environmental agencies have developed initiatives and incentive programs to make offline ac-dc converters more efficient. To reduce power line transmission losses, these same agencies are requesting that offline converters have power factor correction (PFC). Some initiatives are Energy Star, Climate Savers, and the 80 Plus Program for computing power. These programs are very similar in nature, requiring offline power converters to be more than 80% efficient at loads from 20% to 100%, and need to have a power factor greater than 0.9 at full load.

Meeting these power-factor requirements necessitates the use of a PFC pre-regulator, which penalizes efficiency. Two innovative PFC control techniques have been developed to improve PFC pre-regulator efficiency.

The first topology is semi-bridgeless PFC that removes half the bridge-rectifier losses. The second topology is interleaved PFC, which can reduce the converter's I^2R by up to 50%. Both techniques require two boost stages to increase efficiency. So the question becomes, "Which one should you chose for your power supply design?" To help answer this question, we'll evaluate both topologies – theoretically and physically. Our purpose is to share these findings with power-supply designers so they can choose the best topology based on their system requirements.

SEMI-BRIDGELESS PFC

Let's review the semi-bridgeless PFC pre-regulator presented in *Fig. 1*. This topology requires two boost stages (Boost1 and Boost2) to achieve PFC, where the boost inductors are tied directly to the input of the converter. It also requires a full-wave rectifier (D_A, D_B, D_C, and D_D) to peak-charge the common PFC boost capacitance (C_{BOOST}) during initial power up. However, after the boost capacitor has been peak-charged and the converter is up and running, the power converter will only have one rectifier diode in the diode bridge conduction at a time (D_A or D_B), instead of the normal two that are conducting in a full-bridge-based topology. This is different from the traditional PFC boost, where two bridge rectifier diodes are always conducting. This innovative technique improves efficiency by removing the conduction losses of one rectifier diode, which improves overall system efficiency.

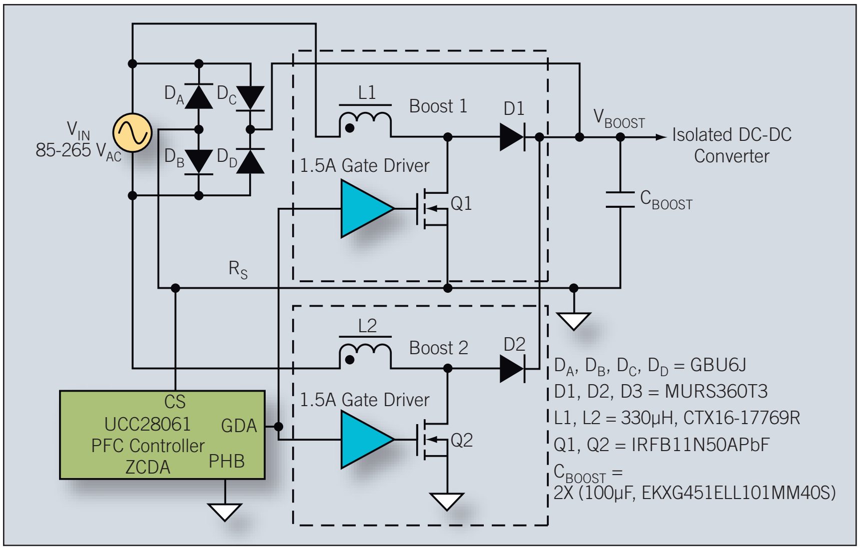

Fig. 1. A semi-bridgeless PFC pre-regulator requires two boost stages to achieve power factor correction.

$$WaAc_T = \left(\frac{L \times I_P}{\Delta B} \times \frac{I_{LRMS}}{Ku \times Cd}\right) = \left(\frac{L \times I_P}{\Delta B} \times \frac{\frac{I_P}{\sqrt{2}}}{Ku \times Cd}\right) \qquad (1)$$

$$P_{CONDUCTION\_INTERLEAVED} = \left(\frac{I}{2}\right)^2 R + \left(\frac{I}{2}\right)^2 R = \frac{I^2}{2} R \qquad (4)$$

Semi-bridgeless PFC does not come free. It makes the design more complex than traditional solutions, and penalizes the inductor's size. You can observe this by studying the inductor area product of a traditional PFC boost pre-regulator ($WaAc_T$), versus the total area product of both semi-bridgeless PFC pre-regulator ($WaAc_S$) inductors. Magnetic designers use area product calculations to select magnetic cores based on winding area (Wa) and core cross-sectional area (Ac). Eq. 1 to 3 calculate the total inductor area products for semi-bridgeless and traditional PFC pre-regulators, where L is the PFC boost inductor and I_P is the peak PFC input current. I_{LRMS} is the PFC inductor RMS current. Variable C_D represents the current density for which the inductor(s) is designed. Variable ΔB represents the change in flux density present in the inductor(s). Ku represents the magnetic window winding efficiency.

From these equations for area product you can see that the total area product for the semi-bridgeless PFC inductors ($WaAc_S$) is roughly 1.414 times larger than the area product ($WaAc_T$) of a traditional PFC pre-regulator. The area product equations show that the total magnetic volume of the semi-bridgeless PFC are at least 1.4 times greater than a traditional PFC pre-regulator that uses a single boost stage for PFC.

(See Eq. 1)

(See Eq. 2 on p.30)

$$WaAc_S \geq \sqrt{2} \times WaAc_T \qquad (3)$$

INTERLEAVED PFC

The interleaved PFC pre-regulator approach interleaves two boost stages. This control technique requires that two power-factor-corrected boost stages operate 180° out-of-phase. The many benefits of this topology have

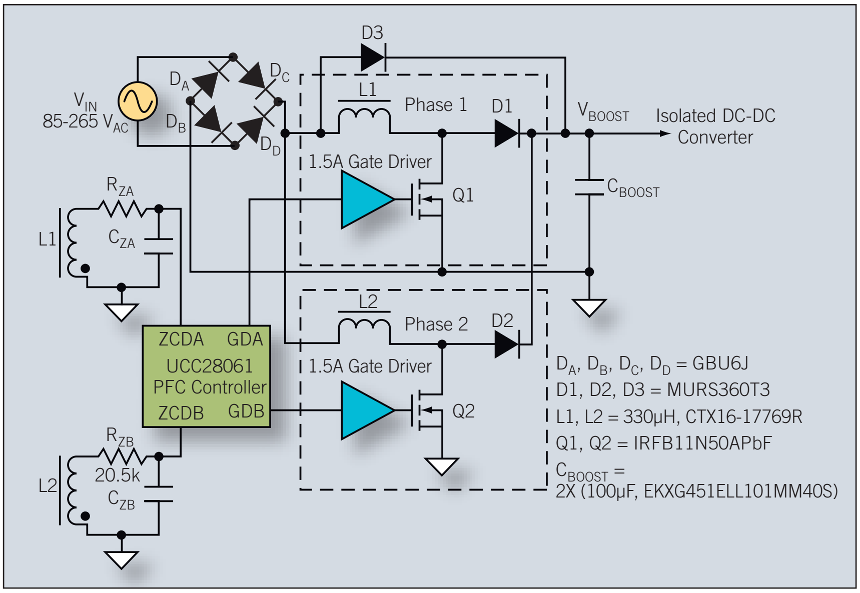

Fig. 2. Interleaved PFC pre-regulators distribute conduction losses between two boost stages.

$$\mathrm{WaAc_S} = 2\times\left(\frac{L\times I_P}{\Delta B}\times\frac{I_{LRMS}}{Ku\times Cd}\right) = 2\times\left(\frac{L\times I_P}{\Delta B}\times\frac{\frac{I_P\sqrt{0.5}}{\sqrt{2}}}{Ku\times Cd}\right) = \sqrt{2}\times\left(\frac{L\times I_P}{\Delta B}\times\frac{\frac{I_P}{\sqrt{2}}}{Ku\times Cd}\right) \qquad (2)$$

$$P_{CONDUCTION\_TRADITIONAL} = I^2R \qquad (5)$$

$$\frac{P_{CONDUCTION\_TRADITIONAL}}{2} = P_{CONDUCTION\_INTERLEAVED} \qquad (6)$$

$$\mathrm{WaAc_I} = 2\times\left(\frac{L\times\frac{I_P}{2}}{\Delta B}\times\frac{I_{LRMS}}{Ku\times Cd}\right) = 2\times\left(\frac{L\times\frac{I_P}{2}}{\Delta B}\times\frac{\frac{I_P}{2\times\sqrt{2}}}{Ku\times Cd}\right) = \frac{1}{2}\times\left(\frac{L\times I_P}{\Delta B}\times\frac{\frac{I_P}{\sqrt{2}}}{Ku\times Cd}\right) \qquad (7)$$

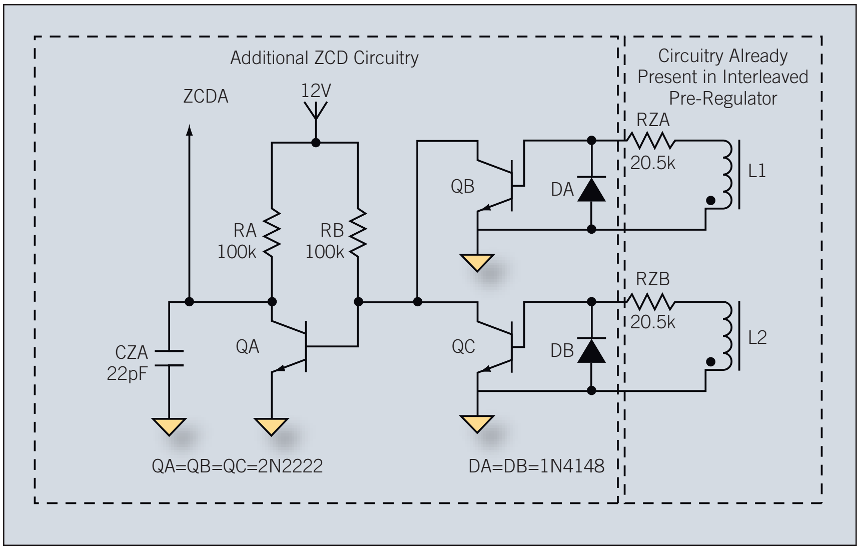

Fig. 3. Additional semi-bridgeless PFC circuitry uses transition-mode zero-current detection in each inductor.

made it very popular. A major benefit is the input- and output-inductor ripple-current cancellation. If designed correctly, it can reduce total boost inductor and/or EMI magnetic volume. The output-inductor ripple-current cancellation reduces the boost-capacitor RMS current, which can lead up to a 25% reduction in capacitor volume. Do not confuse this with the amount of boost capacitance the design requires for hold-up. This is typically determined by hold-up time and output power. *Fig. 2* shows a functional schematic of an interleaved PFC pre-regulator.

Interleaved PFC pre-regulators distribute conduction losses amongst two PFC boost stages ($P_{CONDUCTION\_INTERLEAVED}$). A designer can reduce conduction losses by up to 50% with an interleaved PFC approach versus a traditional single-stage boost. This is evident by studying the simplified conduction-loss equations for an interleaved PFC boost, and a traditional single PFC pre-regulator ($P_{CONDUCTION\_TRADITIONAL}$).

(See Eq. 4 on p. 29)

(See Eq. 5)

(See Eq. 6)

Interleaving PFC pre-regulators can reduce total boost-inductor magnetic volume. To illustrate this, let's study the total inductor area product of both inductors ($\mathrm{WaAc_I}$) used in an interleaved PFC pre-regulator versus the total area product of a traditional PFC pre-regulator's boost inductor ($\mathrm{WaAc_T}$). The total area product of the interleaved approach is half the total area product of a traditional PFC boost inductor. In practice the total boost-inductor volume for both inductors for an interleaved PFC pre-regulator can be up to 32% smaller than the inductor volume of a traditional PFC boost inductor.

(See Eq. 7)

$$\mathrm{WaAc_I} = \frac{1}{2}\times\mathrm{WaAc_T} \qquad (8)$$

INTERLEAVED AND SEMI-BRIDGELESS PFC BENEFITS

Both solutions offer system efficiency benefits. The semi-bridgeless PFC removes half the bridge rectifier's losses, while the interleaved PFC pre-regulator distributes the power to reduce the pre-regulators conduction losses by half. To evaluate efficiency improvements over traditional PFCs, a 300-W transition-mode interleaved PFC pre-regulator was modified to work as a 150-W transition-mode semi-bridgeless PFC pre-regulator and a single-stage traditional 150-W transition-mode boost. Then the efficiencies of the three were evaluated and compared at a load from 30 W to 150 W.

Achieving the constant on-time of the interleaved transition-mode PFC pre-regulator as presented in *Fig. 2* in the transition-mode semi-bridgeless application in *Fig. 1* requires the additional circuitry presented in *Fig. 3* for zero current detection in each inductor. This circuitry can be used with most single-stage constant-on-time transition-mode PFC controllers in a semi-bridgeless transition-mode PFC pre-regulator.

The graph in *Fig. 4* reflects efficiency data for traditional-PFC, semi-bridgeless-PFC and interleaved-PFC pre-regulators. To keep the comparison fair, each FET was driven with a discreet 1.5-A gate driver to ensure identical rise and fall times. The graph shows how at lighter loads, traditional and semi-bridgeless PFC pre-regulators are more efficient than the interleaved PFC because driving two FETs at lighter loads—where switching losses are dominant—is less efficient. The interleaved PFC's light-load efficiency can be improved by turning off a phase under light-load conditions, resulting in a light-load efficiency similar to a traditional pre-regulator. The semi-bridgeless PFC light-load efficiency is roughly 0.5% higher than a traditional PFC.

At 150 W, where conduction losses dominate, the traditional PFC is least efficient. The semi-bridgeless PFC was roughly 0.7% more efficient at full load compared to the traditional PFC. The interleaved PFC is 1.3% more efficient at maximum load than the traditional pre-regulator, and 0.5% more efficient than the semi-bridgeless PFC.

The semi-bridgeless PFC pre-regulator, in my evaluation, proves to be more efficient than a traditional single-stage PFC boost pre-regulator. However, the semi-bridgeless PFC total inductor volume will be at least 1.4 times greater than the traditional PFC boost inductor, which will heavily penalize the pre-regulators power density. The semi-bridgeless PFC offered the greatest light-load efficiency.

However, at maximum load where conduction losses dominate and heat needs to be dissipated, the interleaved PFC pre-regulator is the most efficient. The interleaved PFC pre-regulator offers many benefits over both the semi-bridgeless and traditional PFC topologies. It can be designed for the highest power densities by reducing total inductor and EMI magnetic volume, as well as capacitor volume when compared to a traditional PFC. ⏻

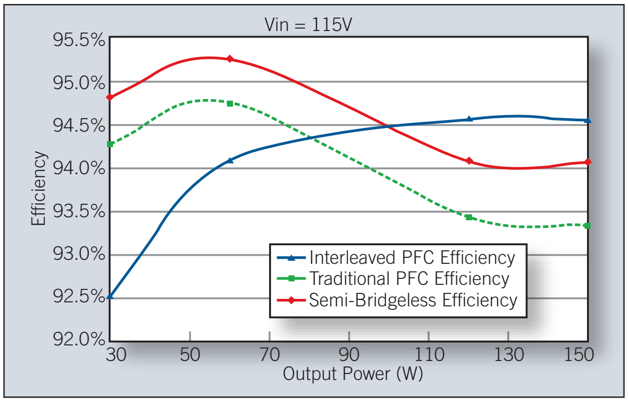

Fig. 4. PFC pre-regulator efficiency comparison for the pre-regulator operating as a traditional PFC pre-regulator, semi-bridgeless PFC pre-regulator, and an interleaved PFC pre-regulator.

REFERENCES

1. www.ti.com/pfc.