Driving up Power Density with GaN

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GaN-Based bridgeless architecture enables 1 W/cc (16 W/in^3) 300 W AC-DC converter

The extremely high operating efficiency of GaN power transistors at high switching frequencies presents an opportunity to improve both the energy efficiency and power density of mid-power AC/DC converters. Common applications include built-in power supplies for flat-screen televisions, power adapters for all-in-one PCs, monitors, game consoles, gaming laptops, and home wireless-networking devices, and small electric drives such as eBikes.

Depending on the vendor, silicon-based adapters in this power range can achieve full-load efficiency of 90-94% (at 90 V_{AC} line input), although power density is often as low as 0.39 W/cc.

These converters, spanning ratings from 100 to 500 W, must implement power-factor correction (PFC), which can be responsible for more than a quarter of the total energy losses in conventional AC-DC converter. The main losses are incurred in the four-diode bridge typically used for full-wave rectification at the input. At any time, two diodes of the bridge are carrying the full input current, which leads to high power dissipation associated with the diodes' forward voltage. This dissipation also generates undesirable high temperatures inside the power supply.

Leaving Silicon Behind

By adopting GaN power transistors, which can operate at a much higher switching frequency than silicon devices can handle, efficiency can be increased by 1-3%. Moreover, the size of magnetic components and filtering capacitors can be significantly reduced to achieve a significant increase in power density. Assisting this transition to efficient, high-frequency power conversion with GaN devices, PWM controllers from major semiconductor manufacturers are now available off the shelf, which can ensure stable operation at the high frequencies required.

Using this approach, engineers can create smaller and less intrusive power supplies that enable consumer product designs to benefit from smaller and slimmer enclosures that give a more stylish appearance, that are easier to carry and occupy less space in the home or office, and benefit from lower surface temperature while in operation. Lower temperature means equipment can be safer to touch, comfortable for owners to live with, and can benefit from increased reliability.

Prototype Architecture

Navitas researchers have built a next-generation prototype power supply to demonstrate the gains in efficiency and power density that are now possible. The architecture combines the latest high-efficiency topologies for each stage, comprising a bridgeless totem-pole PFC, an LLC resonant DC-DC converter, and synchronous rectification at the output, as shown in figure 1.

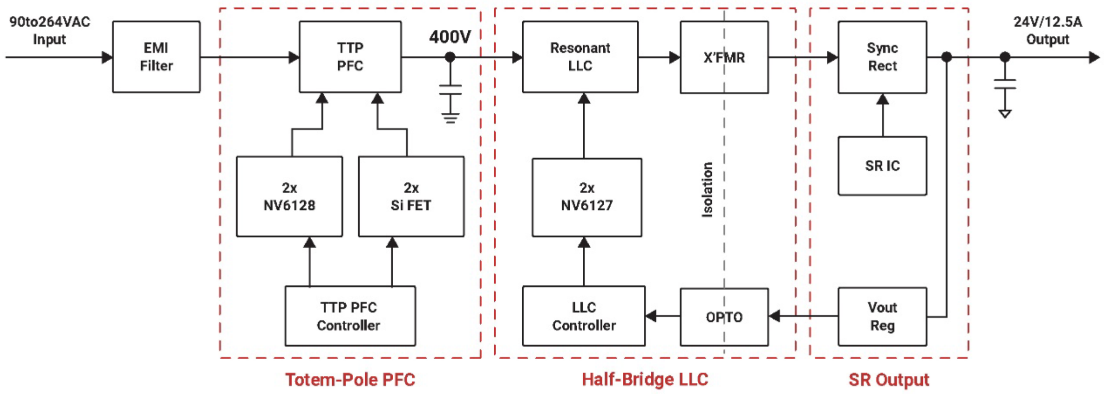

Figure 1: High-efficiency 300 W AC-DC converter

The totem-pole PFC (TTP PFC) topology chosen for this power supply allows the converter to benefit from the increased energy efficiency of a bridgeless design while avoiding the disadvantages inherent in the alternative basic, semi-, and bi-directional bridgeless circuits.

The basic bridgeless PFC connects one switch permanently to the AC line, resulting in high common-mode noise. On the other hand, while semi-bridgeless and bi-directional bridgeless circuits have lower common-mode noise, an additional inductor or power switches with very low on-resistance ($R_{DS(ON)}$) are required.

Unlike these circuits, the TTP PFC has low common-mode noise and requires no extra inductor or special low-$R_{DS(ON)}$ switches. While some circuit complexities associated with voltage and current sensing must be solved, there are control ICs that can simplify these functions, e.g. NCP1680 used in this reference design.

NV6128 GaNFast Power ICs bring the advantages of GaN wide-bandgap technology to the converter reference design discussed here. These ICs monolithically integrate a GaN driver and 70 mΩ GaN FET on the same chip, which simplifies design and ensures optimal performance. Reliability and robustness are significantly greater than is usually possible with discrete GaN devices. The gate and its drive circuit are fully enclosed within the IC package, whereas the gate of a discrete GaN FET is exposed. Integration inside the GaNSafe IC prevents any parasitic inductance in the gate loop and so eliminates any possibility of turn-on/turn-off overshoot/undershoot and ringing. The internal gate is also immune to turn-on/turn-off dV/dt and glitches that can cause false switching, and is generally well protected against surges and other circuit hazards that threaten the reliability of discrete devices. The GaNFast ICs are housed in a thermally efficient PQFN package that permits a simple PCB layout and a large cooling area with an underside exposed pad for efficient dissipation into a heat spreader or thermal vias in the circuit board.

In the reference design discussed here, two NV6128 devices implement the fast-leg half-bridge of the totem-pole PFC circuit. These devices deliver several advantages, including low output capacitance and low gate charge (Q_g), which permits high-frequency operation. In addition, they have zero reverse-recovery charge (Q_{rr}), which eliminates reverse-recovery losses. Turn-on dV/dt control helps to minimize electromagnetic emissions (EMI), and integrating the gate driver and regulator ensures robust and accurate control of the gate voltage. The NCP1680 operates the TTP PFC efficiently at a switching frequency of 200 kHz.

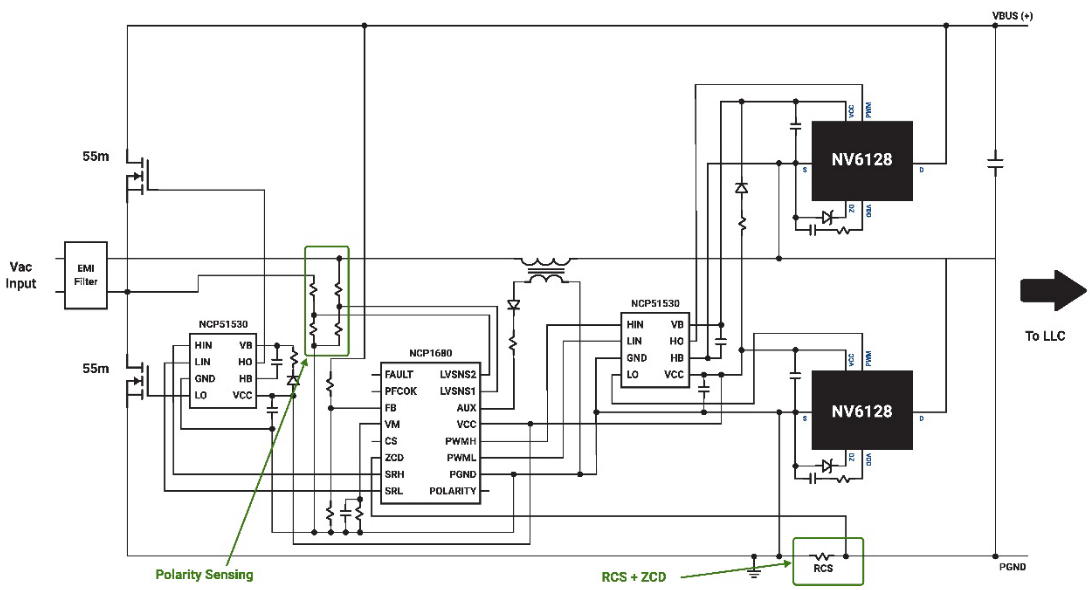

Figure 2: GTTP PFC stage designed to operate at 200 kHz

Following the TTP PFC, an LLC resonant DC/DC converter with zero-voltage switching converts the 400 V output from the PFC stage and provides isolation. Finally, a synchronous rectifier circuit generates the regulated output voltage at 24 V and 12.5 A full-load current.

The LLC half-bridge, shown in figure 3, features two NV6127 (125 mΩ) GaNFast power ICs, chosen for their low capacitance and low Q_g that allow high-frequency operation. These devices also benefit from fast start-up during soft-start and burst modes, with high dV/dt immunity to guard against unwanted turn-on. The NCP13994 is an off-the-shelf controller capable of operating the converter at up to 750 kHz steady-state switching frequency.

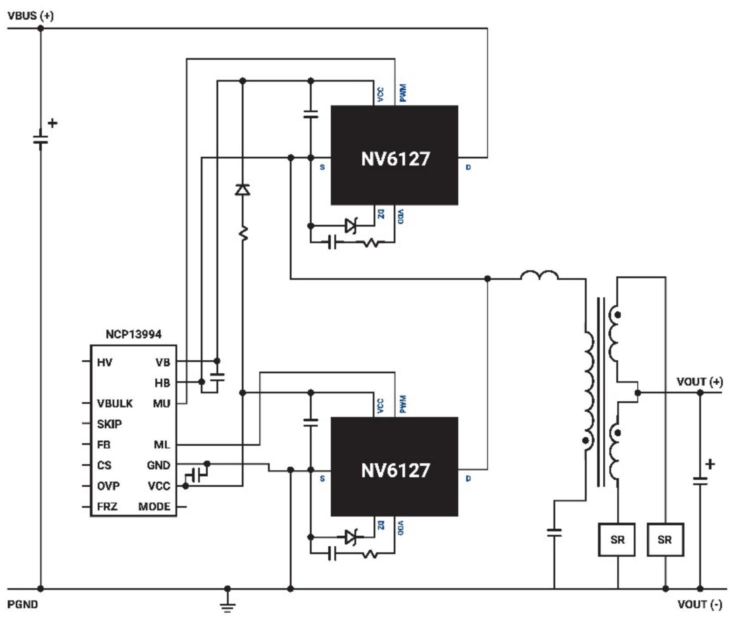

Figure 3: High-frequency half-bridge LLC resonant DC-DC converter

The prototype converter implements the TTP PFC circuit, LLC half-bridge, and synchronous rectifier stage on three separate cards, as shown in figure 4. This modular approach results in an ultra-compact design that permits efficient thermal management. The modularity also facilitates scaling of the design to handle different power levels.

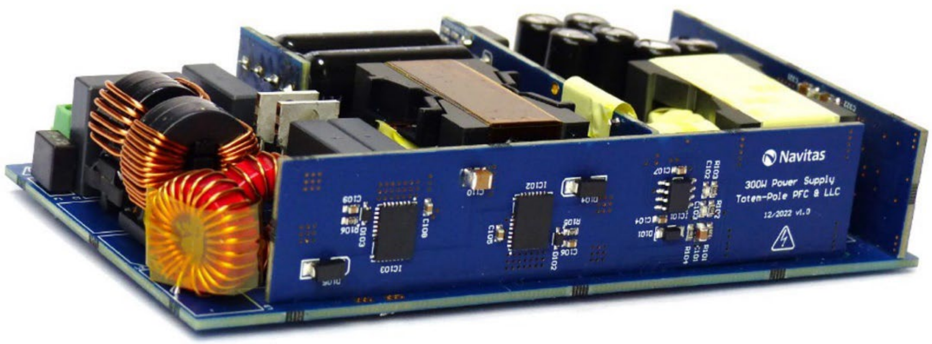

Figure 4: The prototype uncased converter with separate PFC, resonant LLC, and SR daughter cards

With overall dimensions of 69 x 127 x 25mm high, the converter's total volume is less than 220 cc. The assembly could easily fit within a total case volume of 300 cc, showing that power density of 1 W/cc (16 W/in^3) for mid-power applications targeting consumer products is now within reach.

Performance Assessment

Figure 5 shows the totem-pole PFC waveforms when operated with 115 V_{AC} input at 100% load. The operating frequency is 200 kHz at the peak of the AC line voltage.

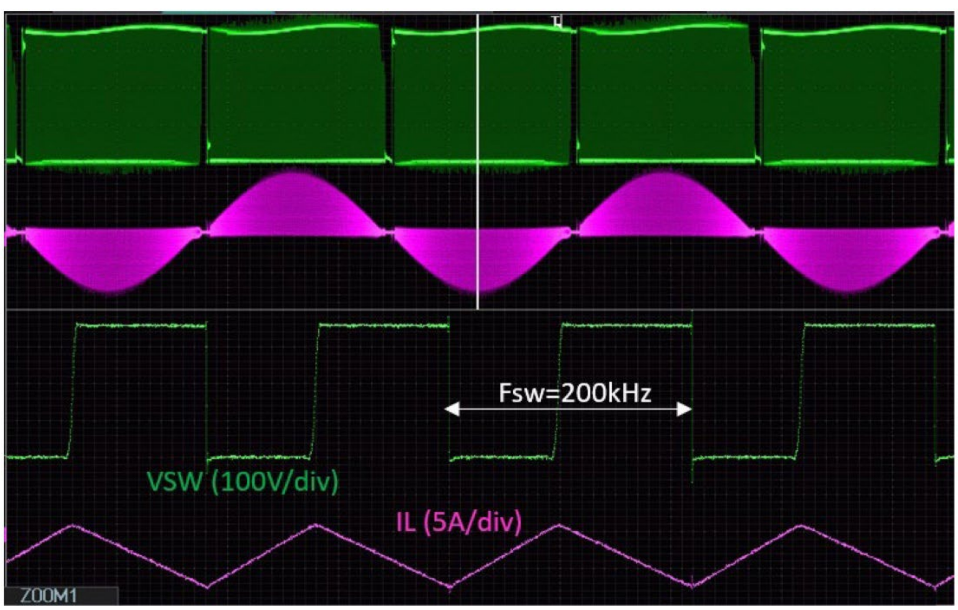

Figure 5: PFC waveforms with sinusoidal inductor current, indicating high power factor, and ZVS at T_{on} and T_{off}

The LLC half-bridge voltage and current waveforms presented in figure 6 show ZVS operation at an operating frequency of 670 kHz during steady-state and full-load conditions. The operating frequency increases above 700 kHz at lighter load conditions.

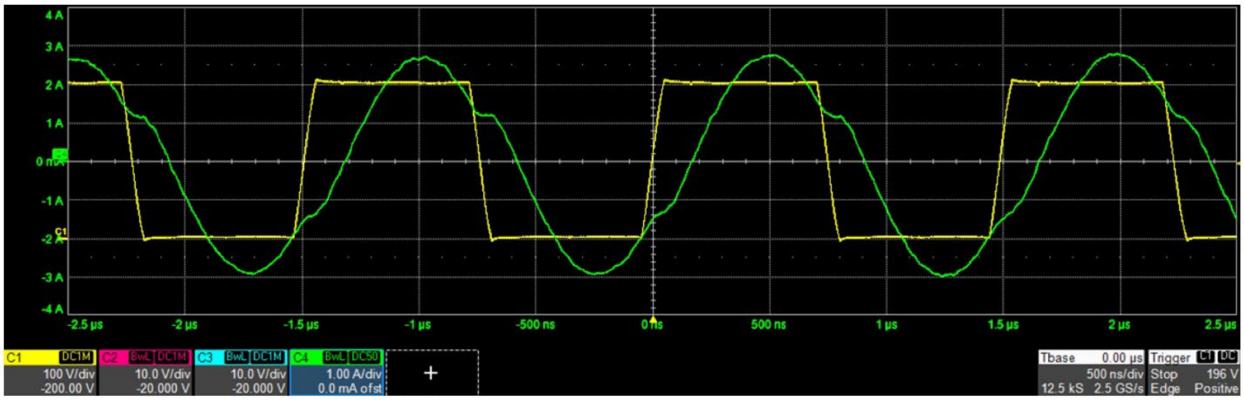

Figure 6: The LLC ZVS waveforms, showing sinusoidal current of the LLC tank circuit and smooth and clean ZVS half-bridge waveforms.

I The efficiency curves shown in figure 7 demonstrate operation at AC input voltages of 90, 110, and 230 V, consistent with the standard domestic AC line voltages available in major markets worldwide. The converter achieves peak efficiency of 94.4% at 90 V_{AC} input, 94.8% at 110 V_{AC}, and 95.8% at 230 V_{AC}. Thermal measurements taken under worst-case conditions, operating from 90 V_{AC} at full load, indicate that acceptable component temperatures can be maintained when the PSU is encased.

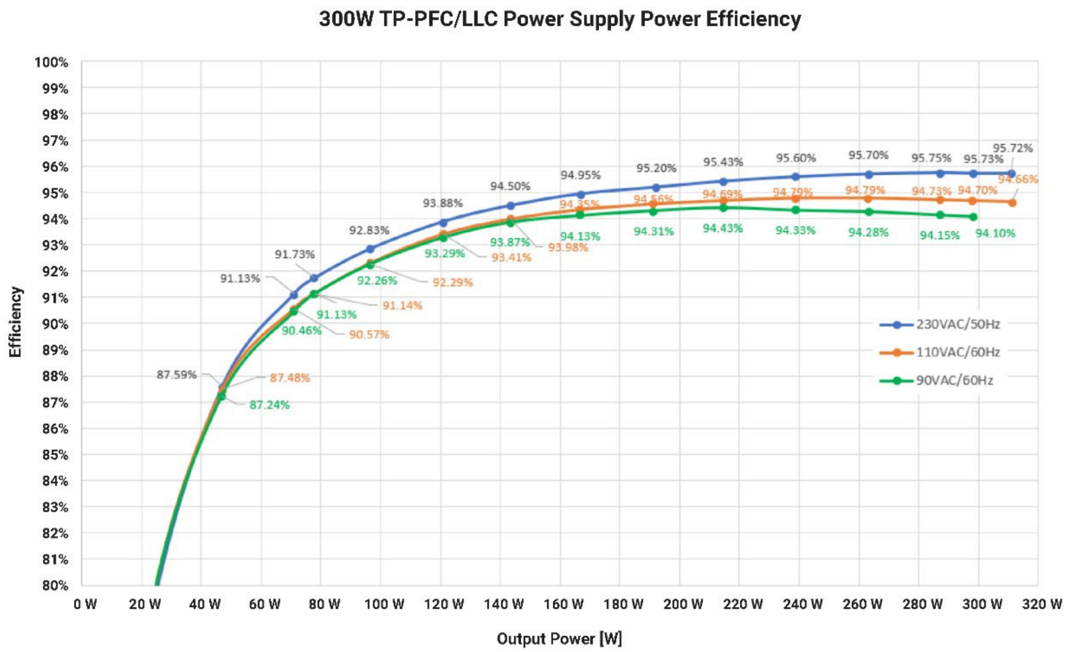

Figure 7: Power supply efficiency across the load range, operating at 90, 110, 230 V_{AC} input

Conclusion

Market demands are calling for greater efficiency and smaller size in mid-power 100-500 W AC-DC converters typically used in consumer products such as televisions, portables, and eBikes. Achieving this means moving away from traditional silicon-based circuits designs that restrict the achievable power densities to below 0.5-0.6 W/cc.

GaN technology capable of significantly higher switching frequencies has enabled a 300 W prototype power supply small enough to fit within a 300 cc enclosure, bringing the opportunity to increase power density to 1 W/cc. Tests have demonstrated 95.8% peak efficiency at 230 V_{AC} input, representing an increase of 1-3% over silicon-based designs, using simple thermal management to ensure an acceptable case temperature and increased component reliability.