Commentary

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Increasing The Power Density Of DC Chargers Using GaN HEMT Devices

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The requirement to charge e-bikes and increasingly powerful portable computers or other mobile devices is driving the demand for higher power levels in USB-C chargers from 65 W to 240 W. At this level, there are some challenges such as the power factor correction (PFC) achieving sufficient power density, and voltage regulation over a wide voltage range. Simultaneously, automobile manufacturers are looking for ways to boost the power density of onboard chargers (OBCs) to help reduce the size and weight of electric vehicles.

Infineon set out to investigate the capabilities of gallium-nitride high-electron-mobility transistors (GaN HEMTs) in order to determine if they could deliver the level of power density required in next-generation charging applications. In this article we discuss their approach and findings.

Next-Generation USB Charger

This design presented several challenges, including wide input (90 to 265 Vrms) and output voltage ranges (5 to 48 V), PFC considerations, and the requirement to provide two independent output ports in a high power-density form factor. Achieving high power density required particular attention because natural convection and radiation were the only means available to dissipate heat from the charger.

The complete design specifications along with a graph of required efficiency versus power density for a 240-W charger are shown in Fig. 1. To achieve maximum power density while maintaining a maximum surface temperature of 70°C, a minimum efficiency figure of 96% was required for this design.

Parameter	Value
Input Voltage Range	1ϕ, $90-265\,V_{rms}$
Rated Output Power	240 W
USB-C PD 3.1 Output Voltage	$5-48$ V
USB-C PD 3.1 Output Current	5 A
EMI Compliance	Class B
Maximum Ambient Temperature	40°
Maximum Surface Temperature	70°

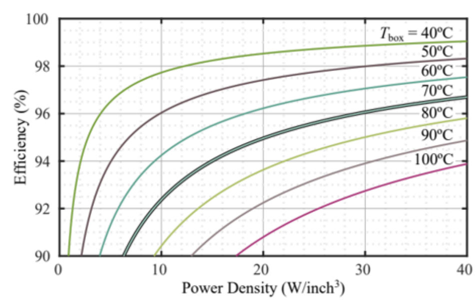

Fig.1. Design specifications for a next-generation USB charger (table) and the efficiency-versus-power density requirements for this design (graph).

Topology Selection

To help identify the optimum topology and approach to system partitioning for next-generation high-density adapters, different options for the control and isolation functions were considered. For the PFC (rectifier) stage, buck, boost, and buck-boost were three options. While boost PFCs provide a dc-link voltage higher than the peak grid voltage, the lower voltage from a buck PFC stage makes the design of the following dc-dc stage simpler. However, in single-phase systems, a buck converter has discontinuous input current which would generate unacceptable harmonics on the grid side, especially at low voltages. For this reason, a buck converter must also be excluded.

Following the PFC stage, the dc-dc conversion stage was required to provide galvanic isolation (for safety) and to enable independent control of two USB-C ports. This could be done in several different ways. The first option was to use a dc-dc converter to provide simultaneous isolation and regulation, like for example, the Hybrid Flyback (HFB) converter, followed by two buck converters.

Another alternative was for the first dc-dc conversion stage to only provide isolation but no regulation, for example by using a dc-transformer (DCX) converter with a fixed conversion ratio. A final option was to use two regulating and isolating converters, one for each output port, like for instance, the HFB. However, this requires two transformers, each rated for the full power of the converter meaning it cannot provide the required power density.

USB Charging Solution And Performance

Having considered the merits of these different options by means of a comprehensive multi-objective (efficiency vs. power density) Pareto optimization, a totem-pole PFC with boost-follower modulation, in combination with a DCX followed by two buck stages was chosen (Fig. 2).

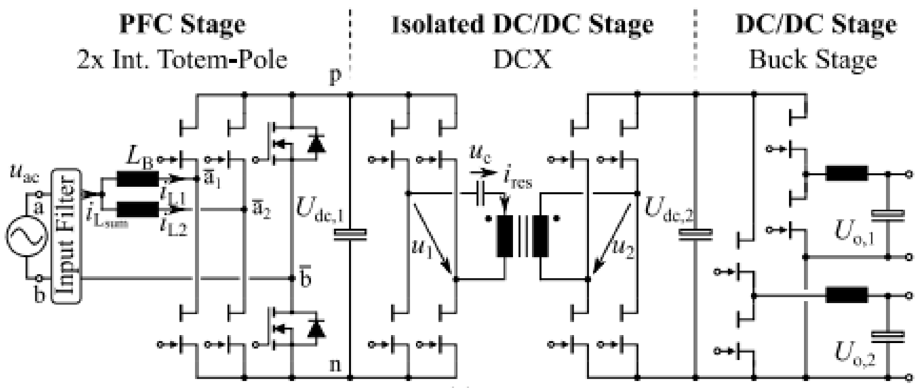

Fig. 2. Final USB charger design.

The PFC stage achieved zero voltage switching (ZVS) over the full line cycle for all load conditions and input RMS voltages by operating with continuous conduction mode (CCM) and with a fixed switching frequency (400 kHz) in each high-frequency bridge leg. Since this mode causes a large ripple current in the boost inductor and the switches, a dual-phase totem pole with two interleaved high-frequency bridge legs were selected and this provided several benefits.

First, the average current in each bridge leg is half of the entire PFC current, which also halves the required current ripple in each inductor, to achieve ZVS. Second, by phase-shifting the bridge legs by 180°, the effective switching frequency seen by the EMI filter was doubled. This reduced the required filter attenuation and therefore the size of the EMI filter. Finally, power losses were dissipated in a greater number of components, thereby preventing hot spots from occurring.

The DCX converter was designed to operate at a resonant frequency of 425 kHz and to achieve ZVS independently of the load by using only magnetizing current for the ZVS transition. The turns ratio of the transformer (5.6:1) was chosen so that the dc-link voltage range of 300 to 400 V was mapped to the input voltage range of the buck stage (52 to 71 V). This allowed 100-V-rated Schottky gate (SG) GaN HEMT devices to be used as synchronous rectifiers for the DCX stage, as well as in the two output buck stages.

The final charger solution (Fig. 3) achieved an overall system efficiency of 95.3% at full load operation (90-Vrms input and 48-V output voltage). The uncased power density attained was 42 W/in.^{3}, a figure which is 100% better than that provided by the best available silicon-based solutions currently on the market.

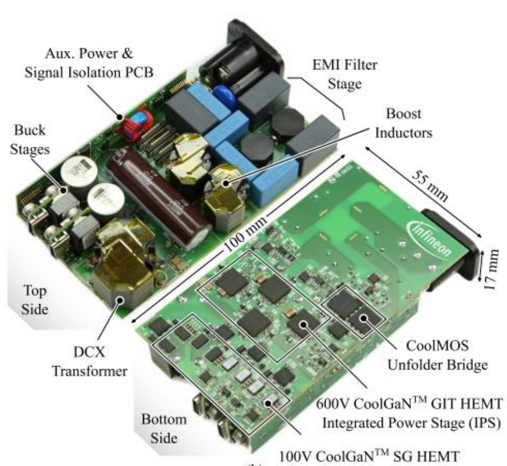

Fig. 3. View of PCB for USB charger.

Ultra-High Density Three-Phase 11-kW On-Board Charger

Reducing the size and weight of on-board chargers (OBCs) is a key objective for electric vehicle manufacturers. Among existing solutions, 2 kW/L is the highest power density currently achievable using silicon-based solutions but it is hoped that 6 kW/L will be attainable using wide-bandgap devices. This figure was used as an outline target in the design of this GaN-based charger.

OBC Charger Specifications

Wide input and output voltage range specifications are the main challenges when it comes to realizing a high-power density OBC solution. The variable grid voltage in different geographic regions also makes the design of a PFC rectifier stage difficult. The output voltage range (which is determined by different EV battery voltages) presents a challenge for the dc-dc stages. These require making an undesirable choice between accepting hard-switching losses or increasing RMS currents.

A further complication is the fact that, as more renewable forms of electricity are supplied to the grid, EVs, while connected, are considered as a way to stabilize the grid by providing peak power trimming, and therefore require an OBC with bidirectional power processing. Finally, OBCs must be able to operate both from single- and three-phase grid supplies.

Assuming that the available per-phase current is limited by a fuse, in European residential settings, a 230-Vrms (line-to-neutral) phase with a 16 A-rated fuse can provide single-phase power of 3.6 kW and three-phase power of 11 kW. While this is suitable for a traditional three-phase OBC system (e.g., one using a Vienna Rectifier as the PFC stage), there will be difficulties in making such a system universal.

For example, residences in the U.S. provide a 240-Vrms split single-phase grid interface, rather than three-phase. In this case, the available power is roughly the same—a 40-A fuse limits available power to 9.6 kW—but the split single-phase line is not compatible with the Vienna rectifier without modifications of the EMI filter and the addition of a fourth bridge leg.

Topology Selection

For demonstrating a path toward highest power densities in OBCs, a 10-kW EV-charger design with 10 kW/L with specs very similar to those of an OBC is taken as a basis (see the Table). This EV charger design used a Vienna rectifier PFC with a regulated split dc-link, to which four cascaded dual active bridge dc-dc converters (DABs) with 600-V rated GaN HEMTs were connected for output voltage regulation.

Table. Design specifications for 10-kW EV charger.

Parameter	Value
Rated output power	10 kW
Input voltage	3Φ, 320 to 530 V_{ll} rms
Output voltage	250 to 1000 Vdc
Max. output current	25 A
EMI compliance	Class B

DABs are inherently bidirectional topologies and can operate with ZVS in both buck and boost mode, making them suitable for high-frequency operation in EV chargers and OBCs. Replacing the rectifier diodes with active switches enables synchronous rectification and fully bidirectional power conversion.

Three key features allow an increase in the power density of this design. First, a novel 1/3-PWM synergetic modulation scheme operated at 560 kHz uses a dc-dc stage to control the dc-link voltage so that in the ac-dc stage only one of the three phases are switching at any time. Secondly, the DABs are modulated using the degrees of freedom of the duty cycles, phase shift and also the switching frequency to achieve ZVS over a wide input and output voltage range.

Finally, GaN GIT HEMT devices have small output capacitance for the same on-resistance when compared to silicon devices, enabling full ZVS at lower currents. These allowed the uncased power density of the final EV charger design (Fig. 4), which measured 17.8 x 400 x 140 mm, to be 10 kW/L.

Fig. 4. PCB of the GaN-based EV charger solution.

The waveforms for the DAB design are shown in Fig. 5.

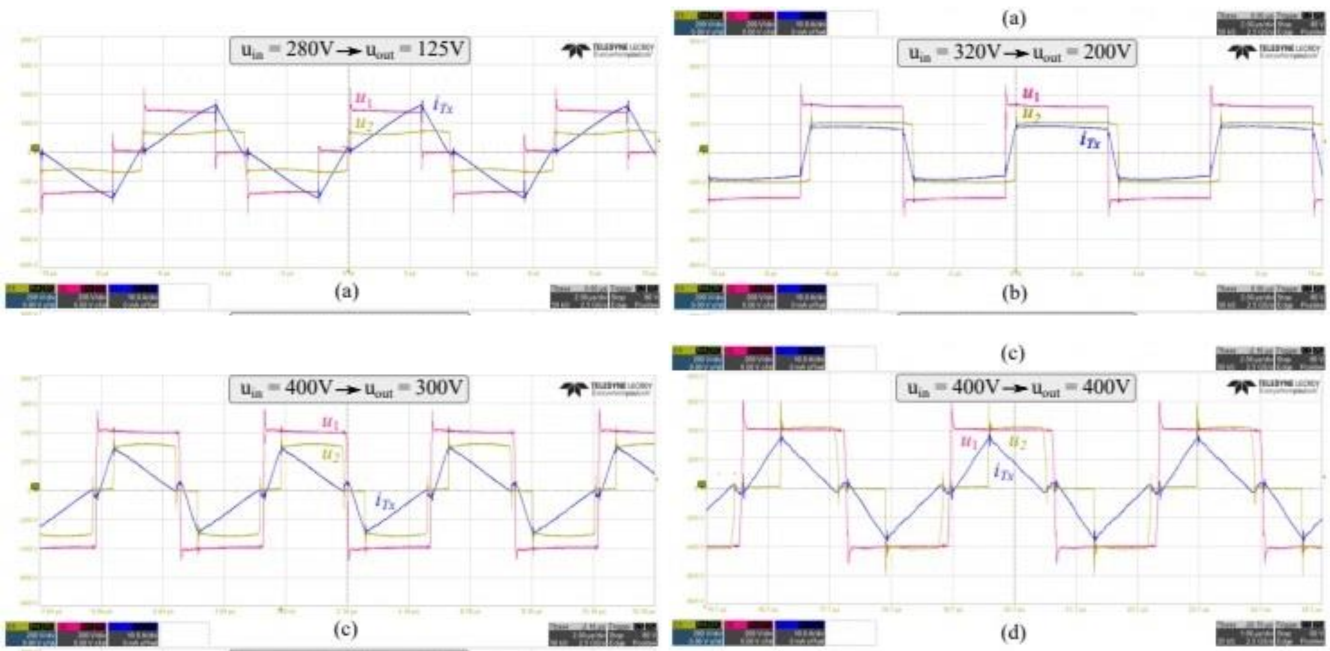

Fig. 5. Key waveforms for OBC.

Conclusion

GaN HEMT devices, with their ability to perform soft and hard switching at high switching frequencies, enable the use of advanced topology, modulation, and control schemes. Infineon has shown that USB-C and EV OBC chargers, which combine the requirement for wide input and output voltage ranges with high power density can be well served by these devices in the future. To learn more about Infineon's HEMT GaN solutions see the reference.

Reference

[GaN HEMT – Gallium Nitride Transistor page](), Infineon website.

About The Authors

Since January 2017, Matthias Kasper has been part of the Systems Innovations Lab at Infineon Technologies Austria where in his role as lead principal engineer he works on novel topologies, control schemes, and multi-objective optimization routines. He has authored and co-authored more than 20 scientific publications and holds 12 international patents. Matthias received the M.sc. and Dr.sc. degrees in electrical engineering from the Swiss Federal Institute of Technology (ETH) Zurich, Switzerland. In his PhD at the Power Electronic Systems Laboratory at ETH Zurich he dealt with multi-cell converter systems for different applications.

Since 2021, Jon Azurza Anderson has served as the senior staff engineer at Infineon Technologies Austria where he is part of the Systems Innovations Lab, working on novel topology, modulation and control methods. He has authored and co-authored more than 15 scientific publications and has several international patent applications pending. Jon received his B.Sc. degree in industrial technology engineering from TECNUN School of Engineering of the University of Navarra, and his M.Sc. and Ph.D degrees in electrical engineering from ETH Zurich. During his Ph.D. studies at the Power Electronic Systems Laboratory at ETH Zurich he focused on ultra-high efficiency three-phase multi-level PWM converters.