GaN Power Behind Mild Hybrid Vehicle Electrification

The hybrid vehicle market has more than doubled from 2017 from 2.0 to 5.1 percent [1] and by 2025, one of every 10 vehicles sold worldwide is projected to be a 48 V mild hybrid. 48 V systems boost fuel efficiency, deliver four times the power without increasing engine size, and reduce carbon-dioxide emissions without increasing system costs. A 48 V mild hybrid is estimated to provide 70 percent of the benefit of a high-voltage hybrid at 30 percent of the cost while boosting electrical power available in the vehicle from 2.5 kilowatts (kW) to 10 kW [2]. These systems will require a 48 V – 12 V bidirectional converter, with power range between 1.5 kW and 6 kW. The design priorities for these systems are size, cost, and high reliability.

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This article discusses the design of a 2 kW, two-phase 48 V/12 V bi-directional converter using GaN FETs in QFN packages, achieving 96% efficiency that is targeted for the 48 V mild hybrid system. The solution is scalable; two converters can be paralleled for 4 kW, three converters for 6 kW or only one phase can be used for 1 kW. Furthermore, the heatsinking capability can be considered infinite given the ultimately function will be inside a vehicle with the unit mounted to the chassis having a significantly larger heat flux capability compared to the losses generated.

Design of the 48V/12V Bi-directional DC/DC Converter

A simplified block diagram schematic of the bi-directional DC-DC converter is shown in Figure 1. The synchronous buck/boost converter is the simplest bi-directional converter, wss selected as the base topology. Other supporting circuitry includes current sensors, temperature sensor, digital controller, and housekeeping power supply.

GaN FETs suitable for 48 V applications typically have 4 times better figure of merit (die area · times $R_{DS(on)}$) compared to equivalent MOSFETs [3]. For the same gate voltage of 5 V, GaN FETs have at least 5 times lower gate charge than MOSFETs. Other important advantages of GaN FETs include lower C_{OSS}, faster voltage transition, zero reverse recovery and they are physically smaller.

The GaN FET chosen for this design is the EPC2302 [4]. It has a low inductance 3 x 5 mm QFN package with exposed top for excellent thermal management. With 1.8 mΩ $R_{DS(on)}$, the rated peak DC current is 101 A. Therefore, the two-phase approach is selected so that the FET current requirement is reduced, i.e., at 14 V 2 kW output, the DC current in each phase is 70 A. This also reduces the current rating requirement for the inductors.

The MPQ1918-AEC1 [5] gate drivers in this design are AEC-Q100 qualified and use bootstrap technique with voltage clamping for driving the high side FET. These drivers also have fast propagation times and excellent propagation delay matching of less than 1.5 ns typical.

Vishay IHTH-1125KZ-5A series inductors [6] offer high current ratings for the inductance. In this design, the 1.0 μH inductor and 500 kHz switching frequency was selected, resulting in 80 A peak inductor current.

To ensure accurate phase current balancing, current sensing using precision shunt resistor is preferred over inductor DCR current sensing. However, shunt resistors that are rated for above 70 A usually have large footprints, and therefore high parasitic inductance. This inductance can result in high noise that saturates the current sense amplifier and voids the measurement. A simple solution is to add an RC filter network with a matched time constant. MCP6C02 current sense amplifier is used in this design, with a maximum bandwidth of 500 kHz and 50 V/V gain. This results in 10 mV/A total current sensing gain for 0.2 mΩ shunt.

Symmetrical layout between the two phases is also critical in phase current

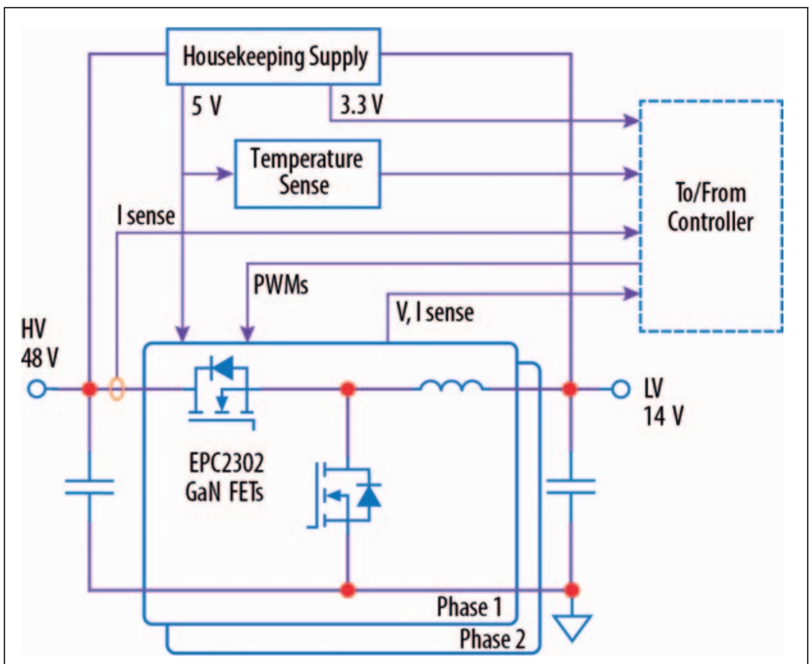


Figure 1: Simplified schematic diagram of the multi-phase bi-directional converter

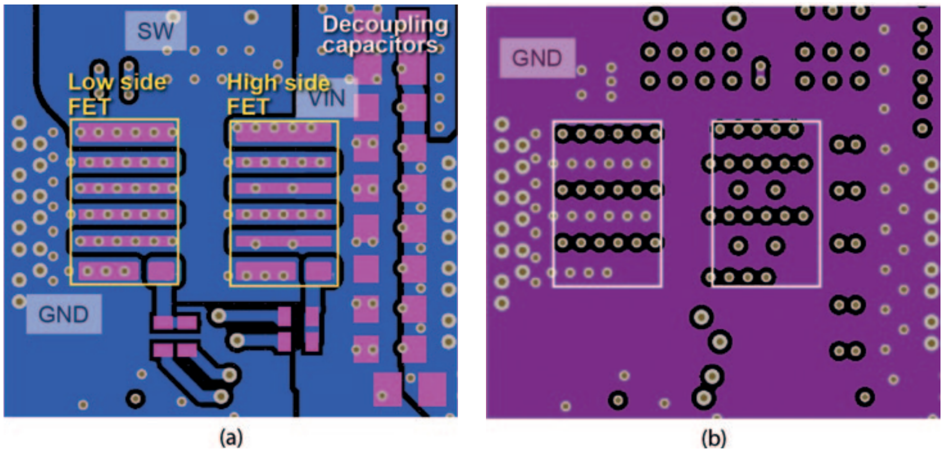
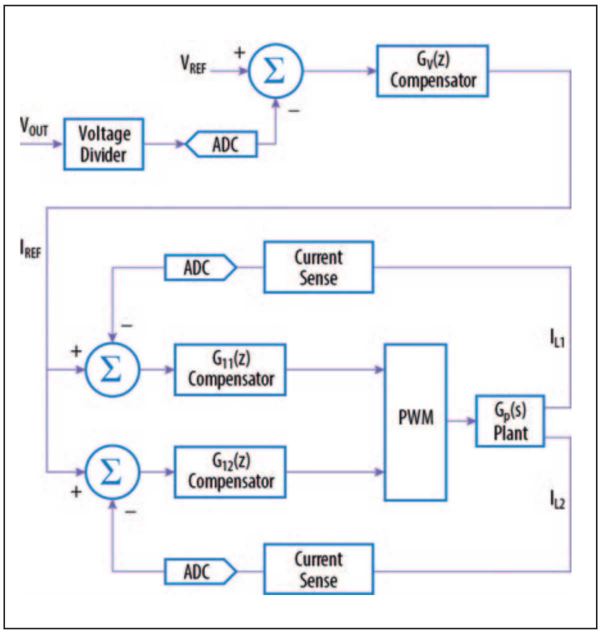
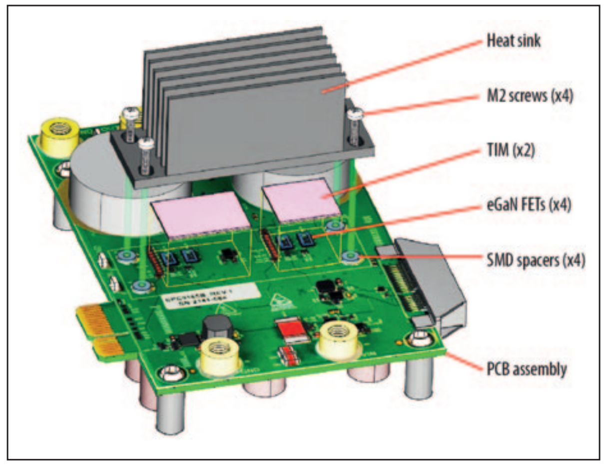


Figure 2: **Example layout of the top two layers of the printed circuit board around GaN FETs; (a) top layer consisting of ground (GND), switching node (SW) and input (VIN) nets, and (b) middle layer 1 of solid ground plane**





LEFT Figure 3: **Digital average current mode control diagram**

ABOVE Figure 4: **Heatsink installation view, showing the metal spacer, thermal interface material**

balancing and minimizing other effects from mismatch, such as gate drive delay, switching transition speed, overshoot, etc. Figure 2 shows the layout example around the GaN FETs in this design, which utilizes the internal vertical layout technique [3] by placing the decoupling capacitors close the FETs with a solid ground plane underneath.

Digital control

A dsPIC33CK256MP503 [5] digital controller from Microchip is used in this design. It is a 16-bit processor with a maximum CPU speed of 100 MIPS. The pulse- width modulation (PWM) module can be configured in high-resolution mode, resulting in 250 ps resolution in duty cycle and dead times, allowing accurate adjustment of dead times to fully exploit the high performance of GaN FETs.

Digital average current mode control is implemented for both buck and boost modes. The current sensing circuitry consists of sense resistors and differential amplifiers. In this design, low loss 0.2 mΩ sense resistors and low-noise amplifiers MCP6C02 are used. The control block diagram is shown in Figure 3. The same current reference IREF is used for the two independent current loops. As a result, the current in both inductors will be regulated to the same value. The bandwidth of the two inner current loops are set to 6 kHz, and the outer voltage loop bandwidth is set to 800 Hz.

Thermal management

At full output power of 2 kW, a heatsink is required for the GaN FETs. A standard commercially available 8th brick heatsink is used. Four metal spacers are installed on the PCB to provide the appropriate clearance for the heatsink mounting. A thermal interface material (TIM) is required between the FETs and heatsink. Usually, the material needs to have a) mechanical compliance due to compression, b) electrical insulation and c) good thermal conductivity. In this design, a TIM with 17.8 W/mK is used. Figure 4 shows the 3D heatsink installation view.

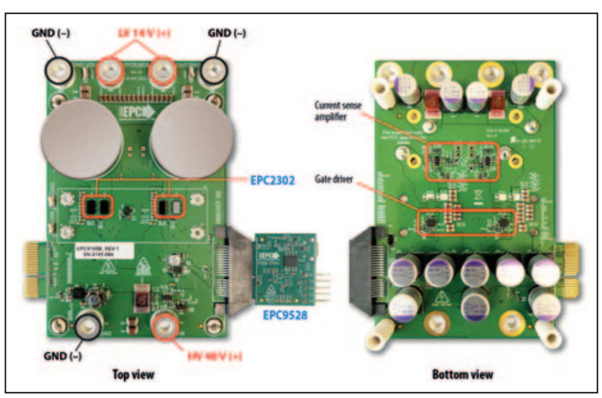
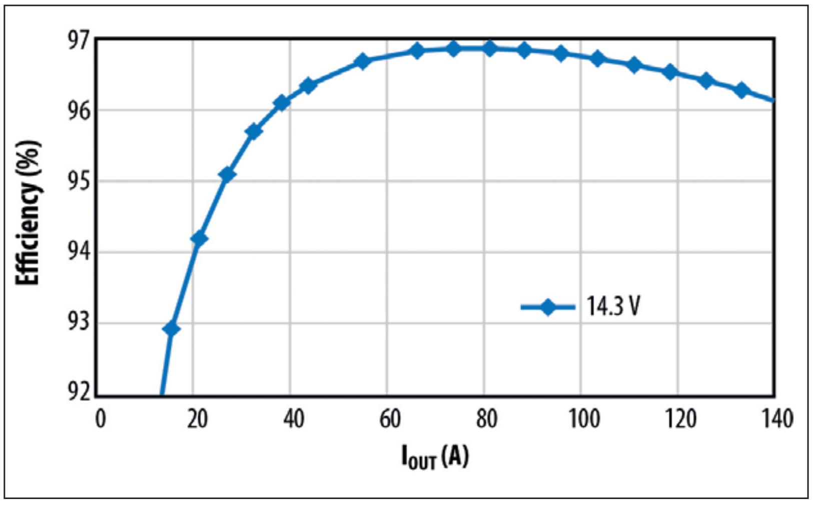
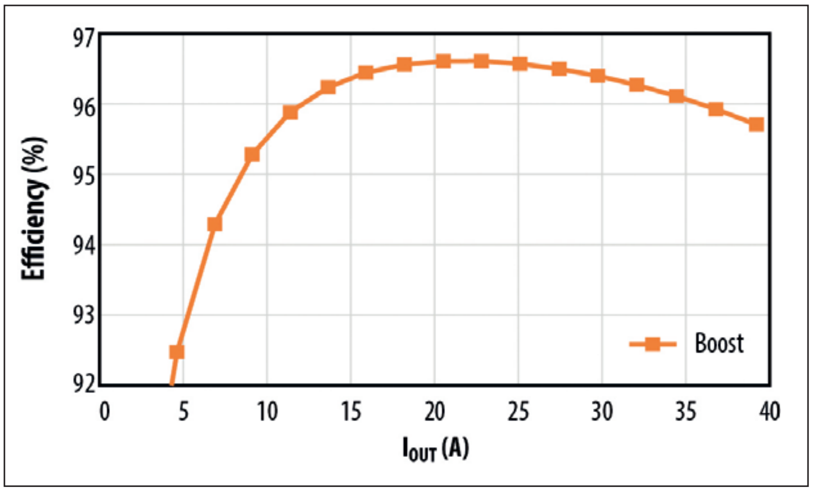


Figure 5: **Photo image of the EPC9165 converter with the EPC9528 dsPIC33CK controller module attached**



LEFT Figure 6: Measured converter efficiency at 500 kHz, 48 V input and 14.3 V output



LEFT Figure 7: Measured converter efficiency at 500 kHz, 14.3 V input and 48 V output

Design validation results

Figure 5 shows a photo of the EPC9165 [6] converter without the heatsink mounted. The dimensions are 4.3x2.8x1.6 inches (108 mm x 70 mm x 40 mm) excluding the edge connectors.

With the heatsink installed and 1700 LFM airflow, the converter was operated at 48 V input, 14.3 V output and tested at 500 kHz, and the efficiency results are shown in Figure 6. At 500 kHz, using a 1 µH inductor, the converter achieved a peak efficiency of 97 %. The converter was also tested at 14.3 V input and 48 V output for boost mode operation, as shown in Figure 7.

At full load, EPC eGaN FETs can operate with 96 % efficiency at 500 kHz switching frequency, enabling 1 kW/phase compared to silicon-based solutions, which are limited to 600 W/phase due to the limitation on the inductor current at 100 kHz maximum switching frequency.

Conclusions

With increasing legislation aimed at higher fuel efficiency standards, vehicle manufacturers are searching for cost-effective solutions to meet these demands while still providing the power required for ever-increasing electronically driven functions. This article introduced a bi-directional high power converter for mild-hybrid cars and battery power backup units using four EPC2302 GaN FETs. When converting between 48 V and 14.3 V, the efficiency exceeds 96 % with 500 kHz switching frequency. This scalable solution can be used to meet the power requirements of the latest 48 V mild hybrid systems.

References

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