Automotive Buck/Reverse-Boost Converter with GaN for Efficient 48 V Power Distribution

Demonstrating the design of a bi-directional DC-DC converter for automotive 48 V power distribution, showing how GaN technology is a powerful enabler for efficient electrification.

The trend towards increasing electrification in the automotive industry enables car makers both to deliver new innovations to market cost-effectively and to meet increasingly stringent emissions legislation. Raising the vehicle's main bus voltage to 48 V helps meet the demands of power-hungry systems such as the start-stop motor/generator of a mild hybrid vehicle, as well as loads such as electric power steering, electric supercharging, and vacuum and water pumps.

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Compared to the traditional 12 V automotive power standard, 48 V distribution can deliver four times the electrical power without increasing cable thickness, weight, and cost. By 2025, one in every 10 vehicles sold worldwide, is projected to be a 48 V mild hybrid.

However, dropping established 12 V electrical systems immediately is not an economical option. In practice, 48 V and 12 V infrastructures will coexist in vehicles for several generations to come. To make such a dual-voltage setup work satisfactorily, each being powered from 48 V and 12 V batteries respectively, a bidirectional DC-DC converter is needed to transfer power seamlessly between the two battery voltages. Depending on the vehicle, the required power rating of the converter can range from about 1.5 kW to 6 kW.

GaN and Power Conversion

When designing an automotive converter, size, cost, and reliability are critical factors. To meet these criteria, the simplest bi-directional topology; the synchronous buck/reverse-boost converter, is chosen. Maximising energy efficiency is also paramount and, here, designers can take advantage of gallium nitride (GaN) technology to achieve significantly greater efficiency than is possible using traditional silicon power transistors. Gallium nitride benefits from exceptionally high electron mobility as well as low temperature coefficient, which allows power transistors to have very low on-resistance (R_{ON}) thereby minimising on-state conduction losses. The lateral transistor structure also results in exceptionally low gate charge (Q_G) with zero reverse-recovery charge (Q_{RR}). In addition, GaN FETs also have much lower output capacitance (C_{OSS}) than comparable MOSFETs [1].

GaN FETs suitable for 48 V applications have about four times better figure of merit (die area x R_{ON}) compared to similar MOSFETs. For the same gate voltage of 5 V, GaN FETs have at least five times lower gate charge than silicon MOSFETs. As a result, GaN FETs can operate more efficiently and at high switching frequencies than silicon MOSFETs, allowing designers to specify smaller capacitors and inductors in their designs. With lower losses across the switching and on states, the heatsink size can also be reduced, ultimately enabling smaller, slimmer module or permitting higher power ratings within the same footprint. Ultimately, this gives vehicle designers extra freedom to pack more new features within the tight space constraints presented by today's vehicles.

Designing the Converter

Figure 1 shows a simplified schematic block diagram for a 1.5 kW bi-directional 48 V/ 12 V converter, which can be scaled to 3 kW relatively easily by paralleling two converters to make it four phases. The two-phase design shown in the diagram can operate up to 1.5 kW with a maximum current of 62.5 A per phase on the 12 V port. This is made possible by using the EPC2206 eGaN® (enhancement-mode GaN) AEC-Q101 qualified FET, which has 2.2 mΩ R_{ON} and rated peak DC current of 90 A. The two-phase design also reduces the required current rating of the inductors.

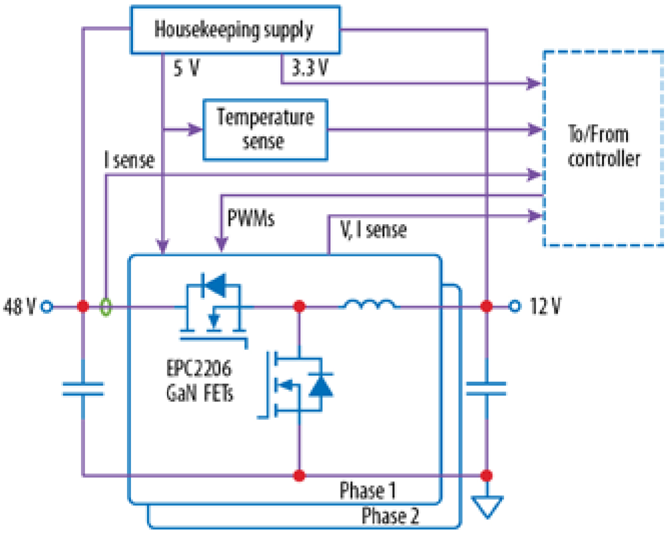


Figure 1: Simplified schematic of two-phase bi-directional converter with eGaN FETs.

In this design, the inductor values and switching frequency are determined using an analytical loss model so that the efficiency at 50% of full rated power is maximized. With the selected 2.2 µH inductor, as shown, and 250 kHz switching frequency, the peak inductor current is 70 A.

To ensure accurate phase-current balancing, current sensing using a precision shunt resistor is preferred over inductor DCR current sensing. However, shunt resistors that are rated for above 70 A usually have a large footprint and therefore also high parasitic inductance that can result in high noise, which can saturate the current-sense amplifier and thus void the measurement. A simple solution to overcome this problem was to add an RC filter network with a matched time constant that cancels the shunt inductance. This design uses a current-sense amplifier with a maximum bandwidth of 500 kHz and 50 V/V gain, which results in 10 mV/A total current-sensing gain when used with a 200 µΩ shunt resistor.

It is also critical to ensure a symmetrical layout between the two phases, so that phase currents are balanced and any effects due to mismatching of gate drive delay, switching transition speed, overshoot, or other parameters, are minimised. The internal vertical loop [2] approach when designing with GaN power devices is to place decoupling capacitors close to the FETs and position a solid ground plane beneath. The microcontroller chosen for this application has a high-resolution PWM module that allows accurate control of the duty cycle and dead-time of 0.25 ns, permitting these to be optimised to take full advantage of the GaN FETs performance.

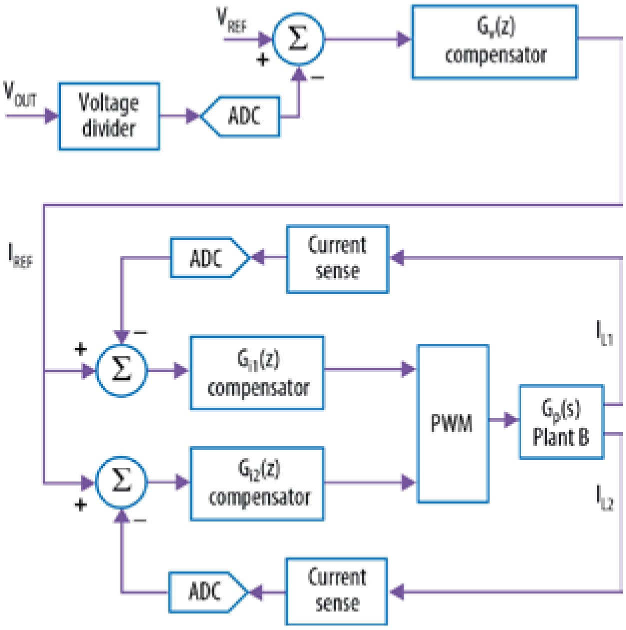


Figure 2: Digital average current mode control diagram.

Digital average current mode control is implemented for both buck and boost modes. The control block diagram is shown in Figure. 2. Using the same current reference, I_{REF}, for the two independent current loops regulates the current in both inductors to the same value. The bandwidth of the two inner current loops is set to 6 kHz, and the outer voltage loop bandwidth is set to 800 Hz.

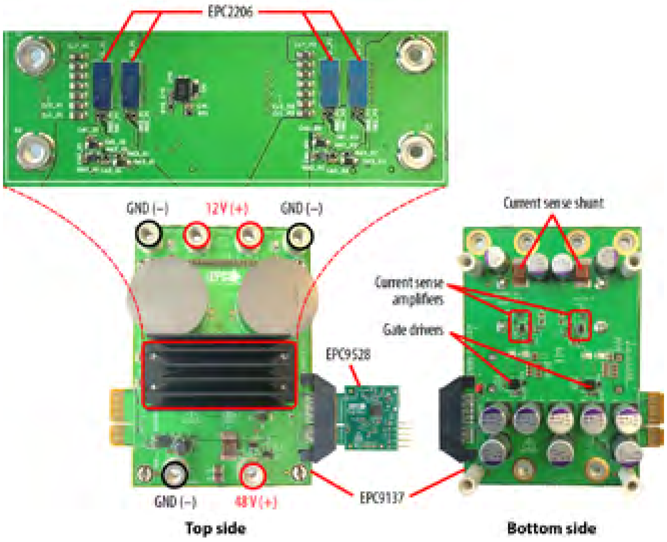
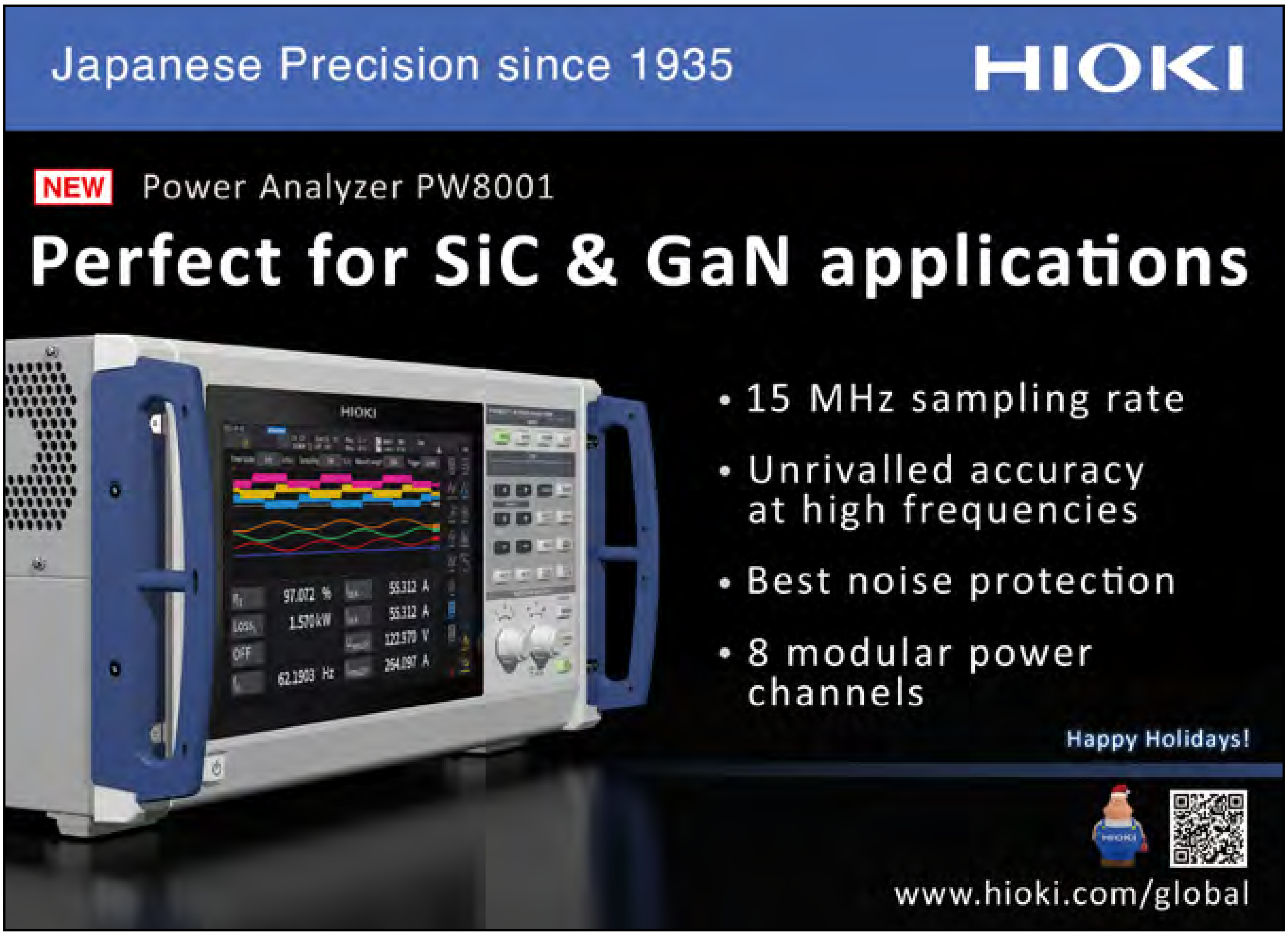


Figure 3: Photo of the EPC9137 converter with the EPC2206 GaN FETs.



The GaN FETs require a heatsink to operate at the full output power of 1.5 kW. A standard commercially available 1/8th-brick heatsink is used. Four metal spacers are installed on the PCB to provide the appropriate clearance for the heatsink mounting. An electrically insulating thermal interface material (TIM) with thermal conductivity of 17.8 W/mK was applied between the FETs and heatsink.

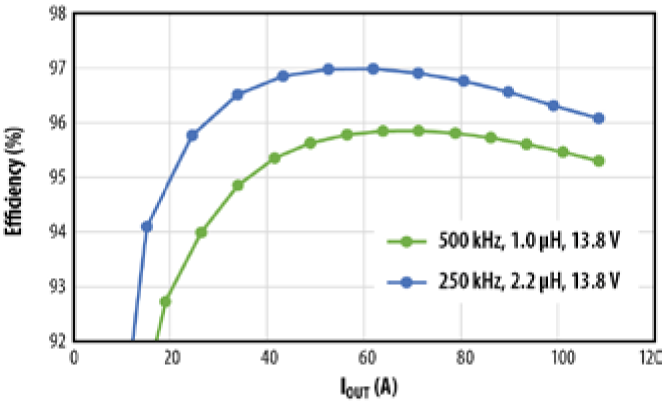


Figure 4: Measured converter efficiency of the EPC9137 at 250 kHz and 500 kHz, 48 V input and 13.8 V output.

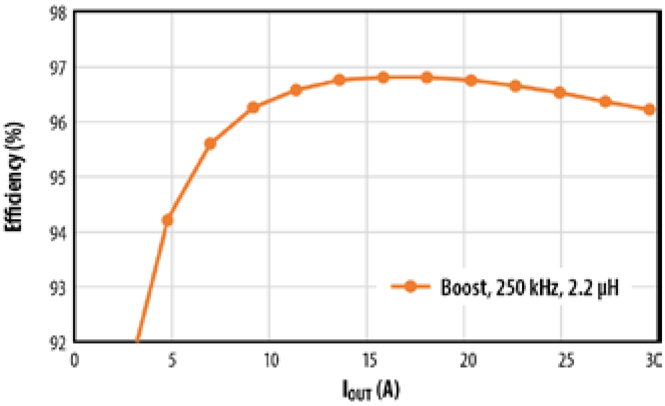


Figure 5: Measured EPC9137 converter efficiency at 250kHz, 13.8 V input and 48 V output.

Performance Analysis

Figure 3 shows a photo of the EPC9137 [5] converter. With the heatsink installed and 1700 LFM airflow, the converter was operated at 48 V input, 13.8 V output and tested at both 250 kHz and 500 kHz. Figure 4 shows the efficiency results. At 250 kHz, using a 2.2 µH inductor, the converter achieved a peak efficiency of 97%. When operated at 500 kHz, using a 1.0 µH inductor, the peak efficiency was 95.8%.

The EPC9137 converter was also tested at 13.8 V input and 48 V output for boost-mode operation, as shown in Figure 5.

At full load, EPC eGaN FETs can operate with 96% efficiency at 250 kHz switching frequency, enabling 750 W/phase compared to silicon-based solutions, which are limited to 600 W/phase due to the limitation on the inductor current at the 100 kHz maximum switching frequency.

Conclusion

Car makers facing demands to increase the pace of vehicle electrification, both to compete in the marketplace and to meet toughening environmental legislation. This design example for a bi-directional DC-DC converter shows how EPC's automotive-qualified eGaN FETs, such as the EPC2206, can help integrate a 48 V bus, needed to electrify power-hungry loads and meet rising power demands throughout the vehicle. When transferring power between 48 V and 12 V domains, the EPC9137 converter achieves maximum efficiency greater than 96% with 250 kHz switching frequency, and above 95% at 500 kHz.

References

[1] A. Lidow, M. De Rooij, J. Strydom, D. Reusch, and J. Glaser, GaN Transistors for Efficient Power Conversion, 3rd ed. John Wiley & Sons, 2019. ISBN: 978-1119594147.

[2] D. Reusch and J. Strydom, "Understanding the Effect of PCB Layout on Circuit Performance in a High-Frequency Gallium-Nitride-Based Point of Load Converter," in IEEE Transactions on Power Electronics, vol. 29, no. 4, pp. 2008-2015, April 2014, doi: 10.1109/TPEL.2013.2266103.

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