Modular Approach to Developing SiC Multi-Level Power Converters

Introduction

As the world weans itself off fossil fuels, automotive Original Equipment Manufacturers (OEMs) and their suppliers look toward the semiconductor industry. Not only are they seeking innovation for the powertrain, they need a replacement refuelling approach. Electric vehicles (EVs) require highly efficient power convertors that, on the one side, extend range as far as technically possible while, on the other side, deliver power for charging the EV as quickly as possible. Of course, quality, reliability, and safety requirements need to be fulfilled too.

The semiconductor industry is innovating with wide bandgap (WBG) technology, and Silicon Carbide (SiC) is well suited to the high voltages, powers, and reliability demands. Passive component manufacturers are also working hard to improve their offering, especially around inductors, as powers increase along with switching frequencies. And researchers continue to explore power converter topologies and the capabilities that digital control can offer us.

The demand is clear. Worldwide, EV revenue is expected to reach over $560 billion in 2023 and grow at more than 10% per year[1]. That's a significant portion of a worldwide passenger car market that should reach $1.93 trillion[2]. And while plug-in hybrids (PHEV) make up around 27% of EV sales, this is expected to fall to around 21% by 2028 as bans come into place regarding the sale of petrol and diesel engines. With countries and regions such as the US, Europe, and China driving battery EV (BEV) sales, we could expect to see around 13.5 million such vehicles added to our roads, and infrastructure, five years from now.

But there is a challenge: How can we rapidly innovate in power converter technology while learning how best to deploy the new SiC MOSFET devices that are released each year? After all, efficiency improvements can't be won at a loss of reliability and robustness. Simulation gets you some of the way but, at some point, you're going to have to commit your concept to hardware. It's clear that the current monolithic approach of building a single board to tackle a PFC design, then a motor inverter, followed by a DC/DC converter is inefficient. It slows down the innovation that comes from evaluating different components and their impact on different design approaches.

To tackle this, Toshiba has developed a modular approach to power converter design with its "SiC Cube". By dividing these power applications into their component parts, modular units have been developed that enable power design engineers to rapidly compare alternatives before committing to a final design.

EV Charger Design

A good example is that of EV charger design, currently a growing application space. Both BEVs and PHEVs have an onboard charger (OBC) with a power class of between 3.6kW and 22kW. One, two, or three-phase AC is delivered via a cable from a wall box (home/workplace) or a charging station (street parking). A conventional wall outlet can also be used in combination with an In Cable Control Box (ICCB) when no dedicated electricity outlet is available. This replicates the safety features and communications of a roadside charger or home wall box charging point. Fast DC chargers deliver 200 – 450 VDC at 40 – 300kW, integrating the power conversion and bypassing the OBC of the vehicle, although proposals are in place for voltages of up to 800V.

In both cases, the basic structure of the charger is the same (Figure 1). AC feeds into a power factor correction (PFC) stage that is linked to a DC/DC converter to supply the voltage required by the charging circuitry. Regardless of OBC or fast DC design, many of the requirements are the same. Efficiency is critical to minimize heat dissipation as well as save energy, with designers aiming for better than 99%, along with a target of > 0.9 for the power factor (PF). Design density, which translates to the dimensions of the end solution, and weight are further factors. This helps vehicle designers to

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hide the OBC within the chassis or ensures that fast DC chargers are made of modular elements that can be lifted, installed, or exchanged by a single technician.

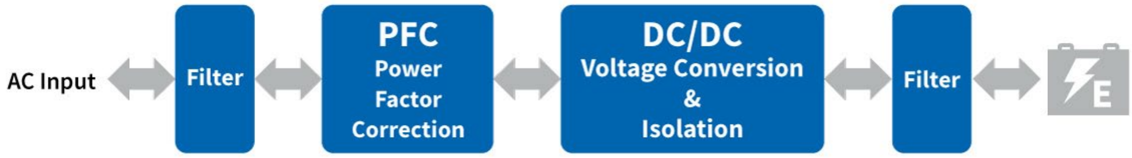

Figure 1: Basic structure of an EV charging system

Chargers are also moving to bi-directional architectures. In the future, vehicle batteries could be used as part of the electrical grid, helping to balance local disturbances or feed the grid during periods of high demand, known as vehicle-to-grid (V2G). Users can expect payment for energy used, helping to offset vehicle running costs. It could also be used to power a home in an emergency, a feature referred to as vehicle-to-home (V2H). Thus, topology choice must also factor in this demand.

In searching for efficient topologies for a bi-directional PFC and DC/DC converter, the totem pole configuration PFC and dual-active bridge (DAB) and LLC converter are often selected. Examining these in more detail, similarities arise with the recurrence of a single bridge leg throughout these circuits. Furthermore, the same bridge leg appears in the design of a motor inverter; another application a design team may wish to evaluate using SiC MOSFETs.

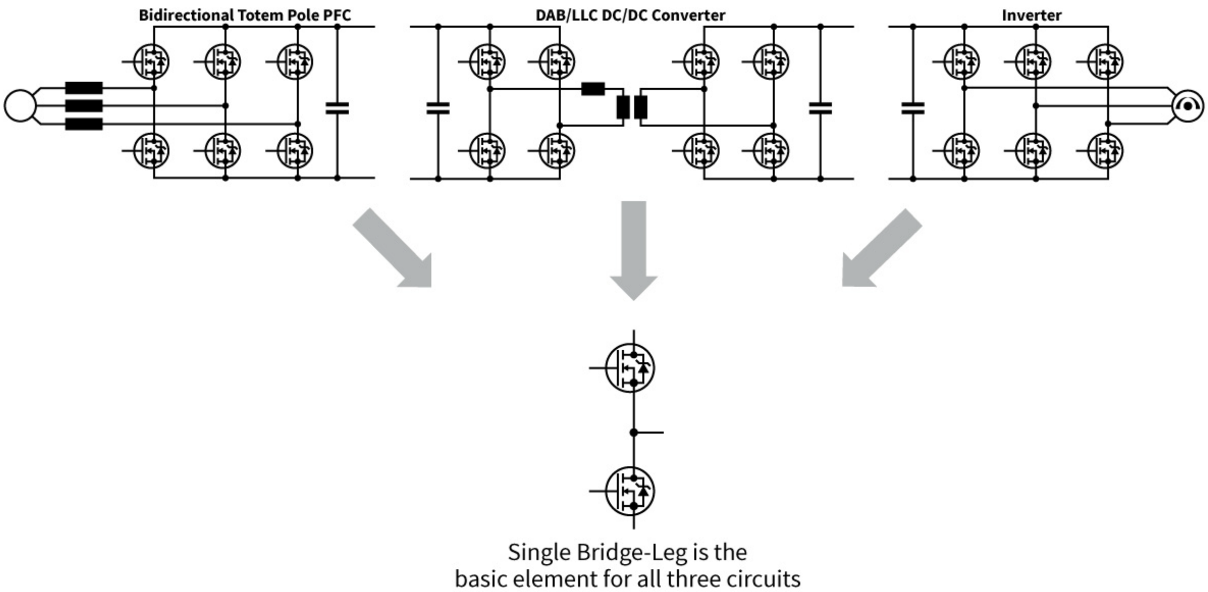

Figure 2: A single bridge leg is common to all three circuits.

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Modularity for Rapid Evaluation

Building a 22kW power application is no simple task. Due to the voltages and currents involved, development requires extra care, as does testing. So, is it possible to come up with a modular design approach that allows simple evaluation of each element of a power converter?

Examining the PFC (Figure 3), we see three clear blocks: the input inductors, the single bridge legs, and the output capacitor. This seems to be a good way of partitioning the design for a modular design where boards can be reused. The capacitor is also common to the DAB/LLC DC/DC converter and inverter. A fourth block is also required: a control system, typically implemented with a microcontroller optimized for digital power applications.

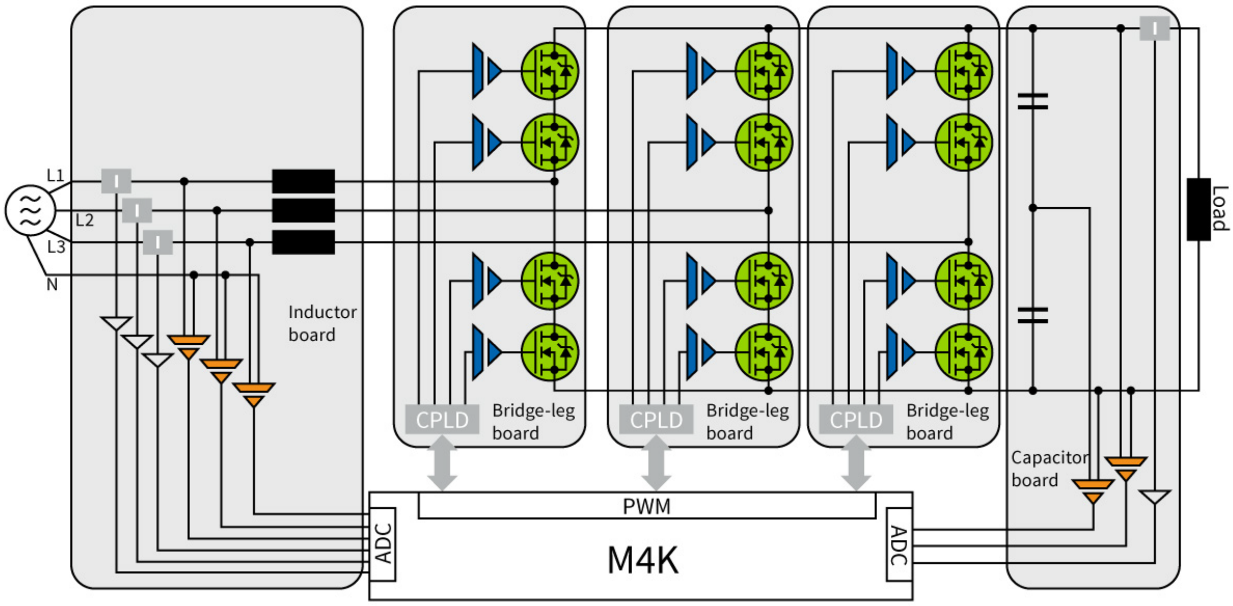

Figure 3: A bi-directional PFC consists of input inductors, switching stages, and output capacitor, coupled with a control system implemented using a microcontroller.

This led Toshiba's engineering team to explore the possibility of a compact, modular PFC design that supported reuse for other power converter applications.

The Modular EV Charger PFC Reference Design Concept, also known as the "SiC Cube", comprises seven printed-circuit boards (PCB). The inner three are the power switches, bridge legs, which stack closely together. On the outsides are the inductor and capacitor boards. Providing both the mechanical and electrical connections are metal spacers. To simplify the PCB design further, copper current rails are integrated into the high-power paths, although the approach sacrifices parasitic inductance over modularity. Monitoring the analogue signals and providing digital control is a microcontroller board that traverses the other five boards (Figure 4).

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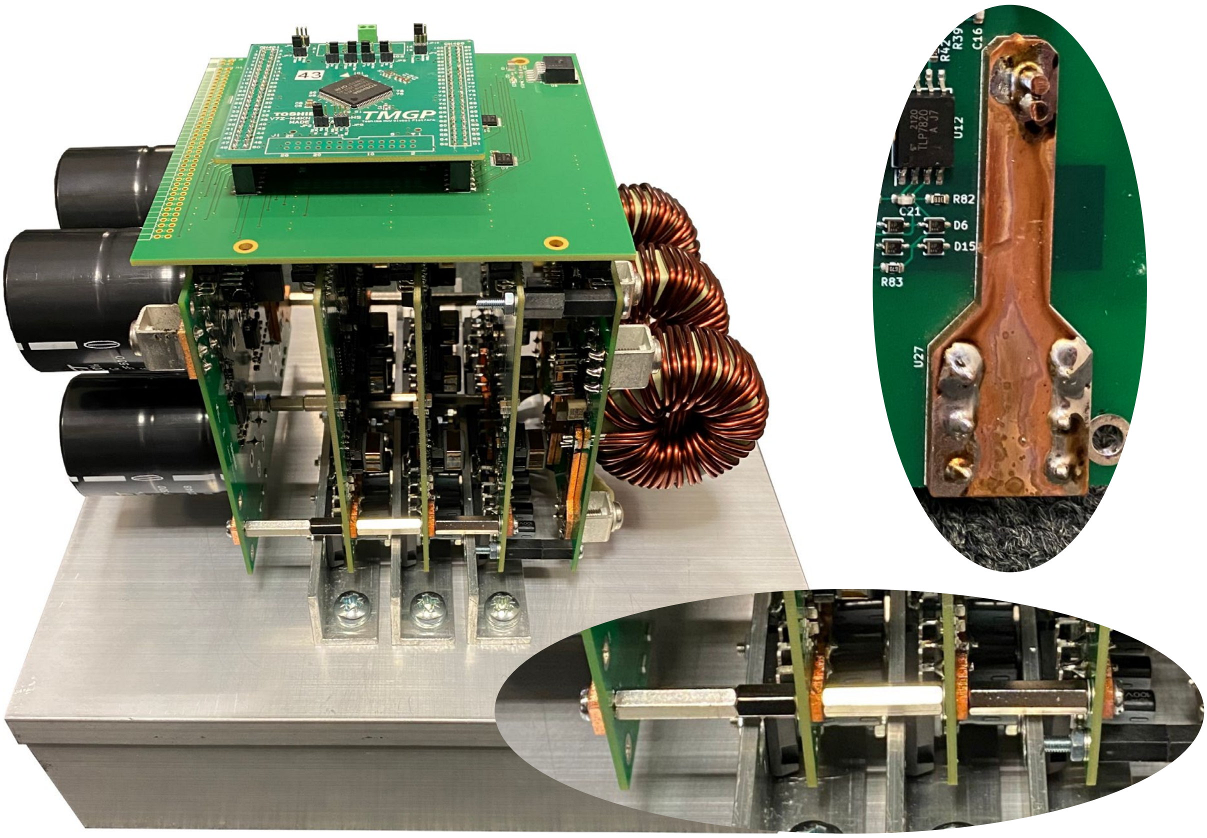

Figure 4: The compact three-phase PFC design with details of the electro-mechanical interconnects and copper rails.

To improve switching efficiency, a three-level bridge-leg design was selected. Multi-level topologies share the thermal load across the switches but with the added advantage of distributing the voltage stresses across multiple MOSFETs. The volt-second (Vs) voltage ripple on the inductors also drops. This allows a low-cost toroid to be used that takes up less space.

Each of the three inner bridge leg boards consists of four SiC MOSFETs, two SiC diodes, four gate drivers, and a complex programmable logic device (CPLD) that handles precise switching timing based on the pulse-width modulated signal from the microcontroller board. The forward voltage of the diodes needs to be as low as possible to minimize losses, and this is an area that has seen ongoing improvement. For example, the third generation of Toshiba's SiC Schottky barrier diodes (SBD) have achieved an industry-leading lowest forward voltage of 1.2 V, 17 percent lower than the previous generation. Improvements in the trade-offs between forward voltage and total capacitive charge, and forward voltage and reverse current, contribute to lower power dissipation and higher system efficiency.

The optically isolated TLP5214A[3] was selected as the gate driver due to its suitability for driving SiC MOSFETs. It offers ±4.0 A current output for fast switching, and photocouplers with long creepage and clearance in its SO16L package for the input control and fault status feedback signals. In combination with an active Miller clamp gate circuitry (integrated into the gate driver) that helps to avoid parasitic dV/dt triggered turn-on, a switching speed of 7 V/ns can be achieved. However, it should be noted that the switching speed has been limited in this design to accommodate the parasitic inductances of the copper current rails used, which are necessary for the modular design approach.

The circuit makes for an excellent match with Toshiba's third-generation SiC MOSFETs[4]. Like previous generation devices, they include a built-in Schottky barrier diode (SBD) with a forward voltage of just 1.35V. The SBD significantly

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minimizes the change in on-resistance over the operational lifetime, ensuring that the design goals can be retained over the life of the application. $R_{DS(ON)}$ × Q_{gd} (gate-drain charge) is 80% lower than second-generation SiC devices, while, the wider V_{GSS} rating of -10V to +25V makes designing an optimal gate drive circuit easier.

The fourth board is for the inductors, supporting three-phase AC with three inductors, and Hall current sensors and isolated voltage measurement in each phase. The fifth is the capacitor board that replicates the current and voltage measurement circuits (Figure 5). Both feed these signals to an edge connector that links to the appropriate inputs of the microcontroller.

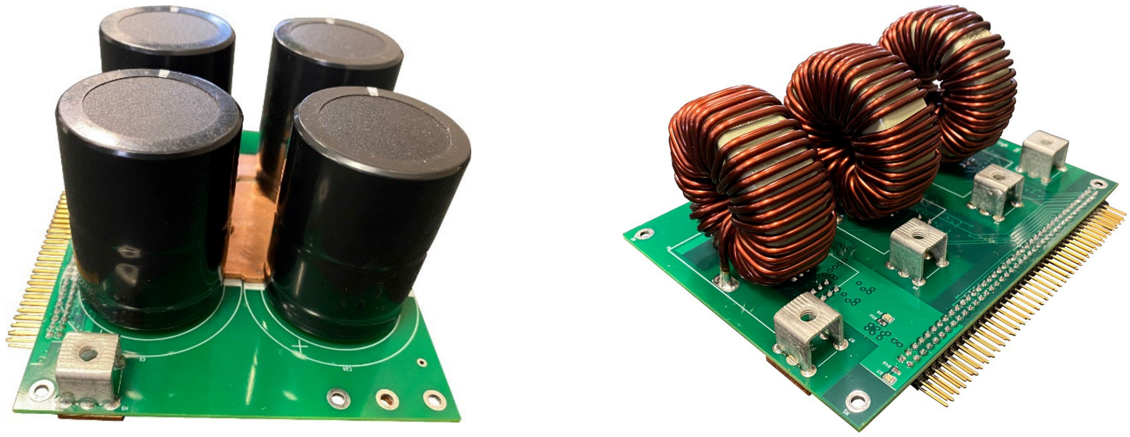

Figure 5: The capacitor (left) and inductor (right) board both use the same current and voltage measurement circuitry.

Voltage is measured differentially using the TLP7820[5] isolated operational amplifier that offers high gain accuracy (±0.5%), small gain drift (0.00012V/°C), and low non-linearity (0.02% for V_{IN} = ±200mV). Furthermore, the amplifier is UL/cUL recognized and VDE/CQC approved. At its input, the design uses a sigma-delta analog-to-digital converter (ADC) driving an LED with its output signal. An optical receiver feeds into an amplifier, which converts the signal back into a differential output voltage through a 1-bit digital-to-analog converter (DAC) and low-pass filter (Figure 6).

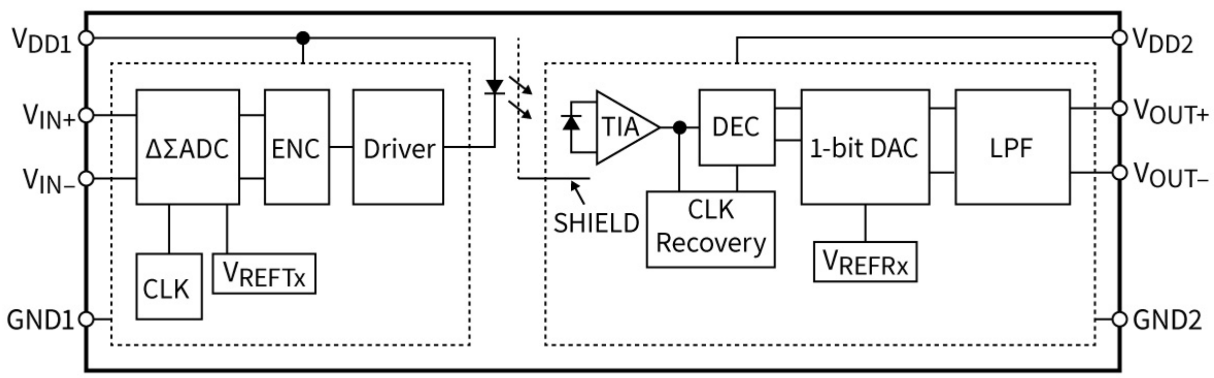

Figure 6: Internal circuit of the TLP7820 optically isolated differential amplifier used for monitoring phase and output voltage.

The sixth board is a backplane that traverses the previous five and has a connector for the seventh board, the microcontroller. This features a device from the M4K group[6] of the TXZ+™ family based upon an Arm Cortex-M4 core

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operating at up to 160MHz. It is suitable for this type of application because of its advanced PWM module that offers a range of control options, including a three-phase complementary output with dead-time control, that can be synchronized with the 12-bit analog-to-digital converter (ADC). Three gain-selectable operational amplifiers are also available. Operating at 2.7V to 5.5V and with up to 256kB flash, 32kB data flash, and 24B SRAM, the family also provides a floating-point unit that can benefit the development of control algorithms. This microcontroller also offers a Vector Engine, a hardware block designed to offload and accelerate complex calculations such as sine/cosine and Clarke and Park transformations.

Overall, the design targets a 22kW output with Toshiba's third-generation SiC MOSFETs, a power efficiency of up to 99%, and a power factor of 0.99. Due to its compact mechanical layout, it should reach a power density of 3kW/dm^3 within a 140 × 140 × 210mm form factor (Figure 7). Additionally, the individual boards can be reused in the design of DC/DC converters or inverter applications.

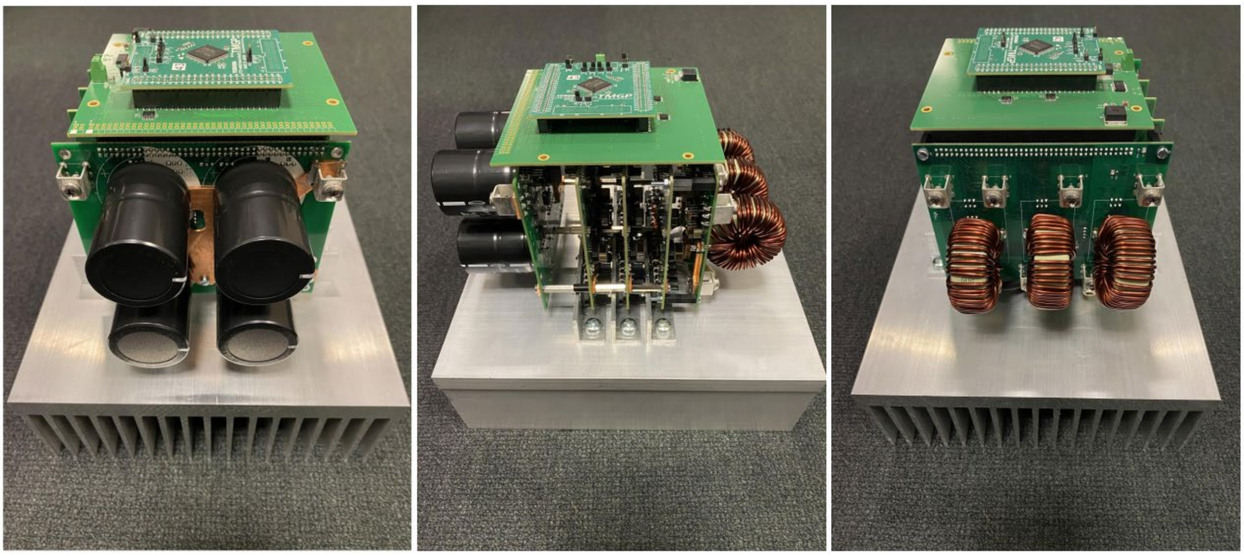

Figure 7: The SiC Cube EV Charger PFC Reference Design Concept showing all seven boards mounted to a PFC system.

Summary

Power converter designers are increasingly turning to SiC MOSFETs to take advantage of their robustness and the improvement in efficiency they offer. However, there is enormous pressure to speed-up development of such applications to support the growth in power converters and inverters while, in parallel, coming to terms with the capabilities of these new devices.

For example, sales of BEVs continue to grow, driven by a personal desire to reduce carbon footprint and/or comply with government mandates. To support the growing number of vehicles expected on our roads, developers need to rapidly innovate in their design of fast DC chargers and OBCs to ensure robust and reliable designs result that are efficient and power dense. Taking a monolithic approach to each and every project that comes in is a slow process.

Toshiba's EV Charger PFC Reference Design Concept, or SiC Cube, makes this easier and, thanks to its modular approach, enables the boards to be trialled in other power conversion applications. This is achieved by speeding up the development processes, making it possible to reuse the fundamental building blocks common across PFCs, DC/DC

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converters, and motor inverters. This helps development teams in their exploration of the benefits of wide bandgap (WBG) technology, such as SiC MOSFETs to benefit from lower $R_{DS(ON)}$, higher switching frequencies, and improved robustness.

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