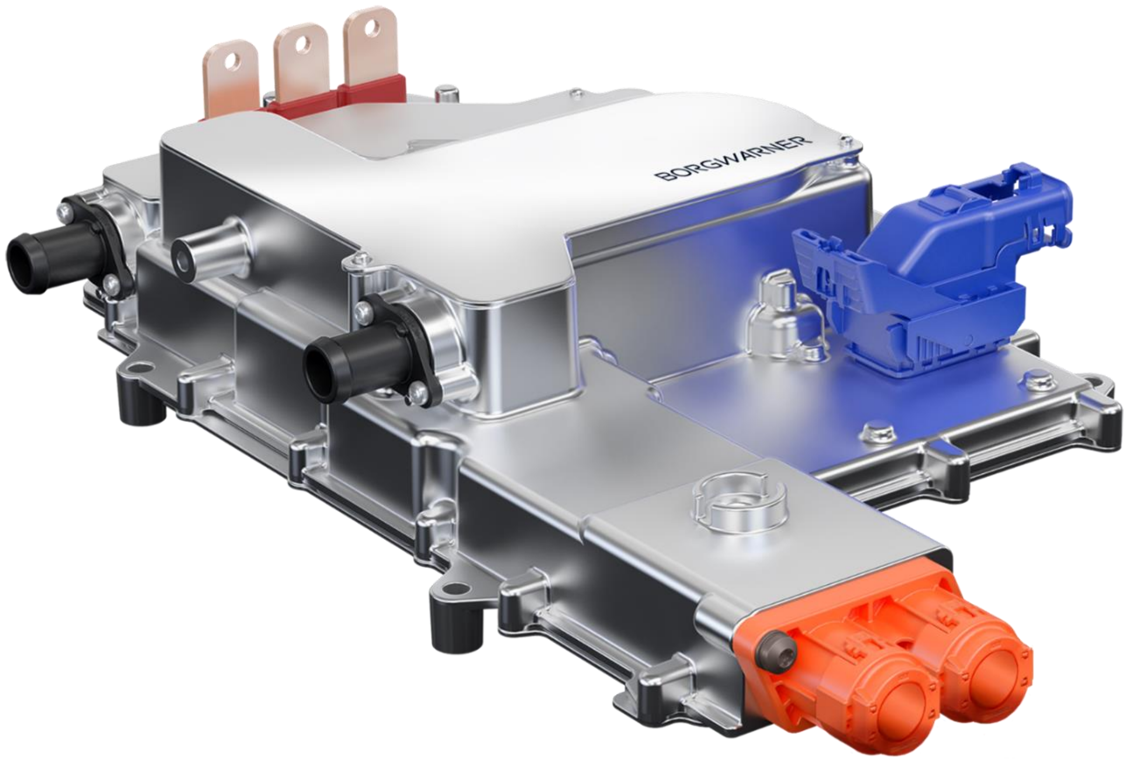

Next Generation Traction Inverter

Safe, Efficient and Compact

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borgwarner.com

BorgWarner has improved the performance, integration and reliability of its inverter technology by redesigning the power, cooling and control systems and simplifying production.

Background and Design targets

As electric propulsion continues to gain market share against the internal combustion engine, it is vital to maintain this momentum by refining technologies in preparation for the next generation of electric drives. Major components such as batteries, inverters and electric motors must become more compact while offering improved safety and efficiency. This paper explores the measures taken by BorgWarner to redesign the traction inverter to meet the latest market demands.

Taking into account the requirements of both passenger cars and medium power commercial vehicles, an 800VDC system was indicated with RMS phase currents of 650A peak/400A continuous to cater for power ratings of up to 400kVA. The power output could be scaled down by modifying the number or size of certain components; for example reducing the silicon carbide (SiC) die count or capacitor footprint. Inverter performance and efficiency should be stable in an environment of -40 to +85°C and at altitudes of up to 5,000m. An IP67 rated enclosure would protect against ingress of dust and water.

The electrical and dynamic safety of a traction inverter are dominant concerns, notable hazards being the high voltage and current values, and the potential for strong acceleration/deceleration. BorgWarner set out to achieve Automotive Safety Integrity Level (ASIL) D, the top safety level defined in the ISO 26262 standard. The company's newly-developed Inverter System Safety ASIC (INSSA) would play an important role in reaching this design target.

It was considered desirable to meet or exceed the US Department of Energy (DOE) Vehicle Technologies Office (VTO) 2025 goal of 100kW/liter power density at a cost of USD2.7/kW or less. To assist in achieving this, BorgWarner limited the design size of the complete inverter package to four liters in volume.

With the basic system parameters determined, BorgWarner identified a number of areas where further innovation could improve existing inverter designs; these are described below.

Implementing design improvements

Power and cooling modules

Power scalability relies on BorgWarner's established Viper switch module. Starting with a single switch module of identical footprint for each power class, the type and quantity of SiC dies and the cooling layout can then be varied to reach the ideal solution for each application.

The improved power device is a single switch package with dual-sided cooling. Uniquely, it accepts various arrangements of different manufacturers' bare SiC dies on the same substrate. The high-temperature SiC devices are assembled using a die-attach process; power connections are screw mounted or laser welded, and auxiliary connections are soldered. A new type of epoxy overmold compound encapsulates the package. The finished module can operate with junction temperatures at or beyond the typical 175°C, reducing system losses and improving current handling without increasing the SiC active material area.

Cooling for the power module is designed for optimum performance but uses simple manufacturing processes, a combination that yields a scalable cooling module to efficiently handle high temperatures at reasonable cost. Aluminum is the standard construction material, with copper substituted where the highest thermal performance is needed, depending on the power devices used in the package. Dual-sided cooling is provided by top and bottom heat sinks featuring a novel heat sink fin design. The fins optimize thermal performance and reduce system pressure drop within the cooling channels, by modifying flow near the fin wall area to improve heat transfer from wall to coolant. Dual-sided cooling also enables different thermal interface materials (TIM) and various joining methods to be used on the top and bottom of the power module. Each heat sink is manufactured by stamping the cover, base and cooling fins from high thermal conductivity copper alloy then brazing the components together.

Controller design with INSSA

BorgWarner's newly developed **In**verter **S**ystem **S**afety **A**SICs (INSSA) have been added to the inverter's electrical control architecture. These enable controller and gate driver circuitry to share a single main board with a reduced footprint, and provide a high reliability feedback loop for sensing, control and actuation. Figure 1 shows a single control/gate driver board with the INSSA outlined in red.

Inverter modifications required to achieve ASIL D compliance inevitably lead to increased package size, component count and cost, but these are significantly offset by the addition of INSSA to the design. Each INSSA helps provide a fully independent power supply to the gate drive circuitry on each side of the high voltage supply, so if a single point electrical fault occurs in the inverter, the system can react independently of micro-

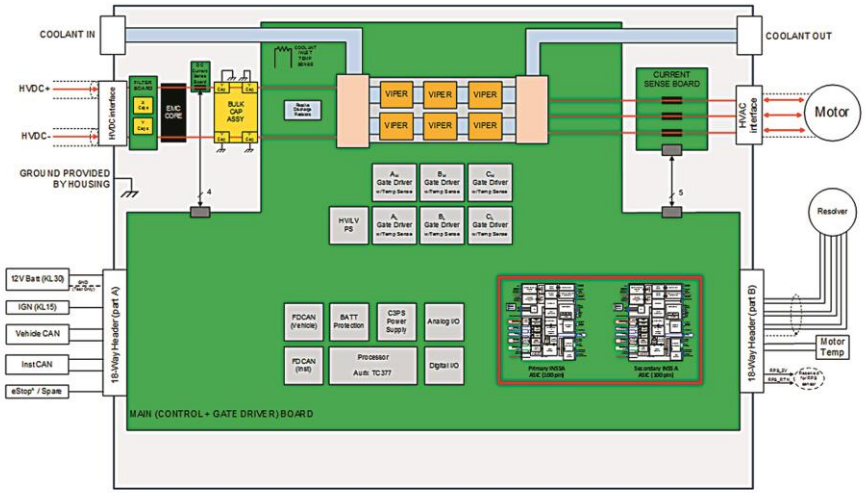

Figure 1: Next generation architecture with INSSA

processor intervention. It continues monitoring the high voltage supply and motor speed, and uses those measurements and the current fault signature to maintain a safe operational state. This is a significant advantage of the latest BorgWarner inverter technology; the INSSA's ability to monitor system diagnostic information and command proper system usage ensures that the high voltage bus is always maintained within a safe range.

INSSA can also save additional space and cost by eliminating the need for large dissipation resistors. Its active discharge feature can instead harness losses across the high voltage power modules to release energy from the high voltage bus lines.

Component integration and assembly

System characteristics such as operating voltage and peak phase current of the electrical machine have a bearing on the design of the inverter components, including power modules and bus bars. These characteristics, plus acceptable voltage ripple and circuit couplings indirectly controlled by inverter switching frequencies and slew rates, also define the physical size of the bulk capacitor, the largest of the inverter components. For ease of inverter scalability and to increase thermal performance and power density, methods of minimizing bulk capacitor size were investigated as part of the design process.

BorgWarner settled on the use of next generation capacitor technology to achieve a significant size reduction but retain the performance and self-healing abilities of conventional capacitors. A further improvement in scalability was gained by segmenting the bulk capacitor into several smaller blocks arranged in parallel, which brings the additional benefits of easier thermal management and reduced equivalent series resistance (ESR). Laser welding the individual blocks to a fully laminated DC bus bar sub-assembly gives the lowest equivalent series inductance (ESL) and maximizes performance. The segmentation of a bulk capacitor into six blocks can be seen in Figure 2.

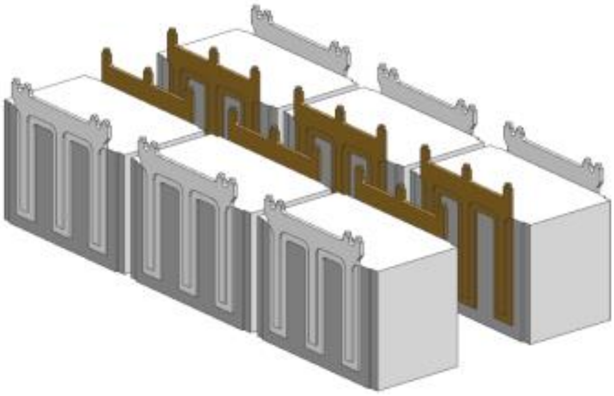

Figure 2: Segmented capacitors and modular bulk construction

The next generation inverter can now be built in fewer stages; the bulk capacitor, HVAC bus bars, HVDC unit, power module and main circuit board are assembled within the main housing, then the cover is mounted. Greater component integration and simplification of the construction process results in an inverter package with a dry weight of approximately 7kg and a sub-four liter active component volume. Figure 3 shows the basic inverter design.

Summary

BorgWarner innovations and design techniques have successfully delivered a safe, efficient and compact next generation traction inverter with industry-leading, fault tolerant control architecture that achieves ISO 26262 ASIL D compliance and the VTO 2025 goal of 100kW/liter power density, all in a cost-balanced package.

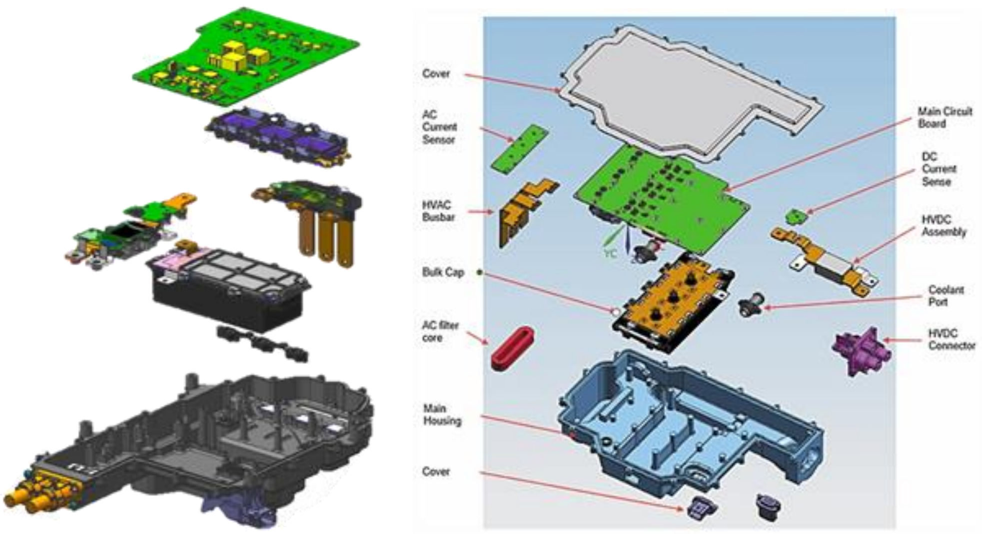

Figure 3: Exploded view of next generation inverter design