Overcoming the multi-discipline design challenges behind EV traction inverters
Electric vehicles (EV) rely on traction inverters to convert the high-voltage DC energy stored in the vehicle’s batteries to drive the AC traction motors. The traction inverter plays a crucial role in driving the vehicle and needs to be extremely robust and reliable, given the high power switching and the likely high dv/dt transients involved. In this white paper, we investigate the role of an EV’s traction inverter, the electrical specifications required for its operation, some of the design challenges engineers face when developing them, and the impact wide bandgap (WBG) devices are having on their design.
A NEW ERA OF ELECTRIC VEHICLES

Electric vehicles (EV) are not a new technology and came about as concerns regarding transportation’s impact on the environment took center stage. It was in 1888 that Andreas Flocken showed off the first practical electric car termed a ‘Dampf-Chaise’ by his local newspaper in Coburg, Germany1. Of course, today’s vehicle owners have benefited from fossil-fuel motive power for so long that a complex array of expectations have formed when it comes to investing in a new car. Because the internal combustion engine (ICE) is a given, we don’t even stop to think about time to refuel, let alone where, nor do we consider range. Instead, we concern ourselves with seats, comfort, practicality, the little luxuries, and price. However, this is changing as government programs and expectations to reduce carbon emissions push us toward cleaner transportation options. Battery electric vehicles (BEV) have been pushed quickly into the public consciousness as automotive newcomers successfully take on the industry giants. Acknowledging today's BEVs' limitations, some manufacturers couple the electric drivetrain with a traditional ICE. These form (plug-in) hybrid versions (PHEV and HEV), thereby upping their green credentials while offering drivers certainty that they will get to their chosen destination.

Currently, worldwide production of EVs is expected to be over 20% by 2025, rising to almost 30% by 2027 (based on strategic analytics forecasts). Japan currently has the lead here with almost double the share of EV production of the next closest region, Europe. Despite the rapid expected uptake around the world, this gap is expected to remain in the short term. However, China is expected to overtake Japan by 2026 thanks to China's EV credit system, regulations, and city policies restricting ICE vehicle sales. (Figure 1).

WHAT MAKES UP THE EV DRIVETRAIN?

One of the last bastions of the mechanical engineer in automotive falls away with the move to electrification. The BEV replaces the ICE with one or more electric motors, while the drivetrain is greatly simplified as there is no need for a complicated gearbox (sometimes any gearbox at all) and clutch (Figure 2). HEVs and PHEVs make for a more complex combination. The ICE may only be present to recharge the battery but may also be used to provide motive power (Figure 3).

![Figure 1: Predicted shares for EV/BEV production in short term](image1)

![Figure 2: Drivetrain configurations for BEVs.](image2)
In addition, the fuel tank makes way for a battery and on-board charging (OBC) system in both BEV and PHEV. Providing anywhere between 200 and 800 V, these batteries also open up new automotive electrical supply system approaches. Whereas vehicles traditionally relied upon a 12 V battery, a higher voltage bus of 48 V is now also in use. This allows power-hungry electrical systems, such as door openers, fans, and HVAC (heating, ventilation, and air-conditioning) to use smaller, lighter-gauge cables.

EVs are generally powered by either an AC permanent magnet machine (PMSM) or an AC induction machine (IM) and these electric machines are also known as EMs. PMSMs evenly distributed windings on their stator that deliver a very low torque ripple and vibration (Figure 4). The rotor assembly makes use of rare-earth magnets that, while very strong, are also expensive. However, thanks to its smooth torque and power delivery, they are often used in EVs without a gearbox, thus saving weight and cost.

IM motors also have stator windings like a PMSM, but the difference lies with the rotor. Instead of magnets, the rotor also has windings and relies on an induced current from the stator to generate a magnetic field and make it turn. Since no magnets are needed, IM motors are much lower cost than PMSMs.

A third option is the switched reluctance motor (SRM). The stator coils are concentrated rather than evenly distributed like the IM and PMSM. The rotor simply consists of steel laminations formed into salient poles. Visually, it looks very similar to a stepper motor. The number of poles on the rotor is less than the number of coil-pairs on the stator. Again, an AC signal must be applied to the coils to generate a rotating magnetic field that the rotor, in essence, follows. Although low in cost, they suffer from high torque ripple, vibration, and noise and are not as efficient as the alternatives.

Almost all production EVs use one of these types of EM, while a few employ two different EMs in their architecture. This allows the benefits of two EM types to be realized, with one motor responsible for responsive acceleration and the other for an efficient cruising speed.
THE TRACTION INVERTER

As indicated, EMs require the application of an alternating current to their stator coils. The coils, conventionally marked U, V, and W, thus need three sinusoidal signals spaced at 120°. This signal is generated by the traction inverter, converting the battery’s DC supply into the AC required by the motor.

The precise application of the high-power, high-voltage AC signal ensures that energy loss is kept to a minimum, and motor torque is maintained at a maximum. This requires a precise understanding of the EM’s rotor angle, something obtained through an encoder or resolver attached to the rotor. Combined with acceleration and deceleration requests from the driver, the traction inverter’s CPU uses complex mathematical algorithms to determine the next phase of motor commutation many times per second.

EM control algorithms aim to keep a 90° angle between the poles of the direct axis of the rotor (D) and the magnetic field, or quadrature axis (Q), generated by the stator coils (Figure 5).

![Diagram of motor control axes](image)

Figure 5: By maintaining a 90° angle between the direct (D) and quadrature (Q) axes, motor control algorithms ensure maximum torque is maintained.

Thanks to the growth of digital signal processing (DSP) techniques, and the integration of suitable instructions into microcontroller (MCU) processor architectures, advanced EM control approaches are available. Known as Field or Vector Oriented Control (FOC/VOC), these generate the sinusoidal signal for the three phases by determining, in real-time, the required output and generate it using a varying duty cycle on a pulse-width modulated (PWM) output. One technique, Space Vector PWM (SVPWM), has, despite its mathematical complexity, proved very popular. Even low-cost MCUs are powerful enough to implement the algorithm and, with suitable integrated resolver/encoder input peripherals and high-resolution PWMs, offer a compact solution. Compared to alternative sinusoidal approaches, the total harmonic distortion (THD) generated is lower, and the maximum fundamental phase voltage amplitude, at \( \frac{V_{DC}}{\sqrt{3}} \), is higher.

A basic, six-step modulation technique is also in use in some EVs. The approach uses SVPWM in the linear modulation region, moving to a six-step technique in the over-modulation region (Figure 6). This allows the full DC-link voltage to be applied to the EM, increasing torque in the flux-weakening region, but raises challenges regarding current harmonics and torque control.

![Diagram of six-step modulation](image)

Figure 6: Six-step modulation, as used for brushless DC motors (BLDC), has some limited use in a few EV traction inverter designs.

With 30 kW continuous power delivery expected and peaks of up to 200 kW, the topology often used to generate the AC control signal in such designs is the voltage-source inverter (VSI). This is well suited to the forward voltage blocking, bidirectional current flow capabilities of IGBT power devices (Figure 7). The DC-link capacitor reduces the ripple voltage and
current caused by the switching of the IGBTs, which also reduces high-frequency current harmonics. Higher power levels are accommodated by placing more power devices in parallel. This can also minimize ripple when using interleaving.

Some traction inverter designs additionally boost the high-voltage battery output to a higher level, known as a DC boost. This provides the inverter with a controlled higher DC voltage (such as 800V), reduces ripple, and relaxes the DC-link capacitor’s requirements, one of the system’s most expensive components. The dual-switch implementation here in the VSI allows energy to be returned to the battery during regenerative braking.

Variations on the classic VSI design are also possible that provide two-level outputs using modified modulation schemes. However, they require additional power devices and are more complex to implement. They are of interest as they reduce the common mode voltage variation within the EM, something that is known to result in failure of the bearings.

Alternative topologies are also under consideration. Current-source inverters (CSI), based upon thyristors, were popular before gate-controlled silicon switches matured in the 1980s. These made use of their unidirectional current and bidirectional voltage blocking characteristics, but were limited by their slow switching capability (Figure 8). An inductor replaces the expensive VSI DC-link capacitor. Additional capacitors are needed on the EM’s output phases, but these are significantly lower in cost compared to the DC-link capacitor. Its key advantage is that it can generate an AC output higher in voltage than that of the battery supplying it.

The DC boost is also eliminated, and the constant power range of the EM can be extended. CSI also reduces the high dv/dt of VSI designs, reducing common-mode EMI. Wide bandgap (WBG) devices, such as silicon carbide (SiC), have the potential to make the CSI simpler to realize and prototype designs have been developed but, currently, it is still seen as prohibitively costly.

In some cases, the traction inverter can convert the motor’s energy during regenerative braking back into DC to charge the battery. The traction inverter may also need to control other brushless motors, such as the oil pump for an ICE in a (P)HEV. Finally, it may be responsible for implementing an auxiliary power module (APM), a DC/DC buck converter, for generating the 12 V and 48 V power busses.
TRACTION INVERTER DESIGN APPROACHES

While the principle of three-phase control of EMs may be clear, implementing a traction inverter is very challenging. The key design goals include cost, weight, efficiency, failure tolerance, safety, reliability, and manufacturability. While traction inverters have traditionally been separate from the motor, today’s focus is on integration with the motor and gearbox. This brings many benefits, such as allowing motor and drive to share a common housing, easing integration into the vehicle; it simplifies cooling concepts; and it reduces electromagnetic interference (EMI) challenges thanks to the short distance of the power cables.

The drivetrain is also considered to be an ASIL-D application from the perspective of functional safety. This means special care must be taken to ensure that, should a failure occur, no loss of life can result. Extra hardware to implement system monitoring, along with software checking, is therefore needed.

Perhaps the greatest challenge lies with the huge disparity between the voltage of the control electronics (just a few volts) and the several-hundred volts and amps of the power electronics.

A typical approach starts with the DC boost circuit (Figure 9), leveling the EM supply voltage from the battery that sits behind a safety disconnect. This supplies the power switches, commonly IGBTs, in a VSI configuration, although SiC MOSFETs are increasingly being used. These feed the three phases of the EM via feedback from Hall-effect sensors or current-sense resistors. Pre-drivers boost the control element signals, the MCU, to that required by the gates of the IGBTs. The current-sense resistors or Hall-effect sensors are linked to an analog-to-digital converter (ADC). This entire section of the design is in the high-voltage domain.

The components in the high-voltage domain (pre-driver and ADC) are galvanically isolated from the low-voltage domain to ensure safety.

The pre-drivers and ADC are connected to the MCU together with the encoder/resolver of the EM. The MCU is powered by a power management IC (PMIC) or system basis chip (SBC), with its power derived from the battery. While the microcontroller’s main task is motor control, using the chosen algorithm and closed-loop proportional-integral (PI) controllers, it also has a host of other responsibilities. Communication with other vehicle systems is typically implemented using CAN or CAN-FD. Safety code must also be executed to continuously ensure the integrity of the system. Being a software-based system, many traction inverters also allow the software to be updated, requiring a security implementation in hardware and software. Finally, the PMIC and CAN transceiver will require transient suppressors to protect them from potential surges and spikes on the power system.

As highlighted earlier, the design may also support multiple motors, using different control approaches, and implement DC/DC converters to generate auxiliary power.

The VSI is perhaps the most complex element when everything is considered. Electrically, it must be efficient and robust. However, its design must consider mechanical factors of volume limitations, along with the proposed heat dissipation concept. The connection from the inverter switches to the EM must also be considered and is typically implemented using a bus bar. The gate drivers will also need cooling, and their proximity to the power switches must be kept short due to the high currents flowing. Despite advances in low on-resistance in power switches, the heat dissipated must often be removed using a liquid coolant (such as water ethylene glycol, WEG), which requires a suitably sealed design and a pump.
STMicroelectronics has a long history in both high-voltage, high-power applications and automotive and is uniquely placed to support development teams as they design traction inverters. This starts with the STPOWER 650 V IGBT M series designed for hard-switching topologies operating between 2 and 20 kHz. Their minimum short-circuit rating of 6µs (at TJ 150°C) and extended operating TJ of 175°C ensures a robust solution in this harsh operating environment. The IGBT’s diode is optimized for fast recovery with a high level of softness as well as low EMI and turn-on losses.

Should support for higher voltages be required, the 1200 V IGBT H series, based upon trench field-stop technology, are a suitable alternative and complement the M series IGBTs. Operating at switching frequencies from 20 to 100 kHz, they combine very short tail current with low turn-off energy losses. Energy efficiency is also boosted thanks to a very fast turn-on. Optimized EMI is ensured thanks to the co-packaged freewheeling diode, providing fast recovery at an adequate level of softness.

Traction inverter designers are increasingly turning to SiC thanks to the much lower switching losses compared to silicon technologies. SiC MOSFETs also deliver more power in a smaller volume, resulting in a more robust inverter for a lower total system cost (Figure 10). STPOWER SiC MOSFETs are available in voltage ratings of 650 V, 750 V and 1200 V, operating up to a TJ of 200°C. They also have a very fast and robust intrinsic body diode.

The packaging options for these power devices are as important as their capability, as they determine the thermal management approach. HiP247 and HiP247 long-lead packages allow vertical mounting and clamping to a metal frame (Figure 11). Top-side cooling in a surface mount package is offered with the ACEPACK SMIT, providing high electrical isolation (2500 Vrms) and low thermal resistance. ACEPACK DRIVE is a very compact power module optimized for hybrid and electric vehicle traction applications targeting a power range from 100 to 300 kW. This easily mounted direct-liquid-cooled power module provides a ready-to-go solution for an effective implementation in large-volume scales. Highly integrated, single-package solutions also exist, which further simplify handling and integration into the cooling concept. ST is also able to supply bare die when customers are already developing their own in-house solution.

Perhaps the next most important choice lies with the isolated gate drivers. To ensure the highest efficiency, the driver must be capable of driving the gate of the power device to move it quickly between its on- and off-state. To support the ASIL-D requirement of the traction inverter, the driver should also provide a diagnostic capability to the host MCU. Finally, protection against shoot-through, dead-time control, and a Miller clamp to eliminate excess currents are needed.

The automotive AEC-Q100 qualified STGAP1AS single gate driver is an excellent choice providing a galvanically isolated drive of up to 5 A for N-channel MOSFETs and IGBTs. The propagation delay from input to output is just 100 ns, ensuring the PWM control accuracy is retained through the driver. Miller clamping, desaturation detection, sense pins for overcurrent detection, and a range of over- and undervoltage protection mechanisms are complemented by an SPI-based diagnostics implementation.

The L9502B and the L9502E are also automotive AEC-Q100 qualified galvanically isolated drivers. Packaged in a SSOP28 format with a pinout optimized for use with ACEPACK modules SiC or IGBT based, they incorporate an integrated Miller clamp.
and a push-pull output stage with a programmable output current capability. Both devices can drive SiC, IGBTs and MOSFETS up to 10 A. The L9502E also integrates an isolated flyback converter. To assist prototyping L9502-based high-voltage traction inverter designs, an evaluation board is available. **

With the drive’s inverter defined, the next step is to consider the MCU. The mathematically complex FOC algorithms will require a device with a processor featuring DSP instructions. Simultaneously, the operating frequency should be high enough that control algorithm, safety checking, self-checking, and communication. Peripherals optimized for motor control, such as advanced timers with PWMs, can reduce the load placed on the processor and reduce software complexity.

The 32-bit SPC58 E line and SPC58 N line Performance MCUs are ideal for such automotive applications. AEC-Q100 qualified and suitable for ASIL-D applications, these triple-core devices operate at 180 MHz (SPC58NE) or 200 MHz (SPC58NN). Utilizing a Power Architecture processor with floating-point unit and DSP block, they are ideal for traction inverter’s mission-critical task. They feature between 4 and 6 Mbytes of flash memory and 448 or 768 Kbytes of RAM, both with ECC, and standard automotive interfaces such as FlexRay, CAN-FD, LIN, and PSI5. The Hardware Security Module (HSM) also provides robust integrity checking of the flash memory, while a Memory Error Management Unit (MEMU) is available to collect and report any memory error events. The generic timer module (GTM343) is highly configurable, offering up to 40 inputs and 104 outputs with five programmable fine-grain multi-threaded cores, its own RAM, and hardware support for safety-related motor control applications.

Figure 12: The 32-bit SPS58NE and SPS58NN MCUs are suitable for ASIL-D applications and feature both the required automotive interfaces and an advanced timer module (GTM343).

To round off the design, it is also necessary to consider protection devices throughout the circuit. Transient Voltage Suppressor (TVS) diodes, such as the SM4TY Transil™ series, can handle peak pulse powers of up to 400 W. Designed according to the surges defined in ISO 7637-2 and the electrostatic discharges (ESD) in IEC 61000-4-2 and ISO 10605, they are commonly placed between the gate and source of switches or at the incoming source of supply to the PMIC.

Protection devices specific to the needs of CAN interfaces are also available. ST’s ESDCAN0x automotive dataline ESD protection devices are compliant with AEC-Q101 and ISO 16750-2 (jump-start and reverse battery tests) and implement a dual-line TVS.

**: L9502 drivers and the related evaluation board are currently under development. They should be released sometime in late 2021.
CONCLUSION

Reliable and robust, efficient and compact, strict cost expectations, and above all safe: EVs are pushing multi-discipline engineering teams to their limits as they develop traction inverters for next-generation, green transportation solutions. With EVs, in all variations, expected to make up for a significant portion of worldwide vehicle sales in the coming decades, there will be plenty of opportunity for innovation. Based around powerful, multicore automotive-grade microcontrollers and integrated with high-voltage and high-current inverters, even with high-efficiency IGBTs, there are still significant thermal issues to resolve. The advent of WBG devices, such as SiC MOSFETs, will usher in a further shrink in volume, increase efficiency, and improve robustness. They may also result in entirely new topologies, such as CSI, from which additional system benefits will emerge. By turning to the engineering teams at STMicroelectronics, and the broad portfolio of innovative silicon and packaging solutions, traction inverter development teams can draw on a wealth of experience to support them.
ADDITIONAL RESOURCES

5kW Low voltage electric traction inverter [Solutions page]

Electric traction for small vehicles (up to 48V BLDC motors) [Solutions page]

Main Inverter (Electric Traction) [Application page]

Automotive Solutions for Electro-Mobility [Brochure]

Driving smart power in automotive [Brochure]

Electric vehicle (EV) ecosystem [Brochure]

Traction Inverters in Electric Vehicles video [Youtube video]
