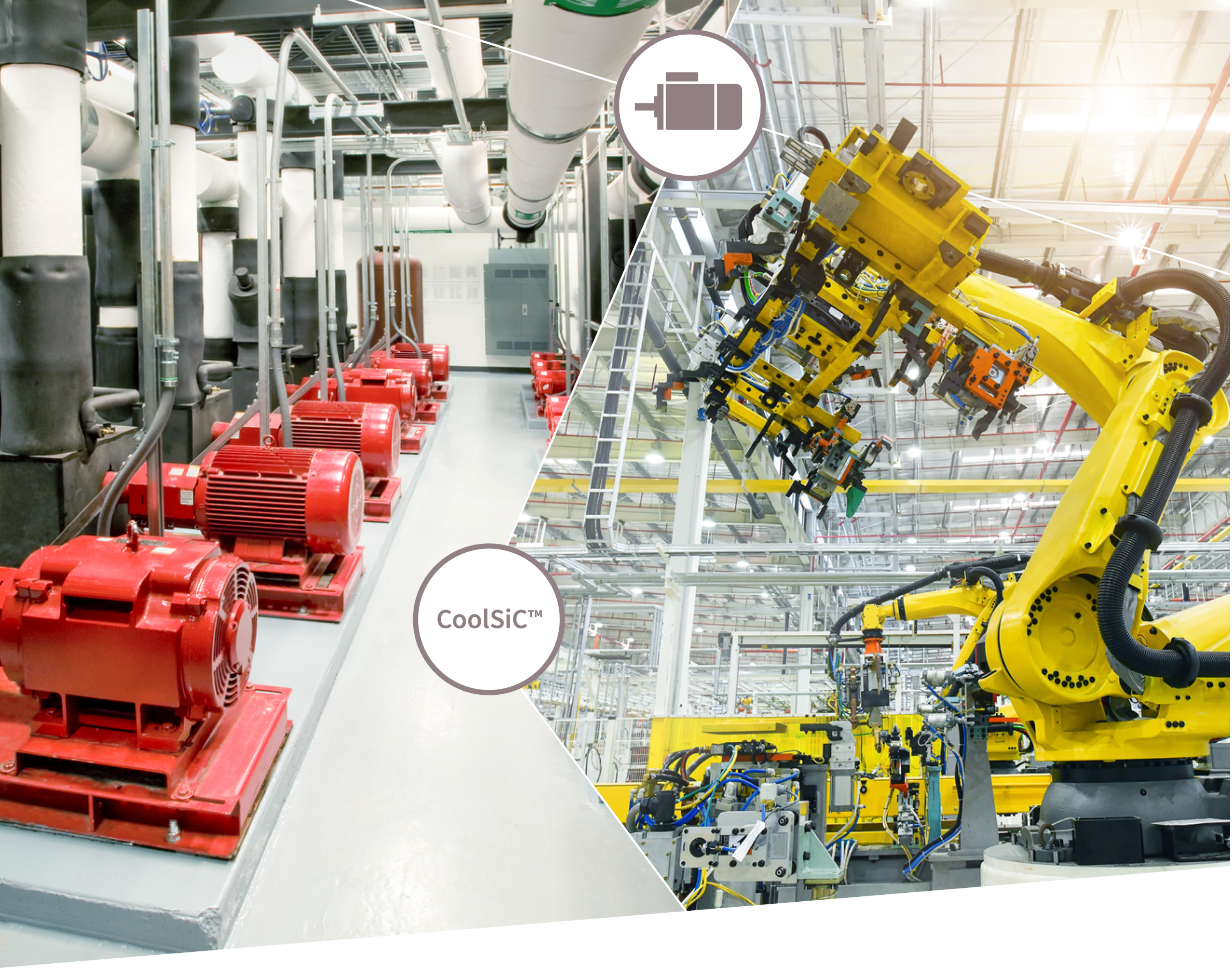

CoolSiC™ – The perfect solution for servo drives

Whitepaper
12-2020

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1 Industrial servo drives

When it comes to attaining accuracy and speed in automation applications, servo drives are a key component. Ranging in power from a few hundred watts to kilowatts, they established themselves during the 1970s as the performance of the electronic solutions required to control them accurately improved. The DC servo motors of the time were cleaner than the hydraulic servos on the market that often suffered from oil leakage. But one remaining challenge was related to maintenance due to the need to replace motor brushes, and deal with the dust generated.

Commercially available AC servo motors were developed in the 1980s and, being brushless, offered a low-maintenance alternative to their DC counterparts [1]. However, it took some time before the required microcontroller-based control technology matched, then exceeded, the performance of DC motor servos.

The servo motors and drive systems on offer today would be the envy of the automation engineers of yesteryear (Figure 1). But this does not mean that the quest to deliver further improvements is over – far from it. Increasingly, servos are integrated into compact spaces where volumetric limitations place constraints on the location of the motor, drive, and connecting cable.

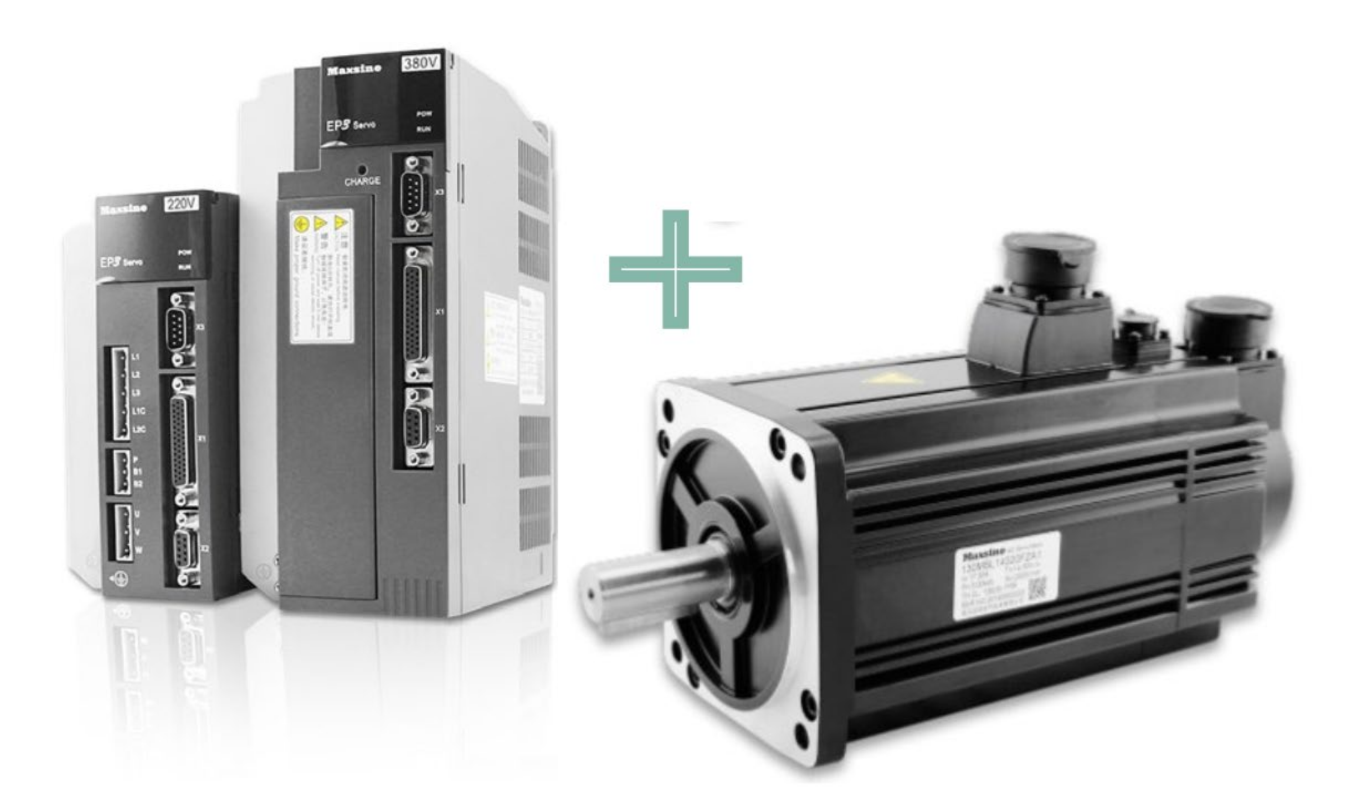

Figure 1 Servo motors and drives are typically separate components connected by an expensive cabling harness providing power and control.

But perhaps the most frustration results from the cabling. Servo motor cables are notoriously expensive, having to handle both control signals and high currents passing from the drive to the motor. Furthermore, they can be the source of significant electromagnetic radiation, resulting in issues fulfilling the electromagnetic compatibility (EMC) testing. Finally, traveling wave reflections caused by an impedance mismatch between the cable and the motor are often a source of trouble [2] [3]. The fast-rising edges caused by the pulse-width modulated (PWM) drive inverter can result in damaging stress on the insulation of the motor windings.

1.1 Relocating the motor drive

One obvious answer to this dilemma is to combine the motor and drive into a single unit. While this is easily said, the challenge lies with the precise implementation [4] [5]. Drive inverters use silicon IGBTs in their power stages. These are chosen for their excellent performance at high voltages. Today's most advanced solutions have been continuously refined to offer very low on-state losses, enhanced free-wheeling diodes with lower forward voltage drop, and improved reverse-recovery softness. This, coupled with packaging technology advances to simplify heat dissipation, has allowed servo drives to shrink considerably. However, the advancements achieved still do not provide enough improvement to consider mounting the drive directly to the servo motor.

The conditions under which servo drives are used are a significant contributing factor to the challenges designers face. As robotic arms move quickly from one position to another, high levels of acceleration result in levels of overload unmatched by other motor applications. A high level of overload is considered to be pushing to 200% of rated current for three seconds in a ten-second period. Very high overload lies at around 300% of rated current for one-quarter of a second in a four-second period. This leaves little time for the power devices to recover from the resultant rise in die temperature.

With increasing temperature, silicon IGBTs display a rise in the tail current at turn-off and higher reverse-recovery charge losses (Q_{rr}) at turn-on (Figure 2). This is one reason why a passively-cooled, IGBT-based, motor-mounted servo drive is not attainable.

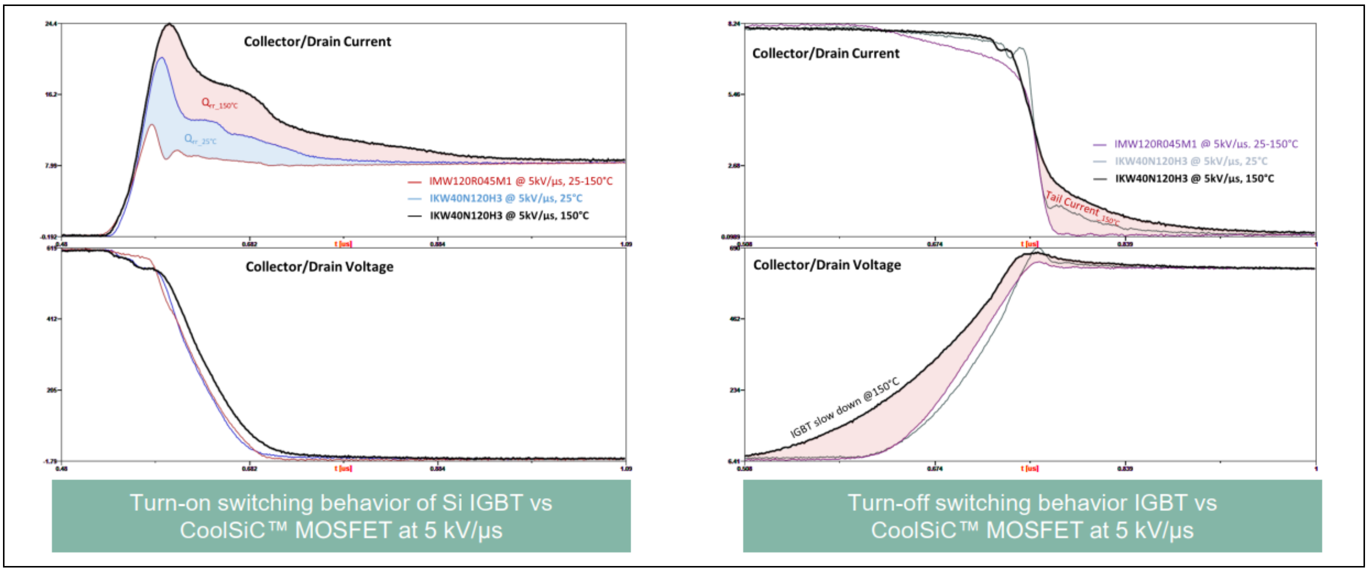

Figure 2 **High-speed silicon IGBTs suffer from significant energy loss due to Q_{rr} at turn-on (left) and tail current at turn-off (right) compared to SiC MOSFETs, worsening at high operating temperatures.**

1.2 Enhanced power switches

The semiconductor industry has been working hard to develop new substrates as an alternative to silicon. One of these, silicon carbide or SiC, is a highly suitable replacement for silicon IGBTs for applications looking to resolve the issues discussed, belonging to the family of wide bandgap technologies (WBG). Compared to traditional silicon switches, they offer higher temperature endurance and operation, enable higher frequency switching through lower switching losses, and higher drain-source voltages.

A direct comparison of silicon IGBTs with SiC MOSFETs in the context of servo drives helps to understand the differences further and from where the advantages emanate. Silicon IGBTs use a PNPN, four-layer structure that results in a further junction voltage at the additional collector-side PN junction. It leads to a knee voltage drop in addition to the one caused by the freewheeling diode. By comparison, under servo-drive operating conditions, SiC MOSFETs offer a much lower forward voltage over the relevant load current region (Figure 3).

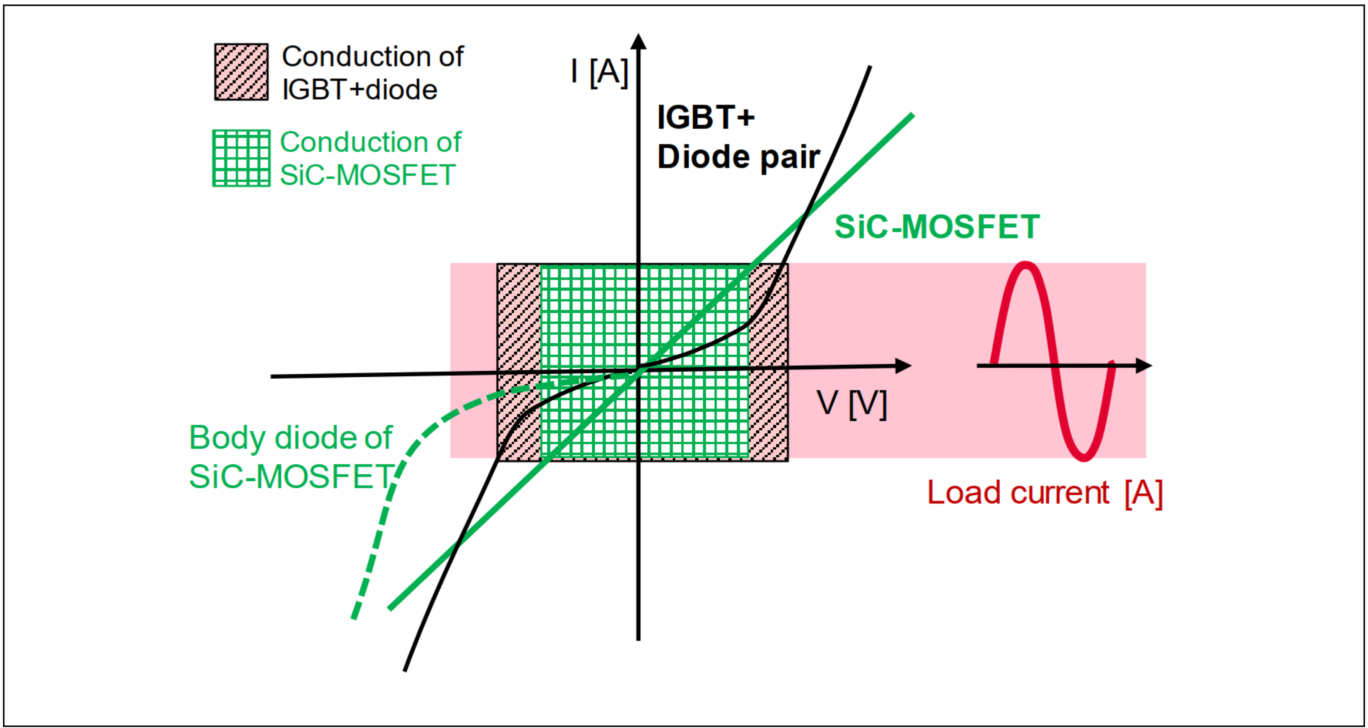

Figure 3 **Comparison of conduction losses between SiC MOSFETs and silicon IGBTs in servo drive applications.**

Like their silicon counterparts, SiC MOSFETs also integrate a body diode but, due to its WBG characteristics, the forward voltage is higher than that of the diodes selected to partner a silicon IGBT device. Reverse current during freewheeling inevitably leads to passive conduction, but it is not recommended to rely on this effect for the entire cycle. Instead, since SiC MOSFETs can conduct from source to drain through the channel at very low resistance, synchronous rectification (also known as 3rd quadrant operation) can be used. All this contributes to the significant energy-saving improvements of SiC MOSFETs over silicon IGBTs.

1.3 Comparison of SiC and IGBT in the lab and simulation

Lab experimentation using double-pulse testing quantifies the improvement. Here a DC link voltage of 800 V, together with a load current of 40 A, was used. For the MOSFET, a CoolSiC™ 1200 V, 45 mΩ device from Infineon was selected (-5 V/+15 V gate voltage), while the silicon IGBT used was a 1200 V/40 A device (-5 V/+15 V gate voltage). The power devices were placed in the low side of a half-bridge for the tests, together with a 20 A SiC Schottky diode in the high side for freewheeling.

At room temperature, the CoolSiC™ MOSFET displays only half the turn-on losses of a silicon IGBT and one-fifth of the losses at turn-off. More importantly, the results highlight the exceptional stability over temperature of CoolSiC™ with almost no difference in losses at 175°C compared to room temperature (Figure 4).

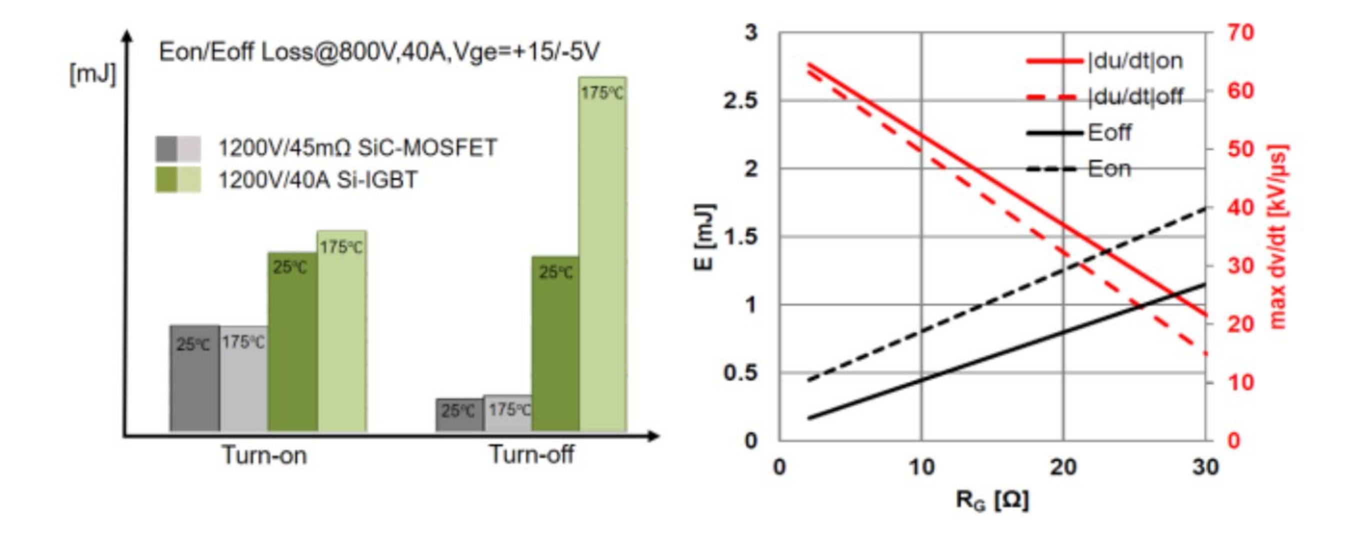

Figure 4 **The CoolSiC™ MOSFET, compared to silicon IGBT technology, shows little change in losses at high temperatures and offers a linear dv/dt control through R_G.**

The dv/dt of the CoolSiC™ MOSFET also shows itself to be highly controllable, along with switching losses, displaying a linear relationship between the gate resistor, R_G, and these parameters [6]. Smaller values of R_G lead to a higher di/dt on the body diode, leading to EMC challenges. Ultimately, the minimum R_G value is determined by the motor windings. The important point to take from this testing is that CoolSiC™ MOSFETs enable a significant improvement in efficiency in hard-switching DC/AC inverter topologies and a resultant drop in heat dissipation challenges.

SiC also provides design engineers with the option to move to higher switching frequencies. This eases the design of compact designs, as the volume of magnetic components required can be reduced. Also, compared to a comparable silicon-IGBT design, and when moving from 4 kHz to 8 kHz, it offers the choice of lowering the operating temperature of the drive solution by up to 40% or providing up to 65% more power at a similar operating temperature (Figure 5). The higher switching frequency also delivers a faster servo response time to dynamic changes in load.

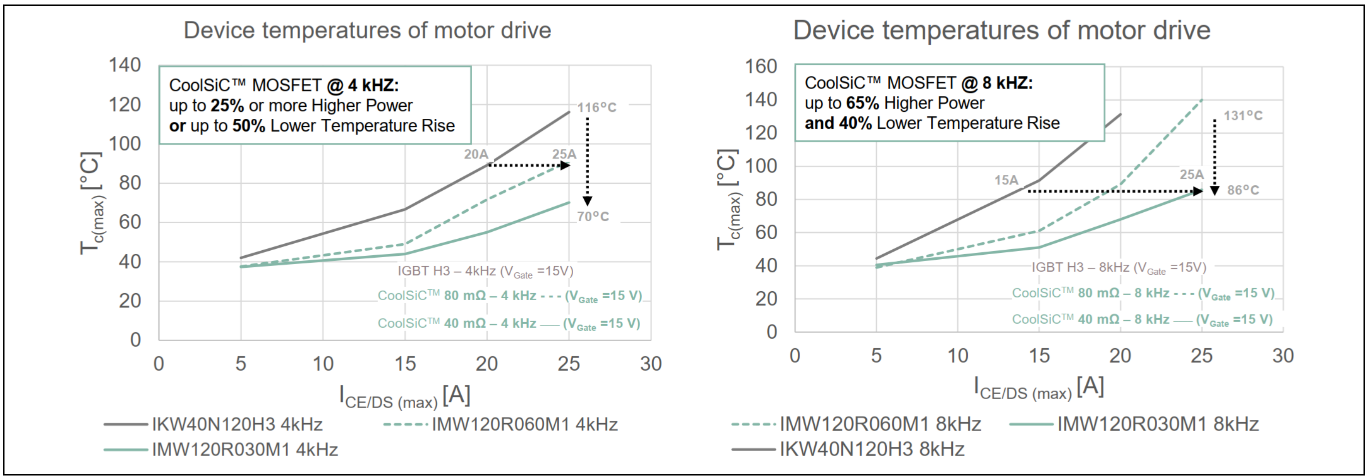

Figure 5 **The move to CoolSiC™ MOSFETs and changing from a 4 kHz (left) to 8 kHz (right) switching frequency provides manufacturers with options to reduce operating temperature and increase drive power.**

Further simulations undertaken also highlight the benefits of SiC MOSFETs in the extreme environment of servo drives and their ability to minimize temperature dissipation issues compared to silicon IGBTs. Using an inverter operating from a 400 V_{ac} (50 Hz) line voltage, with 800 V_{dc} link voltage and output current of 20 A_{rms} and power factor cosφ of 0.8, 20% duty (20 kHz switching) was analyzed. With an Infineon IMBG120R030M1H (30 mΩ), it demonstrated a loss of just 22 W during operation with the maximum junction temperature rising from 110°C to 146°C during 200 ms of operation. After a further 200 ms, the temperature dropped to its initial value (Figure 6). This provides a safe margin for the junction of around 30°C.

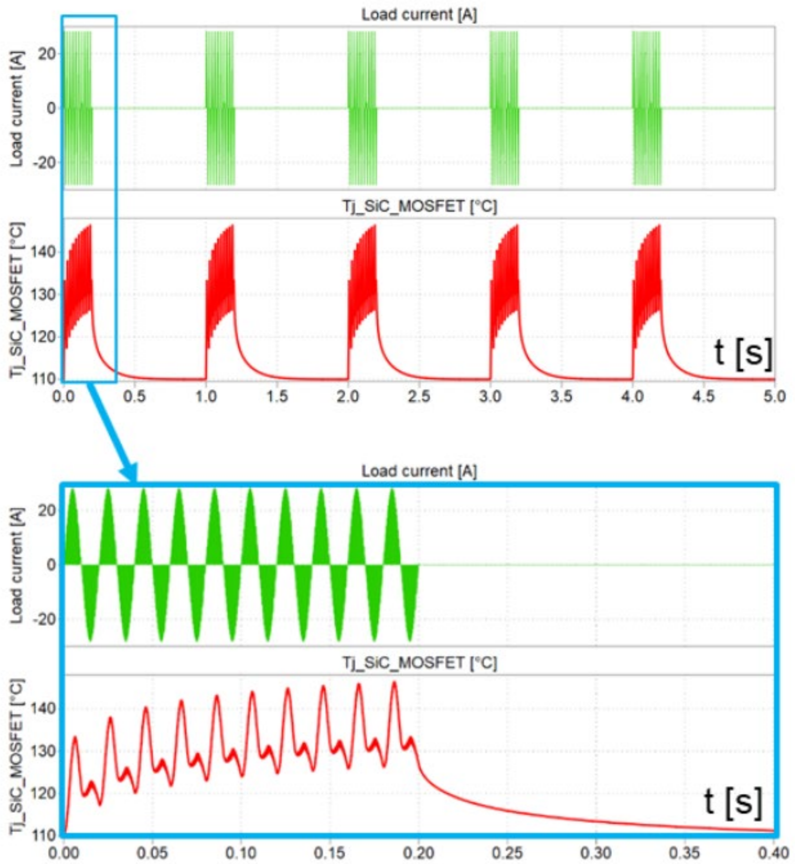

Figure 6 **An IMBG120R030M1H CoolSiC™ MOSFET thermal simulation under 20% duty operational conditions (20 kHz switching).**

While the SiC MOSFETs are the main contributor to heat generation, the effect of the current and voltage monitoring resistors and other components must also be considered. Thermal analysis of the power stage using a metal core printed circuit board (MCPCB) showed that under 20 A intermittent operation, total auxiliary power losses amounted to less than 3 W. For a self-cooling design, heat dissipation must occur via the back cover of the servo to which the MCPCB is attached using a high thermal conductivity epoxy resin. Calculations for the area of this back cover deliver a required surface area of 300 cm^2, something that can be achieved by using a toothed design. Finite-element thermal simulation for an ambient temperature of 40°C showed that the top side of the MCPCB reaches around 113°C, while the surface of the back case lies in the range of 70°C to 80°C (Figure 7).

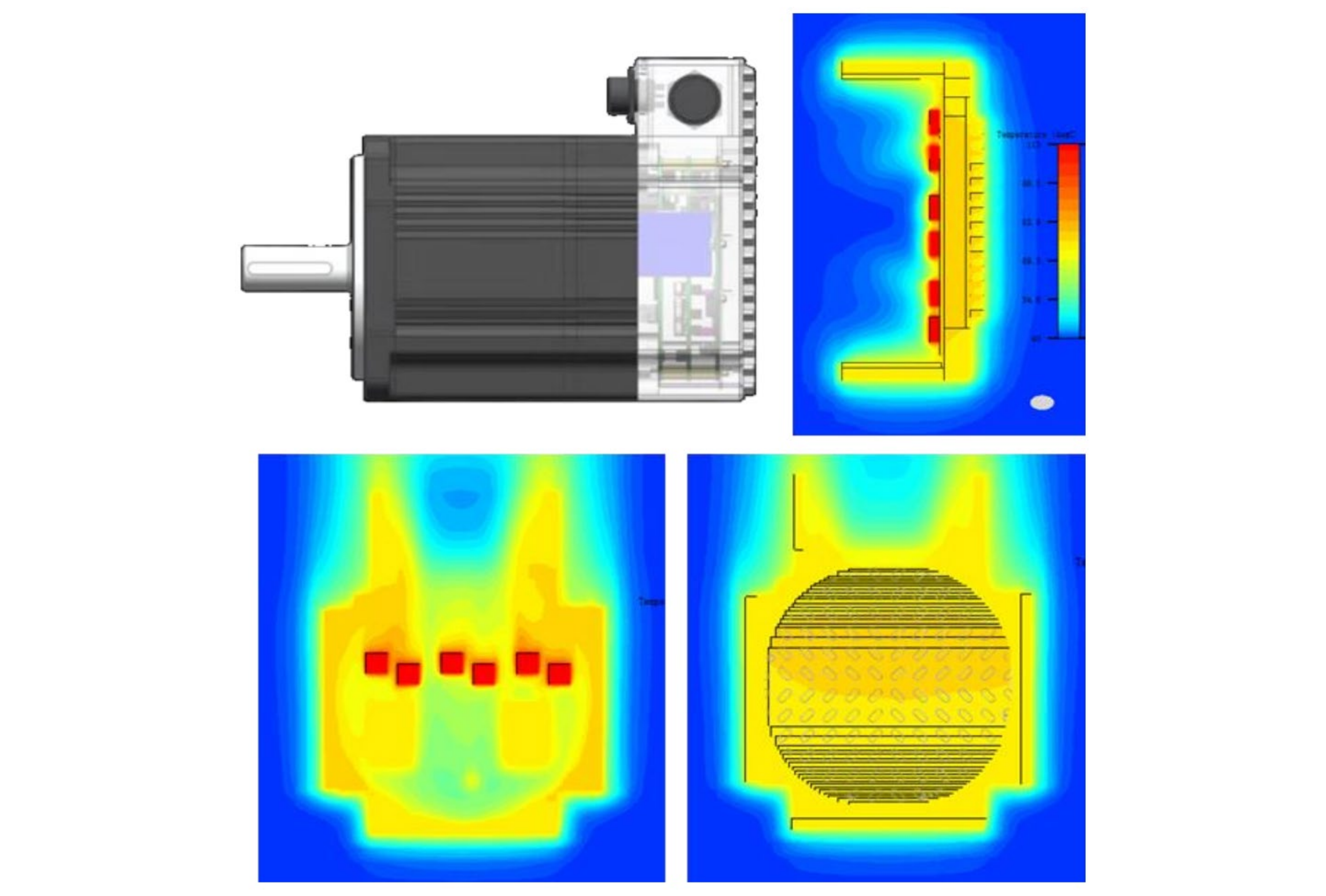

Figure 7 **Finite-element thermal simulation of drive circuit implemented using an MCPCB using the servo housing as a heat sink.**

1.4 Integrated servo motor drive implementation

Based on the lab testing's success and the results seen from the simulation, a compact, servo motor-mounted evaluation design has been developed. It fits flush with the motor when integrated into its self-cooling housing. A three-board approach spreads the functionality across a controller board, a driver board, and a power board. This allows the SiC MOSFETs to be thermally bound to the housing (Figure 8).

The power stage of the power board is implemented using the IMBG120R030M1H, 1200 V/30 mΩ CoolSiC™ MOSFET that was analyzed and compared with the silicon IGBT in the double-pulse tests already mentioned. Thanks to the PG-TO263-7 package, its compact size is well suited to this type of application's volume constraints. The gate is provided on a single pin next to a Kelvin source sense pin. The source sense is imperative in such designs, as it can lead to a threefold reduction in E_{ON} losses compared to the same MOSFET without the sense pin. The remaining five pins are source-connected, while the drain is provided on the device’s tab. Package creepage and clearance distance of greater than 6.1 mm is provided, while the device is qualified for industrial applications according to JEDEC 47/20/22.

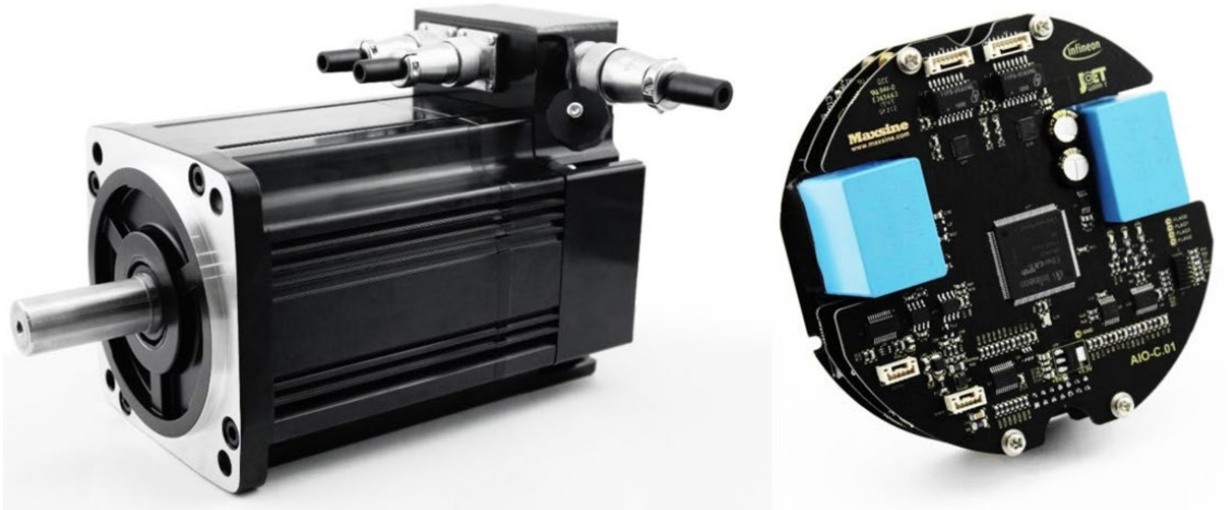

Figure 8 Integrated servo motor and drive (left) and compact driver board featuring CoolSiC™ MOSFET technology with XMC4800 microcontroller (right).

Further contributing to the mitigating of the thermal challenges is the use of Infineon's .XT interconnection technology. This uses a diffusion soldering method to connect the CoolSiC™ chip to the copper package leadframe, essentially eliminating the solder joint. The result is an $R_{th(j-c)}$ MOSFET/body diode thermal resistance of just 0.5 K/W, some 25% lower than that of a conventionally soldered implementation.

To ensure the proper control of the SiC MOSFETs, the design uses the Infineon 1EDI20I2MH EiceDRIVER™ for the driver board (Figure 9). These drivers offer a typical peak current of up to 6 A rail-to-rail output, and are ideal for use with the 1200 V capable IMBG120R030M1H. The single-channel drivers are galvanically isolated using a coreless transformer technology, and include an integrated Miller clamp circuit that protects against parasitic turn-on. To simplify their integration with a microcontroller, they also feature logic inputs, an undervoltage lockout (UVLO), and active shutdown. Their low internal voltage drop also contributes to limiting the power dissipated by the device. The PG-DSO-8-59 package provides a creepage distance of around 8 mm between the two isolated sides of the UL 1577-certified, 8-pin package.

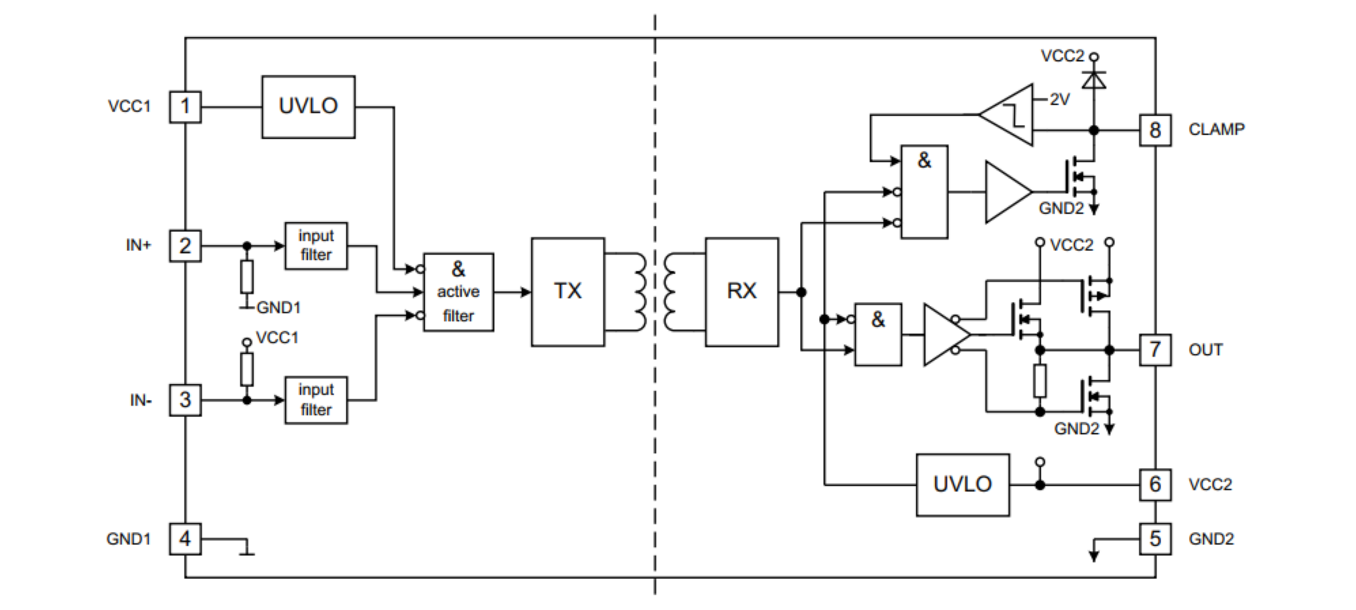

Figure 9 **Block diagram for the single-channel, galvanically isolated 1EDI20I2MH gate driver.**

While optimal power conversion is essential, servos also have exacting demands on positional accuracy. Rotor-position sensing is implemented by the TLE5109, a magnetic field sensor that uses magneto-resistive (MR) elements (Figure 10). This anisotropic MR (AMR) sensor offers a high level of precision in a single package, providing analog sine and cosine outputs that describe the rotor's magnetic angle between 0 and 180°. MR sensors are implemented as a differential bridge that ensures the output is independent of the magnetic field strength, and provides a constant output voltage over a wide range of temperatures. Internal temperature compensation is also integrated for higher accuracy. Dual-die versions are available that offer a higher level of safety in safety-critical applications. The family also provides both 3.3 V and 5.0 V optimized solutions.

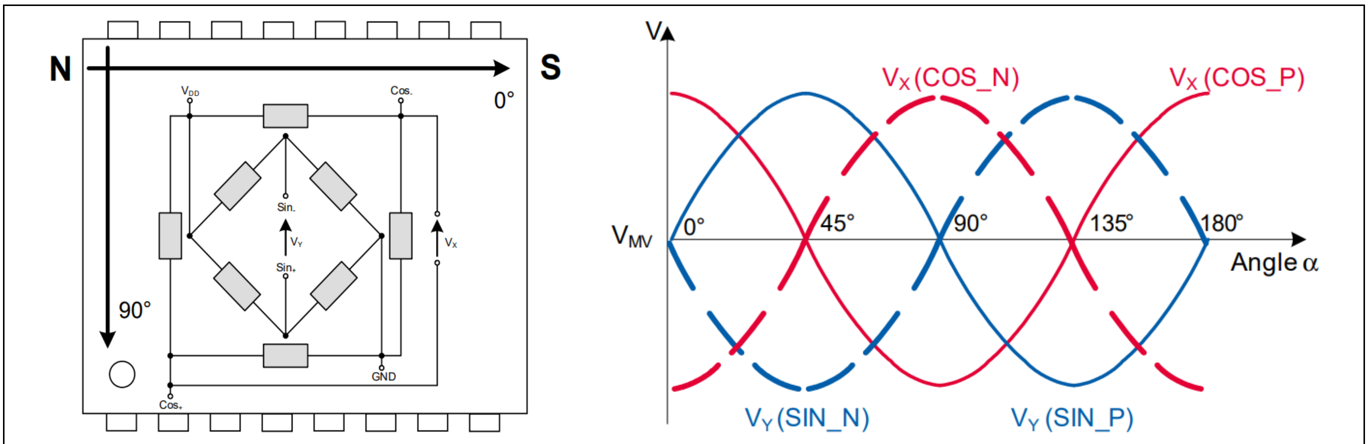

Figure 10 **The MR bridges implemented in the AMR sensor (left) together with the sine/cosine analog output signal (right).**

The control board houses the XMC4800, 144 MHz ARM® Cortex®-M4 industrial microcontroller that provides the servo's digital control and the required networking communication interface. Featuring up to 2048 Kbytes of flash memory and up to 352 Kbytes of SRAM, it is an ideal platform for an upgradeable, powerful motor control solution. DSP and MAC instructions provide the necessary boost in computing performance for three-phase motor control algorithms and feedback loop implementations. Up to 12 channels of DMA help offload the demands on the CPU during the capture of sensor data and implementation of low-latency communications busses, such as an EtherCAT® slave. It also features a CAN interface together with a host of other established, embedded serial interfaces. A four-channel, 12-bit resolution analog-to-digital converter (ADC), offering four parallel samples and conversion and 26 analog input channels, is the perfect complement to the TLE5190 AMR sensor and current and voltage sensing circuitry.

1.5 Real system performance

A standard method used to verify the performance of servo motors is through acceleration and deceleration testing. The compact driver design described here, coupled with a servo motor, was tested using a conventional industrial servo controller and computer software, operating from a 600 V DC power supply, and connected to an inertia simulator. Under these conditions, the servo motor is accelerated between +1500 RPM and -1500 RPM over a slow cycle (150 ms) and a fast cycle (50 ms). Over a period of 150 ms, peak line currents reached around 11 A while, over a period of 50 ms, peak values of roughly 28 A were measured (Figure 11). The servo motor's successful operation under these conditions is considered to prove that the resultant drive design is reliable.

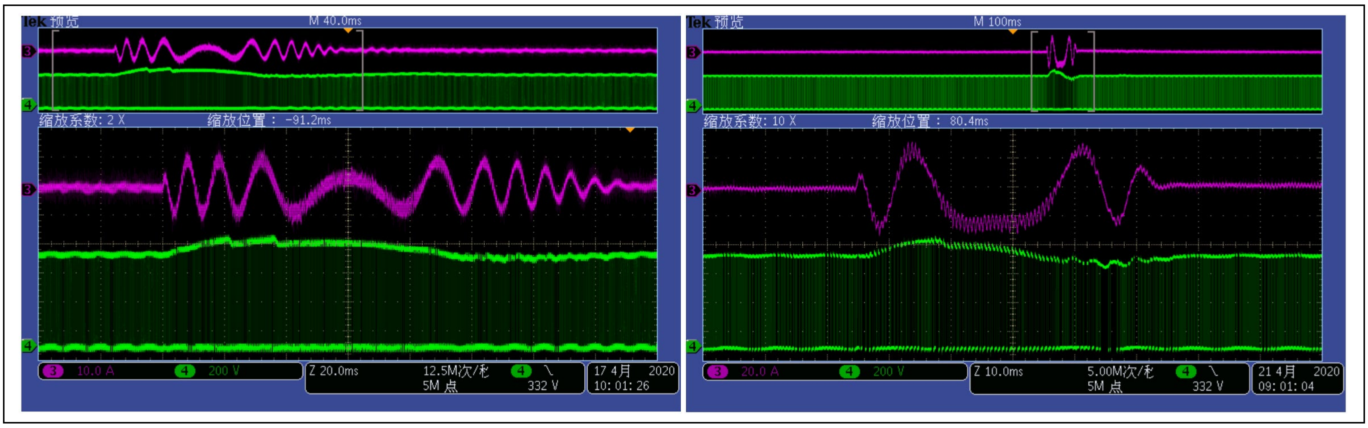

Figure 11 AC line current (magenta) and SiC MOSFET Vds (green) results for 150 ms (left) and 50 ms (right) acceleration/deceleration testing of the final drive design with servo motor.

1.6 Integrated, fast, and efficient servo drives

This CoolSiC™ MOSFET approach provides a short-circuit robustness (2-3 µs). However, the device can be protected by state of the art solution e.g. desat-Detection through gate drivers ICs or Itrip-protection. The lower switching losses highlighted, which are largely independent of temperature, deliver up to a 50% reduction in losses using CoolSiC™ MOSFET technology at a similar dv/dt to silicon IGBTs. The light-load conduction losses are also lower than comparable silicon IGBT designs.

Combined with advanced industrial microcontrollers, such as the 32-bit XMC™ family, galvanically isolated EiceDRIVER™, and advanced magnetic sensors, servo drive designers can confidently integrate servo drives into the servo itself. This delivers a compact servo solution that is self-cooling, and requires no more cabling than a power connection and digital connectivity (such as that combined in EtherCAT® P [7]). Since SiC MOSFETs can be switched at higher frequencies, they also provide improved dynamic control under changing motor load conditions. This applies equally to the integrated design shown here as well as to servo control implementations using external drives.

This evaluation design shows that drive circuitry can be mounted next to the servo motor, negating the need for the cable between it and the servo drive. The result is a highly compact servo solution that is easy to install and can be integrated into applications with severe space limitations.

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