Enhancing Power Conversion from Watts to Megawatts with 1700 V SiC MOSFETs

In the world of power electronics, bigger is never better. This holds particularly true for high-voltage power systems, where designers are clamoring for better semiconductor technology to meet customer demand for converters that are smaller, lighter, more reliable and efficient, and less expensive. With Silicon MOSFETs and IGBTs, compromises must be made; for example, one must select either the most reliable design or the most efficient design, but not both. High-voltage Silicon carbide (SiC) MOSFETs are the key that designers need to unlock themselves from Silicon's handcuffs. In this article, the benefits offered by 1700V SiC MOSFETs over the incumbent silicon solutions across a wide range of power levels–from watts to megawatts–are discussed in detail. **Kevin Speer, Sr. Manager SiC Solutions, and Xuning Zhang, Sr. Tech Staff Engineer, Microchip Technology, USA**

For nearly two decades, SiC power devices rated from 650 to 1200 V have permeated the marketplace, at last allowing designers to make disruptive advancements to technologies and end equipment – simultaneously improving performance, reliability, size, weight, and even cost. The recent release of a 1700V SiC product family extends SiC's myriad benefits up the power food chain to help shift the power conversion paradigm into new end segments, such as electrified commercial and heavy-duty vehicles, light rail traction and auxiliary power, renewable energy, and industrial drives (Figure 1).

Tens to hundreds of watts

At such a low power level, what cause

Figure 1: **Examples of electrified vehicles which will reap the benefits of high-voltage SiC MOSFETs**

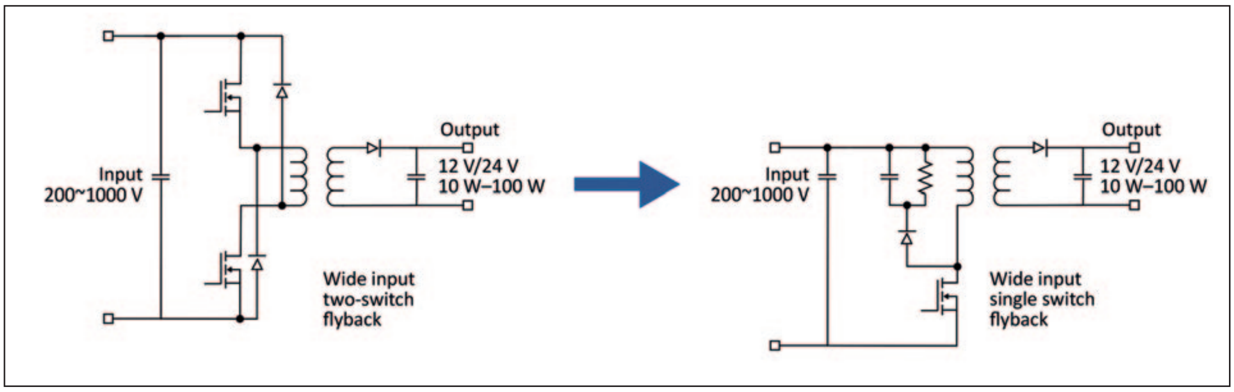

Figure 2: **The two-switch topology (left) using Silicon transistors can be replaced with the much simpler single-switch flyback (right) using better-performing and lower-priced 1700V SiC MOSFETs**

might there be for a 1700V transistor? Though there is just one, it is ubiquitous: Found in every power electronics system, the auxiliary power supply (AuxPS) is essential to the routine operation of industrial motor drives, electric vehicles, data center and backup power, solar inverters, charging infrastructure, and more. The AuxPS is system critical because it provides power to gate drivers, sensing and control circuits, and cooling fans; consequently, the AuxPS must not fail, and any associated risks should be mitigated.

Because these low-power, isolated, switch-mode power supplies are used in diverse applications, they must accept a wide-ranging, high-voltage dc input (300 to 1000 V) and output a low-voltage (5 to 48 V) source. Perhaps the most powerful method of failure mitigation is a simplified circuit design. As shown in Figure 2, the most reliable circuit design is the single-switch flyback topology (Figure 2, right), which offers simplicity and reduced component count – the latter adding a benefit of lower overall cost.

The introduction of 1700 V SiC MOSFETs provides an ideal solution for the AuxPS. Combining a high breakdown voltage, lower specific on-resistance, and fast switching speed, these devices are well-suited for the single-switch flyback topology. In contrast, Silicon-based solutions either have too low voltage rating, which necessitates a two-switch architecture (shown in Figure 2, left) and doubles the possibility of failure; or they have an adequate voltage rating but poor performance, few suppliers, and compared to SiC, a higher price.

Beyond the improved reliability, simpler control scheme, reduced component count, and lower cost, an AuxPS utilizing 1700 V SiC MOSFETs can also be smaller. The area-normalized on-state resistance, also called specific on-resistance ($R_{on,sp}$), of SiC MOSFETs is a fraction of that for Silicon MOSFETs. This means smaller packages may be used for the smaller die, and conduction losses are reduced which can ultimately result in smaller (or completely removed) heat sinks. Furthermore, SiC MOSFETs have lower switching losses, providing a pathway to shrink transformer size, weight, and cost by increasing the switching frequency.

Tens to hundreds of kilowatts

Moving up the power range, 1700V SiC MOSFETs also provide many advantages over Silicon MOSFETs and IGBTs in applications ranging from tens to hundreds of kilowatts. Examples include string and central solar inverters, auxiliary power units (APUs) in commercial transportation vehicles, induction heating and welding machines, industrial drives, wind converters, and more.

As the processed power increases, so does the impact of SiC's faster, more efficient switching.

Compared to the Silicon IGBT, SiC MOSFETs reduce switching losses by an average of 80 %, allowing converters to increase switching frequency and shrink the size, weight, and cost of bulky, expensive transformers. And though the conduction losses of SiC MOSFETs and Silicon IGBTs are similar under heavy loads, many applications spend most of their service lifetimes operating under so-

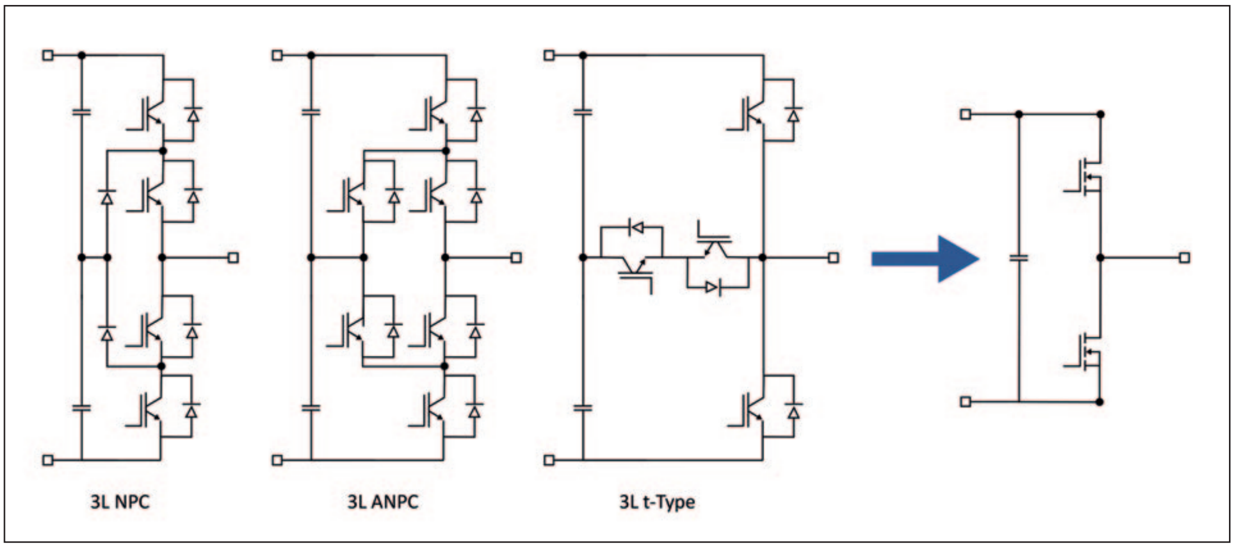

Figure 3: **The complicated three-level circuit topologies (left) using Silicon IGBTs can be simplified to the more elegant and reliable two-level topology (right) using half (or fewer) 1700 V SiC MOSFET power modules**

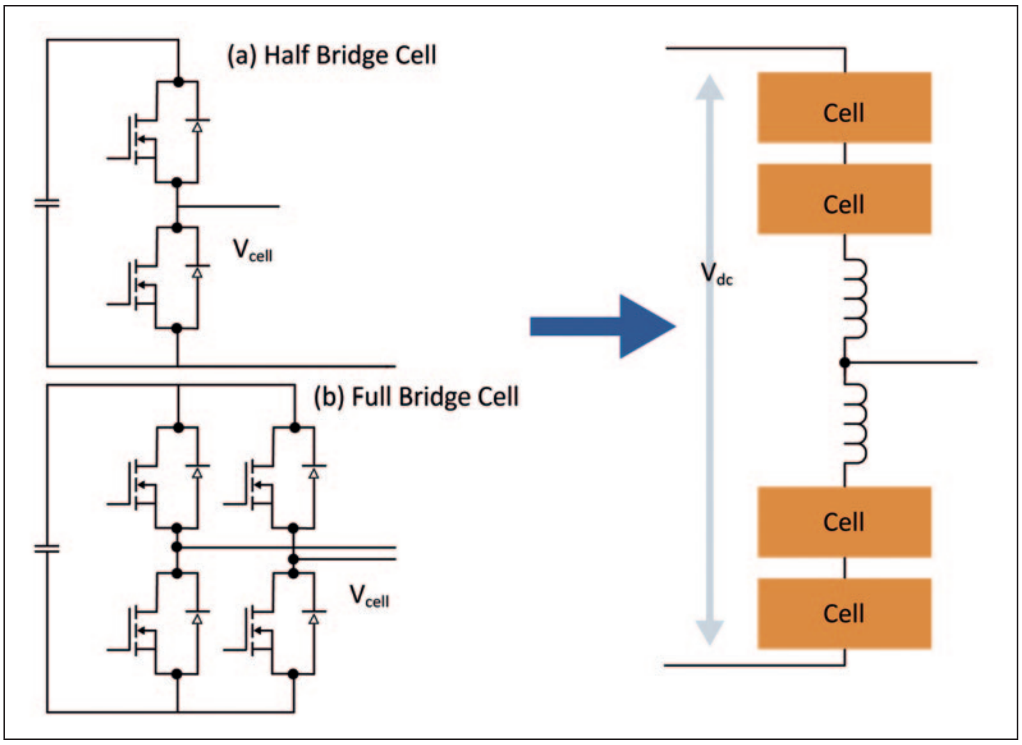

Figure 4: Modular multilevel converter (left) with multiple cells to achieve required power rating and (right) two examples of how a simple, two-level unit cell configuration may be used with 1700V SiC MOSFETs

called "light load conditions". Consider a few examples: solar inverters operating on cloudy days or under shade; wind turbine converters on still days; or train doors (opened/closed by transportation APUs) that are closed nearly all the time. Under these highly common light load conditions, SiC MOSFETs offer lower conduction losses to complement its reduced switching losses, making possible the reduction of heat sinking or other thermal management measures.

From a reliability standpoint, SiC MOSFETs empower designers with the ability to simplify the circuit topology and control scheme, as well as reduce component count – associated, of course, with a lower cost. Due to the higher-power delivery needs of these medium-power converters, a higher DC bus voltage is used – typically between 1000 and 1300 V. When selecting Silicon transistors for use at these high DC link voltages, efficiency requirements dictate that designers must choose among a few complex, three-level circuit architectures. Shown in Figure 3, these include the diode neutral point clamped (NPC) circuit, the active NPC circuit, or T-type circuit. In contrast, the use of 1700 V SiC MOSFETs allows designers to break free of these constraints and return to the more elegant two-level circuit shown in the right side of Figure 3, slashing device count in half and streamlining control.

The importance of power packaging and proper gate driving of SiC MOSFETs is worth mentioning. Because SiC can switch high levels of power at very high speeds, care must be taken to avoid voltage overshoot and reduce noise emissions. Medium-power converters in these applications routinely turn off hundreds of amperes across a 1000-1300 V bus in under a microsecond, necessitating the lowest possible package inductance, intelligent and fast-acting gate drivers, and optimal system layout. Combining Microchip's SP6LI power package with the AgileSwitch® family of digital gate drivers (see also the sidebar article) provides designers with ready-made solutions to get the maximum benefit out of 1700 V SiC MOSFETs without facing these common challenges.

Megawatts

In the multi-megawatt power range, key design factors include ease of scalability and minimal maintenance, prompting the use of modular solutions based on a basic unit cell. As shown in Figure 4, the unit cells, sometimes referred to as power electronic building blocks or sub-modules, are configured as cascade H-bridge converters or modular multi-level converters (MMCs). Megawatt-scale applications include solid-state transformers (SSTs), medium-voltage DC distribution systems, traction power units (TPUs) in commercial and heavy-duty vehicles, central solar inverters and offshore wind converters, and shipboard power conversion systems.

Traditionally, the power semiconductor devices used in the unit cells have been 1200 to 1700 V Silicon IGBTs. Much like the lower power applications, the deployment of 1700 V SiC MOSFETs at the unit cell level extends their power handling capability and electrical performance. As mentioned previously, 1700 V SiC MOSFETs have much lower switching losses, making it possible to increase switching frequency and drastically reduce the size of each unit cell. Moreover, the high blocking voltage of 1700 V reduces the number of unit cells required for the same DC link voltage, which ultimately heightens system reliability while slashing cost.

Summary

The arrival of 1700V SiC MOSFETs benefits a variety of applications and end equipment by offering higher reliability at reduced cost – both possible even while simultaneously making converters smaller, lighter, and more efficient. From watts to megawatts, high-voltage SiC MOSFETs are allowing designers to move beyond Silicon's compromises and make disruptive improvements to power conversion systems. Alongside the industry's most rugged SiC power devices, advanced power packaging with ultra-low parasitic inductance and digital gate drivers are helping designers to get the most value out of SiC and accelerate time to market.

Digital Gate Drivers Enable Next Step in Optimizing SiC Power Management in Electrified Heavy Transport Vehicles

SiC-based power-management solutions are proving their superior efficiency as compared to silicon especially in applications including electric buses, trains, trams, and other heavy transport vehicles. The same is true for higher-voltage solar inverters, rapid electric vehicle (EV) chargers, energy storage systems and aircraft flight actuators. Complicating SiC adoption, however, are the secondary effects produced by its faster switching speeds, including noise and electromagnetic interference (EMI), limited short circuit withstand time, overvoltage due to parasitic inductance and overheating that cannot be sufficiently managed using traditional analog gate drivers. **Nitesh Satheesh, Tomas Krecek and Perry Schugart, Microchip Technology**

To solve this problem, developers are turning to configurable digital gate driver technology to help them achieve new levels of SiC power density in these transportation and other industrial systems. The technology reduces switching losses and unlocking the full capability of SiCs by making all secondary-effect mitigation configurable. There are multiple ways to optimize the success of today's digital gate-driver solutions so that designers can fine-tune configurations on the fly to reduce system cost and size by using lower-voltage parts and smaller heat sinks. These solutions also transform the design experience by substituting computer keystrokes for the many hours previously spent with a soldering iron and bins of gate resistors.

Move to digital gate drivers

Because SiC devices run faster than Silicon, designers have had only one choice: slow down the SiC device to avoid the secondary effects of faster switching, but this was at the expense of SiC technology's fullest possible return on investment. While designers have used traditional analog gate driver techniques with Silicon-based designs to try and reduce a system's EMI noise, catch short circuit conditions before they became a hazard, cut down thermal losses, and control voltage overshoots and ringing, these techniques are not adequate for SiC MOSFETs.

Even with modifications, standard analog gate drivers are simply not designed from the ground up to address the special needs of SiC technology. Moving to digital gate drivers and combining them with SiC devices squeezes significantly more productivity from less energy. Plus, configurability enables designers to experiment with and then save configurations for a variety of gate driver parameters including gate switching profiles, system critical monitors and controller interface settings, cutting development time by months. The result is a gate driver that is tailored to its applications without having to change hardware, which helps to speed

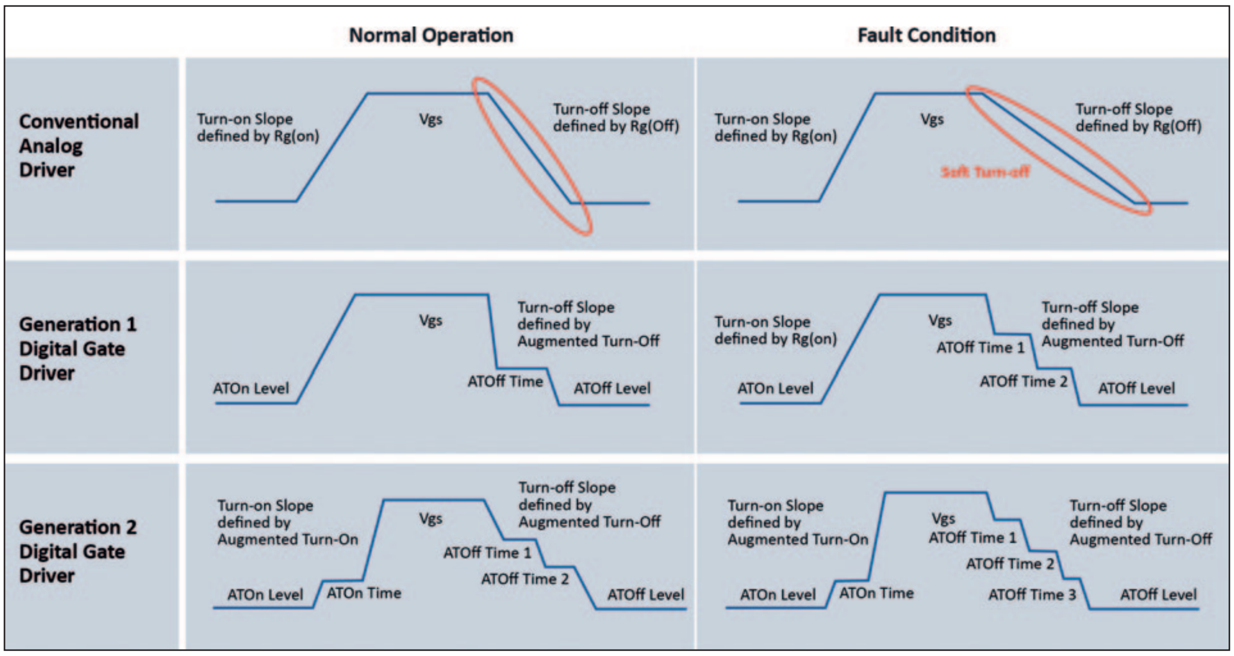

Figure 1: **A conventional analog gate driver compared to the first and second generations of digital gate driver**

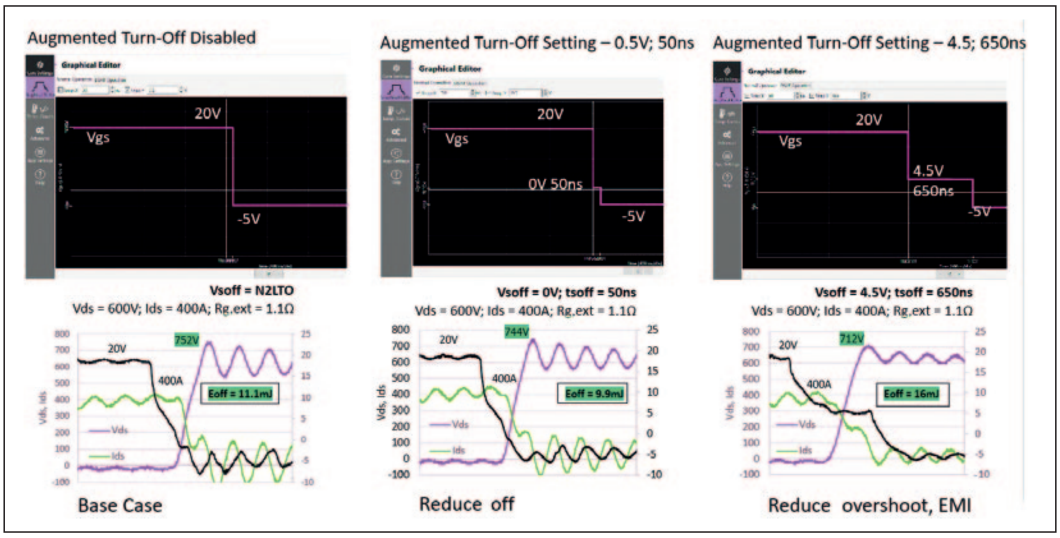

Figure 2: Benefits that the latest, more granular augmented switching solutions have on overshoot, ringing and turn-off energy, among other variables

development time from evaluation through production while enabling designers to change their control parameters throughout the design process.

New set of best practices

To ensure reliable, safe operation of SiC MOSFET-based power systems, digital gate drivers provide multiple levels of control and a higher level of protection than is possible with analog solutions. The drivers can dampen drain-source voltage (V_{ds}) overshoots by up to 80 % compared to their analog counterparts while cutting switching losses by as much as 50 %. They can also source/sink up to 20 A of peak current and include an isolated DC/DC converter with low capacitance isolation barrier for pulse width modulation signals and fault feedback.

Digital gate drivers can be used to augment switching capabilities in several ways, including providing independent short-circuit response along with robust fault monitoring and detection. Unlike traditional analog gate drivers that control turn-off slope through gate resistors for normal and short-circuit situations, the latest digital gate drivers enable designers to much more precisely control MOSFET turn-on and turn-off, as shown in Figure 1.

Furthermore, the second generation takes augmented switching even further to provide up to two steps of control at turn-on compared to the single step of traditional analog drivers, and up to three levels of control at turn-off. This ensures a "soft landing" during turn-off that is analogous to tapping a foot on the brakes of an antilock system. Four levels of short-circuit settings enable digital gate drivers to deliver similar advantages for controlling this secondary effect of SiC switching speeds.

Figure 2 shows the benefits that the latest, more granular augmented switching solutions have on overshoot, ringing and turn-off energy, among other variables. It illustrates how the increasing demands of SiC require not only faster switching but also more precise, and dynamic, multi-step turn-on and turn-off. In each of these three examples, the graphical editor toolbar is shown on the top and an associated scope image is shown on the bottom. The scope image on the far left shows a base case with augmented turn-off disabled, while the others depict two turn-off configurations. The one in the center example shows the configuration's impact on Turn-Off Energy Loss (E_{off}) and the one on the right shows how augmented switching settings control both voltage overshoot and EMI.

Configurable augmented turn-on capabilities are particularly important in applications involving motors, which are highly susceptible to the rate of change of voltage (dV/dt). A dV/dt that is too high deteriorates the motor's lifetime, increasing warranty costs. Manufacturers are working on higher-frequency motors but, until then, the only way to reduce dV/dt with analog gate drivers is to compromise efficiency by reducing SiC speed. Tuning this to speedily find the most appropriate compromise is only possible with digital gate drivers.

Maturing SiC ecosystem

Digital gate drivers are tightly integrated digital hybrid mixed-signal ICs that reduce end-product costs through a combination of processing horsepower and low component count. They are entering the market as production-qualified, fully configurable devices that are just one element of a total system solution for implementing SiC MOSFET-based designs. These solutions include the gate driver core, module adapter boards, a SP6LI low-inductance power module, mounting hardware, connectors to the thermistor and DC voltage, and a programming kit for the configurable software. Together, these elements provide a direct path from evaluation to production.

Adapter boards are pivotal to maximizing flexibility, enabling designers to configure a gate driver's turn-on/turn-off voltage and then use it across many different suppliers of SiC MOSFETs with different positive or negative voltage ranges. These SiC devices can be used without any redesign, even if they previously were used with an analog gate driver – the digital gate driver is simply reconfigured. Once a module has been chosen and the digital gate driver circuitry has been completed, the solution can immediately move into production. Because the core driver board will work across multiple adapter boards, designers can continue mixing and matching gate driver cores and adapter boards with a similarly fast path to production. Figure 3 illustrates how today's maturing SiC ecosystem is transforming the design experience while accelerating time to market.

Increasing a designer's module options has important benefits. Some SiC MOSFETs have more robust intrinsic body diodes, and designers should select those that show no perceptible shift in tests of pre- to post-stress ON-state drain–source resistance (R_{DSon}). They do not degrade after many hours of constant forward current stress when conducting reverse current and commutating whatever energy remains after a switching cycle. Other MOSFET options show some level of degradation, and some actually become unstable, so reviewing SiC MOSFET test results is critical. Choosing correctly enables designers to eliminate the die cost and power module real estate that comes with adding an external antiparallel diode to solve the degradation problem. These savings, however, also come at the cost of potentially choppy body diode performance (some more choppy than

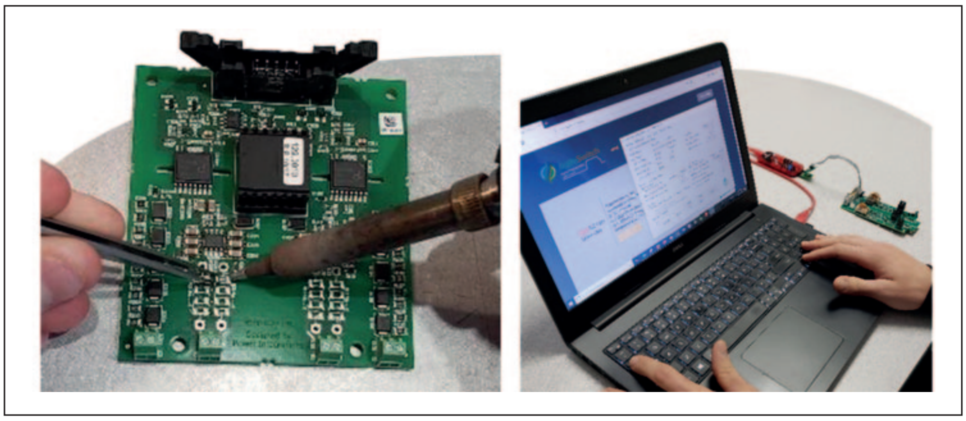

Figure 3: **The digital gate driver design example on the right shows an SP6LI low-inductance power module with connections to a laptop computer and a phase leg. Testing can begin immediately, without the laborious process of soldering gate resistors onto a board, shown on the left**

others), which can be eliminated by using digital gate drivers to adjust the MOSFET's turn-on parameters.

Utilizing 1200V MSCSM120AM042CD3AG SiC MOSFET and AgileSwitch® 2ASC-12A1HP digital gate driver, a jointly with French Mersen designed high-performance stack reference design allows to rapidly develop high-voltage systems using kits predesigned for typical and individual applications, reducing time to market by up to six months. This reference design provides 16 kilowatts per liter (kW/l) of power density, up to 130°C Tj and peak efficiency at 98 % with up to 20 kHz switching frequency.

Looking to the future

The ability to configure a digital gate driver creates new opportunities to change switching profiles in the field as MOSFETs degrade. This can already be done on a periodic basis – such as after a month or year of deployment. But there is no reason why it could not also be done dynamically, in real time, by sending a command to a controller that instructs the gate driver to change its settings.

In the meantime, combining SiC power modules with digital gate drivers is enabling designers to quickly and easily influence critical dynamic issues including voltage overshoot, switching losses and EMI. The most granular turn-on/turn-off configuration options reduce or even eliminate the secondary effects of operating SiC switches. Packaged into total system solutions, these digital gate drivers are paving the way for significantly smaller auxiliary power units in metro, subway, and other heavy transportation vehicles that make room for more paying passengers. They also greatly accelerate time to market by eliminating months of system development time, transforming the design experience from soldering resistors onto a board to simply entering keystrokes to change gate driver behavioral parameters.

Microchip Enters 3.3 kV SiC Power Market

3.3 kV SiC MOSFETs and Schottky Barrier Diodes (SBDs) extend designers' options for high-voltage power electronics in transportation, energy and industrial systems

Microchip's new 3.3 kV SiC power devices, lauched at APEC 2022, include MOSFETs with lowest on-resistance of 25 mΩ and Schottky Barrier Diodes (SBDs) with high current rating of 90 A. Both MOSFETs and SBDs are available in die or package form. Many Silicon-based designs have reached their limits in efficiency improvements, system cost reduction and application innovation. While high-voltage SiC provides a proven alternative to achieve these results, until now, the availability of 3.3 kV SiC power devices was limited. Microchip's 3.3 kV MOSFETs and SBDs join the company's comprehensive portfolio of SiC solutions that include 700 V, 1200 V and 1700 V die, discretes, modules and digital gate drivers. Customers can combine Microchip SiC products with the company's other devices including 8-, 16- and 32-bit microcontrollers (MCUs), power management devices, analog sensors, touch and gesture controllers and wireless connectivity solutions to create complete system solutions at a lower overall system cost.

To the question, if an internal body diode is suitable for replacing an external diode and save space in a power module, SiC manager Rob Weber commented: "In general, yes, because of the reliable body diode of our devices, you may not need to use an external Schottky diode. However, it depends on details of the design. The Schottky diode has a lower forward voltage in most conditions and lower reverse recovery, resulting in overall lower losses. If there is enough margin in the thermal design then the body diode may be sufficient."

Adding an SBD in parallel with the MOSFET reduces power dissipation in most cases due to the lower forward voltage (V_f) of the Schottky. The positive temperature coefficient of the SBD at higher current (increasing V_f with temperature) and the negative temperature coefficient of the MOSFET's body diode means that at high temperature and high current, the body diode and SBD will share current. Therefore the first order improvement in power dissipation may not be realized due to this current sharing and higher V_f of the SBD at high temperature. The MOSFET gate turn-off voltage is recommended to be -5 V to prevent the MOSFET's channel from partially turning on during reverse current flow. A lower negative turn-off voltage would lead to increases current sharing between the SBD and MOSFET and negate the benefit of the Schottky diode. A 1:1 ratio of MOSFET to SBD is usually not required. In most cases, we use a 2:1 ratio of MOSFET to SBD, which saves on cost and area.

The expanded SiC portfolio is supported by a range of SiC SPICE models compatible with Microchip's MPLAB® Mindi™ analog simulator modules and driver board reference designs. The Intelligent Configuration Tool (ICT) enables designers to model efficient SiC gate driver settings for Microchip's AgileSwitch® family of configurable digital gate drivers.