

SiC MOSFETs for Bridge Topologies in Three-Phase Power Conversion

Efficiency, productivity and legislation are main market drivers in power applications today. Making more out of less energy, and saving energy costs is putting a greater focus on better conversion efficiency and smaller, lighter systems. Here, power semiconductors provide new potential along the entire electrical energy supply chain, whether it be the growing share of renewables as part of the energy mix in generation, transmission or consumption of electricity in power converters. Although the latest generation of Si-MOSFETs and IGBTs are still good solutions in many cases, transistor functionality in the wide bandgap materials SiC and GaN offers a new degree of design flexibility for achieving new target requirements. Thus the use of SiC MOSFETs to improve power conversion performance or implement system innovation is nowadays a popular scenario for many system designers. In this article, Infineon takes the reader through SiC MOSFET design-in guidelines in bridge topologies, used for example in battery charging and servo drive applications. **Dr. Fanny Björk, Senior Specialist, and Dr. Zhihui Yuan, Technical Marketing Manager, Infineon Technologies, Munich, Germany**

Infineon will complement each leading-edge solution in silicon by a wide bandgap technology. A recent portfolio addition is the comprehensive 1200 V CoolSiC™ SiC MOSFET portfolio in TO247 packages. The intrinsic characteristics of SiC components, primarily the low dynamic losses, at an order of magnitude lower than Si IGBTs in the 1200 V class, can be translated into significant loss reduction at the system level. A performance-based design of the SiC MOSFET product features is here the key. Specifically, this means that Miller capacitance and threshold voltage ratings strongly affect the possible dynamic loss reduction as opposed to Si components. That is in turn crucial for the final result at the power conversion level, i.e. saving percentage points in battery power during bi-directional charging or integrating the inverter into a servo motor.

From Silicon to Silicon Carbide

A 1200 V rated SiC MOSFET offers various reasons for replacing 'next-best' Si technology. Compared to a 1200 V Si IGBT, lower dynamic losses are the most prominent feature. The lack of minority carriers in conduction mode eliminates tail currents, and thus, enables very small turn-off losses. Turn-on losses are also reduced compared to IGBTs, predominantly due to the smaller turn-on current peaks coming

from the low reverse-recovery loss nature of body diodes. Both loss types do not show an increase in temperature. However, in contrast to IGBTs, turn-on losses for MOSFETs dominate, while turn-off losses are small, which is often the opposite situation with IGBTs.

Another reason is the similar switching performance with a SiC MOSFET in the 1200 V class as with a Si super-junction MOSFET in the 650 V class. A SiC MOSFET exhibits a low-loss body diode, which is perfectly suitable for hard commutation due to the lack of a super-junction device structure causing snappy behavior. Topologies and solutions that have been up to now only possible in the single-phase power conversion using 650 V rated devices are now feasible at higher bus voltages in three-phase power conversion.

Practical loss reduction

To achieve the low dynamic losses that SiC MOSFET technology promises in theory, there are in reality certain device-design parameters that must come out right. Dynamic losses might be high due to parasitic turn-on effects caused by a gate-voltage rise from capacitive feedback via the Miller capacitance, C_{dg} . The parasitic turn-on phenomenon occurs when the MOSFET is in the off-state and the antiparallel diode is turned off. If the

coupling voltage is at a higher level than the gate threshold voltage of the device, then a shoot-through event occurs. The severity of the shoot-through and associated energy losses depends also on the operating conditions and hardware. More critical is high bus voltage, fast dv/dt switching transients, low gate resistance for turn-on, and high gate resistance for turn-off, as explained in detail by Sobe et al [1]. While a MOSFET's susceptibility to the unwanted effect can be estimated by the MOSFET capacitance ratio $C_{dg}/(C_{dg}+C_{gs})$ and its gate threshold voltage, $V_{gs,th}$.

In Figure 1, a datasheet comparison of the latest generation of SiC MOSFETs available on the market reveals large differences in coupled gate voltage from the Miller capacitance, as well as in the gate threshold voltage. For the example using a bus voltage VDC of 600 V, there are only two vendors that come out with an inherent immunity against parasitic turn-on (PTO) effects, i.e. there is a positive balance between gate-threshold voltage and induced voltage.

It is worth noting that even the switching transients are moderate for several devices; the resulting turn-on loss reduction versus a fast-switching IGBT is still significant. This confirms the impressive functionality of using a MOSFET device in 1200 V class. As also reflected in

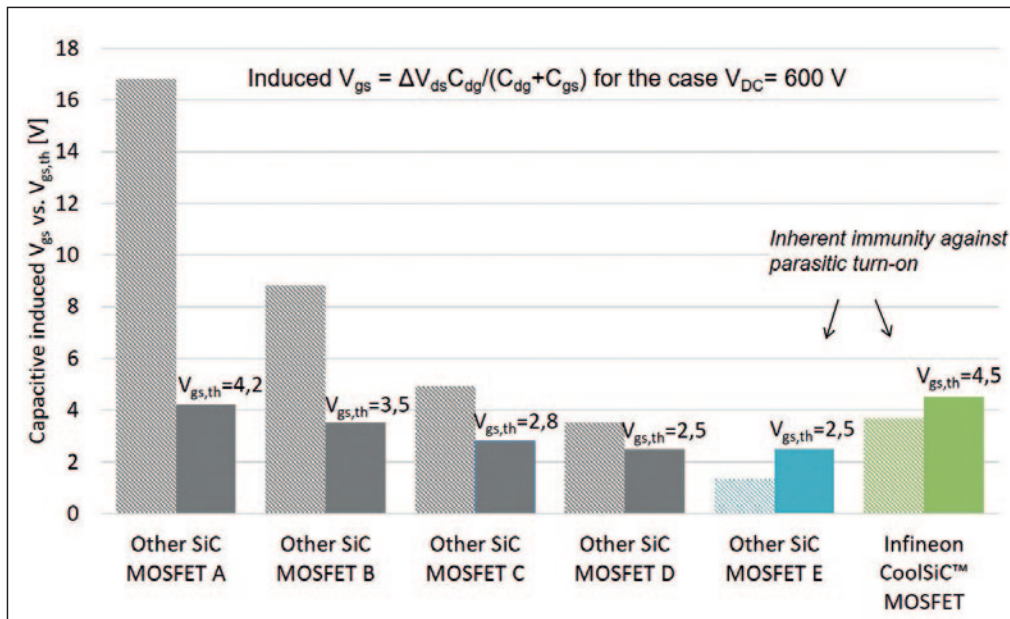


Figure 1: Datasheet comparison of susceptibility to unwanted parasitic turn-on by calculating the capacitive induced gate voltage rise in comparison to the typical V_{gs,th} rating of the devices. The various 1200 V SiC MOSFET devices have a nominal on-state resistance of 60-80 mΩ

Figure 2, a TO247 4-pin package with a Kelvin source connection operates at even faster dv/dt compared to a 3-pin package, >50 V/ns is reached. This lowers the switching energy by more than 10 % at the 15 A test current condition. For higher currents, the loss reduction from the 4-pin package will be even larger, thanks to the extra driver source pin and its virtual elimination of voltage drop over the lead inductance.

Safe-operation gate-driving scheme

Parasitic turn-on effects in SiC MOSFETs not only affect dynamic losses, but also safe operation with regard to maximum gate-voltage ratings, which is critical for gate-oxide reliability. A negative gate-voltage supply may be used to suppress a parasitic turn-on effect. But instead the problem occurring in many cases is an insufficient margin versus the maximum

negative gate voltage specified in the device datasheet. In other words, the coupling voltage may exceed the limitation. Figure 3 shows the schematic overview of such a situation.

The voltage due to a capacitive coupling creates an under-shoot voltage in addition to the turn-off gate voltage. Referring back to Figure 1 and Figure 2, CoolSiC MOSFETs in TO247 can be switched at fast dv/dt and low losses without any significant parasitic turn-on and under-shoot voltage occurring. Thus, CoolSiC MOSFETs are tailored towards both performance (lowest dynamic losses) and safe operation within datasheet limits. Assuming a carefully designed PCB layout with minimized gate-drain capacitance, Infineon encourages power electronic designers to operate CoolSiC MOSFETs with a turn-off voltage of 0 V. Thus, a simple unipolar gate drive scheme is

feasible without sacrificing performance.

Next generation servo drive with up to 80 percent loss reduction

Servo drive systems, typically characterized by high-performance and compact inverters for industrial robots or in automation, are one application that is impacted by SiC MOSFET performance [4]. Conduction and switching loss reduction can be obtained in all operation modes: acceleration, constant speed and breaking mode. Constant speed mode – when the motor is normally operated with low torque, i.e. low current – is typically ≥90 % of operation time. Here SiC MOSFETs (see Figure 4) enable approximately 80 % total loss reduction versus a Si IGBT. Such loss reduction is not only from the dynamic loss but also from the conduction losses thanks to Ohmic output characteristics without a knee voltage.

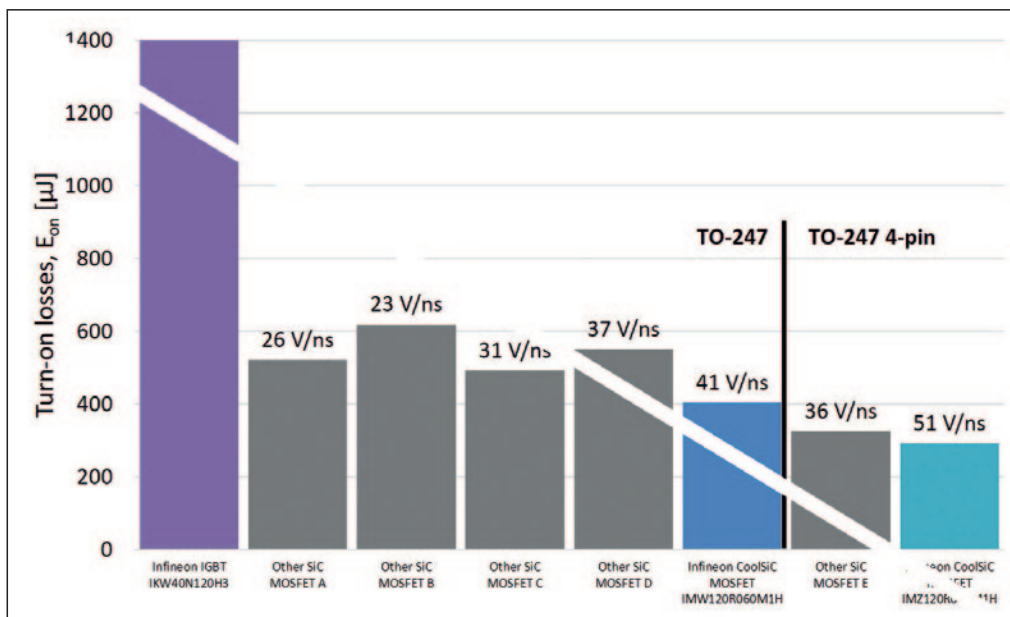


Figure 2: Minimum achievable turn-on switching losses and associated dv/dt switching transients for 0 V turn-off gate voltage, measured in an Infineon double-pulse evaluation board [2] for 60-80 mΩ rated SiC MOSFETs on the market. The high immunity of CoolSiC MOSFETs against parasitic turn-on energy losses are confirmed by lowest losses for both TO247 package versions. Test conditions were 800 V, 15 A and 150°C

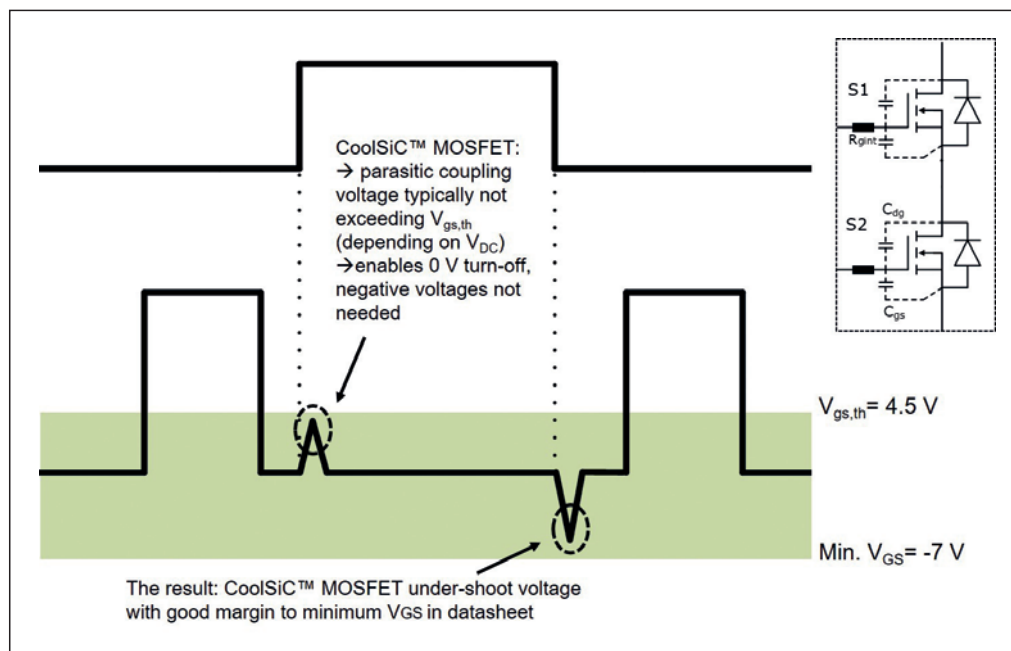


Figure 3: Schematic view of turn-on and under-shoot voltages related to capacitive coupling voltages. Parameters indicated refer to product datasheet for IMZ120R060M1H [3]

In the acceleration and braking mode, the drive normally operates at a much higher current range. Here the dynamic loss could be reduced up to 50 % compared with a SiC IGBT, even at the same dV/dt of 5 V/ns. The semiconductor loss reduction of about 80 % can in turn be used for the servo drive to increase pulse current capability, make it more compact (same frame with higher current), reducing fan and/or heatsink, and even integrating the inverter into the motor. Due to hard-switching operation in the typically used B6 topology, key SiC MOSFET features for improving application performance are low dynamic losses, no significant parasitic turn-on, and a robust

internal body diode rated for hard commutation.

Doubling power density while improving efficiency in battery chargers

Fast DC battery charging connected to a three-phase power supply is the game changer for electric vehicle (EV) market development, as it reduces user’s anxiety in terms of range. Bi-directional charging for energy storage solutions is also emerging with battery containers stationed on more and more sites where sustainable energy sources such as solar panels can be used for charging EVs and for other purposes. State-of-the-art battery chargers

use soft-switching LLC topologies in the DC-DC stage, see top picture in Figure 5 (if bi-directional charging is not needed in the user application, the secondary side switch positions use diodes). As low enough dynamic losses are only found in 650 V rated Si devices, two cascaded LLC full-bridges are needed to support an 800 V DC link voltage.

With a 1200 V rated SiC MOSFET, the number of switch positions including driver ICs can be cut in half (middle schematic in Figure 5). Besides the 50 % part count reduction, and thus smaller board space requirement, also efficiency may be optimized. For a SiC MOSFET solution, only two switch positions are turned on in every on-state, in comparison to four switch positions in the 650 V solutions. With system efficiency today typically optimized around 97 % in Si-based systems, the 50 % reduction of conduction losses and lowered turn-off switching losses coming from smaller output capacitance in a SiC MOSFET, over 1 % higher efficiency can be obtained. For bi-directional charging, this means 2 % or more savings of battery power.

The low overall switching losses of a 1200 V SiC MOSFET, combined with a fast internal body diode suitable for hard commutation, also encourage traditional hard-switching solutions such as the dual active bridge (Figure 5 bottom). Significantly less control effort, overall less complexity and a reduced part count are making such solutions increasingly attractive.

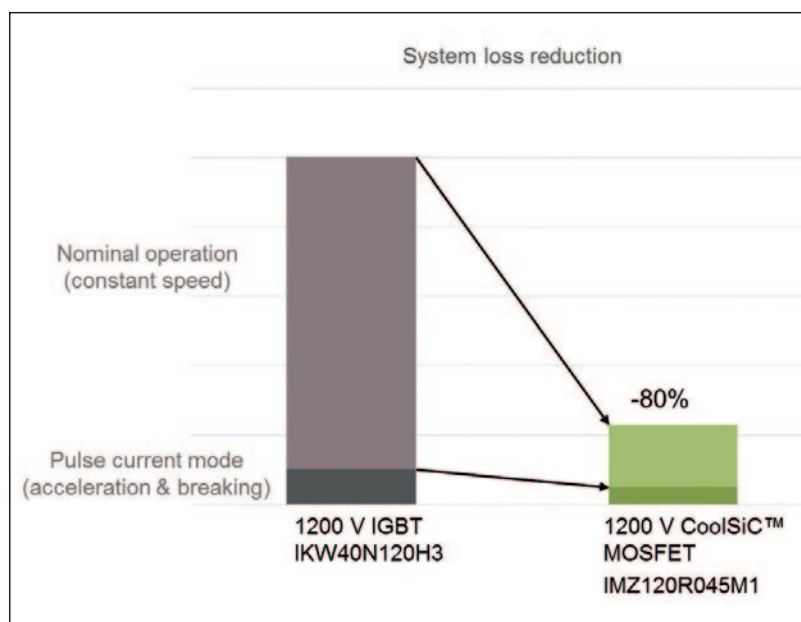


Figure 4: Typical system loss reduction in a servo-drive inverter considering all operation modes. For the calculation, a 45 mΩ rated 1200 V CoolSiC™ MOSFET was compared to a 40 A rated 1200 V Si IGBT in a two-level B6 topology

Conclusion

The 1200 V CoolSiC MOSFET portfolio in TO247 packages is the go-to solution for both emerging applications such as battery-

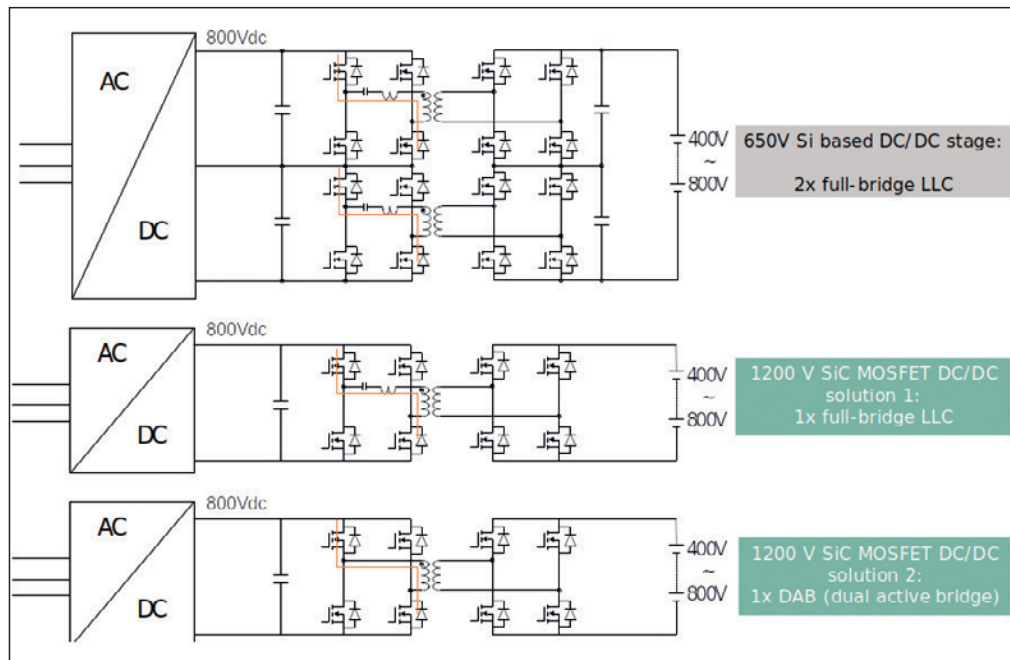


Figure 5: Three-phase fast DC battery charging including bi-directional feature on secondary side: comparison of Si-based solution with solutions using a 1200 V rated SiC MOSFET. Arrows indicate the 50 % conduction loss reduction feasible with SiC MOSFET due to less switch positions in turn-on current path

charging infrastructure and energy-storage solutions, as well as for established applications such as servo drives. In hard-switching and soft-switching topologies, CoolSiC MOSFETs improve efficiency, and reduce part count and system complexity. CoolSiC MOSFETs exhibit an excellent immunity against unwanted parasitic turn-on effects. The result is lowest dynamic losses among SiC MOSFETs, easy design-in regarding safe operation within datasheet limits, and an enabling of 0 V turn-off gate

voltage. A simple unipolar gate drive scheme is feasible without sacrificing performance.

Literature

[1] K. Sobe et al, "Characterization of the parasitic turn-on behavior of discrete CoolSiC™ MOSFETs", PCIM Europe 2019, Nuremberg, Germany, 2019

[2]

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[3]

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[4]

<https://wirautomatisierer.industrie.de/messe/sps-ipc-drives/beckhoff-zeigt-dezentrales-servoantriebssystem-amp8000/>

Evaluation Board for 7.5 kW Motor Drives

The evaluation board EVAL-M5-E1B1245N-SiC will help to pave the way for SiC in motor drives. It was developed to support customers during their first steps in designing industrial drives applications with a maximum of 7.5 kW motor output.

The evaluation board comprises an EasyPACK™ 1B with CoolSiC™ MOSFET (FS45MR12W1M1_B11), a 3-phase AC connector, EMI filter, rectifier and a 3-phase output for connecting the motor. Based on the Modular Application Design Kit (MADK) the board is equipped with the Infineon standard M5 32-pin interface which allows the connection to a control unit such as the XMC DriveCard 4400 or 1300. Its input voltage covers the range of 340 to 480 VAC.

The new member of the MADK family is optimized for general purpose drives as well as for servo drives with very high frequency. It features the EasyPACK 1B in Sixpack configuration with a 1200 V CoolSiC MOSFET and a typical on-state resistance of 45 mΩ. The power stage

contains sensing circuits for current and voltage; it is equipped with all assembly elements for sensorless field oriented control (FOC). The EVAL-M5-E1B1245N-SiC has a low inductive design, integrated

NTC temperature sensors and a lead-free terminal plating, which makes it RoHS compliant.

www.infineon.com/cms/de/product/evaluation-boards/eval-m5-e1b1245n-sic/

