How SiC MOSFETs can replace IGBTs in advanced motor inverter applications

The benefits SiC MOSFETs offer over IGBTs, where they come from, and how they can be applied to a 400V AC motor inverter

Introduction

Everyone is exploring how to reduce their carbon footprint. In the EU, the Net-Zero Industry Act[1] (NZIA) provides a platform aimed at enhancing manufacturing capacity for net-zero technologies and the components needed to create them. Part of the goal is a net-zero manufacturing capacity that meets 40% of the EU's annual deployment, implemented through enhancing skills in the workforce that also encompasses the products, components, and machinery needed.

This supports the Fit for 55[2] climate law, making it a legal obligation to reduce the EU's emissions by at least 55% by 2030. There is also the REPowerEU initiative[3] which, in the face of growing energy prices and energy market disruption, helps the EU to save energy. They declare that saving energy is the cleanest, safest, and cheapest way to reduce reliance on fossil fuel imports and state that, thanks to voluntary efforts since August 2022, gas demand has fallen by more than their 15% target.

Electric motors account for a significant portion of the electrical energy used worldwide by industry. For example, energy consumption by industrial electric motors in the US for three-phase motors over one horsepower consumes almost 30% of the total electrical grid load[4] (2021). And according to the International Energy Agency, electrical motor system upgrades to more energy-efficient solutions offer, at 70%, the largest energy savings potential[5]. This is why there has been a trend to upgrade, to correctly match the motor to the load (rather than over-specifying), and use inverters to control motor speed. New wide bandgap (WBG) devices, such as Silicon Carbide (SiC), are seen as a key technology to enable next generation, higher efficiency motor inverters.

IGBTs for AC Motor Inverters

IGBTs have been the switching component of choice for AC motor inverters for decades. Supporting industrial and energy generation power conversion applications, IGBTs adequately cover voltages from 300V to over 6,000V and currents from several amps to kiloamps. Built like a bipolar junction transistor with a MOSFET-like gate structure, they are ideal for switching converters operating at up to around 30kHz. Current only flows in one direction, so circuits requiring a freewheeling path need to include a diode or select an IGBT that has one integrated.

Over the years, packaging and design have adapted to the high-power, high-voltage applications where they are deployed. This includes using a Kelvin source pin that helps designers with the gate circuit design, improving switching performance and reducing electromagnetic interference (EMI).

In the 300V to 600V space, there has always been some overlap between IGBTs and silicon MOSFETs for switching inverters. Design requirements such as cost, target application volume, and desired efficiency push a designer one way or another. However, above 600 V, IGBTs were essentially the only device under consideration. But this is rapidly changing thanks to the growing range of WBG SiC MOSFETs.

Benefiting from SiC MOSFETs

Silicon carbide MOSFETs have been gaining traction as an alternative to IGBTs thanks to three key benefits:

- Lower switching losses
- Higher switching frequencies
- Better thermal conductivity

One issue with IGBTs is the tail current during turn-off. The current, I_C, drops relatively slowly as V_{CE} stabilises, during which time the resulting power is dissipated as heat. The length of the tail current impacts the maximum allowable switching frequency before switching losses become unreasonable.

SiC MOSFETs show a much faster turn-off and considerably shorter tail current. As a result, the turn-off losses can be better than 60% lower than an IGBT. Further improvements are seen in the turn-on switching losses (better than 50%). Research undertaken by Toshiba has shown that a move from IGBTs to SiC in a real application can reduce the total switching losses by up to 66% (Figure 1).

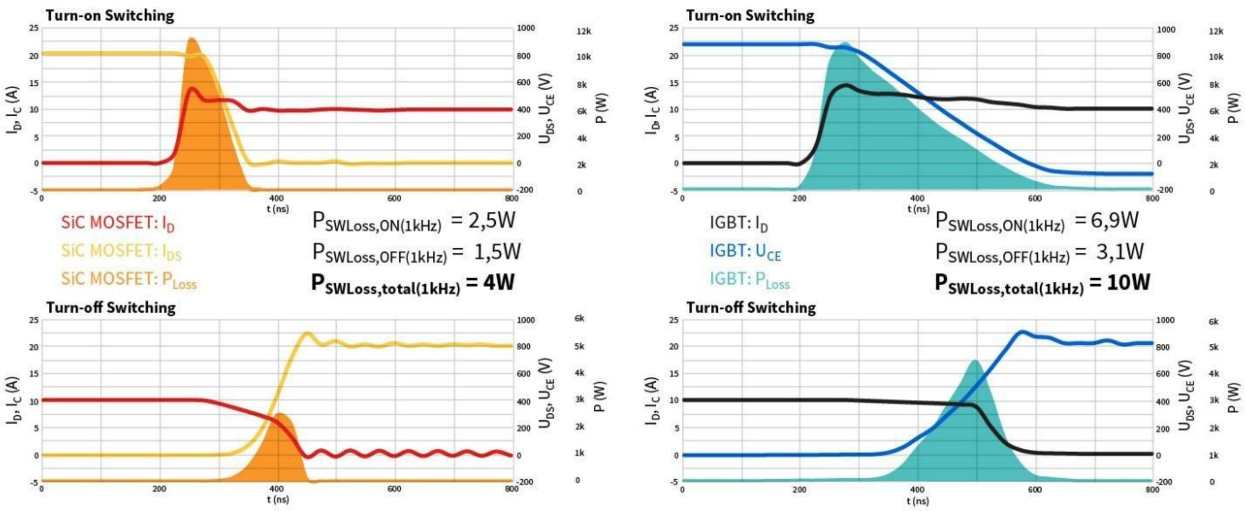

Figure 1: Comparison of switching losses for a SiC-based (left) and IGBT-based (right) design.

There is little improvement to be found in conduction losses. In fact, some applications may see a slight increase compared to a comparable IGBT. When comparing the characteristic curves of a SiC MOSFET (I_D vs. V_{DS}) with an IGBT (I_C vs. V_{CE}), the MOSFET shows a benefit below a V_{DS} of 1.5V (Figure 2). This can be beneficial when power converter designs operate under partial load conditions. However, it should be remembered that conduction losses are small compared with turn-on and turn-off losses. Diode losses remain comparable with IGBT-based designs.

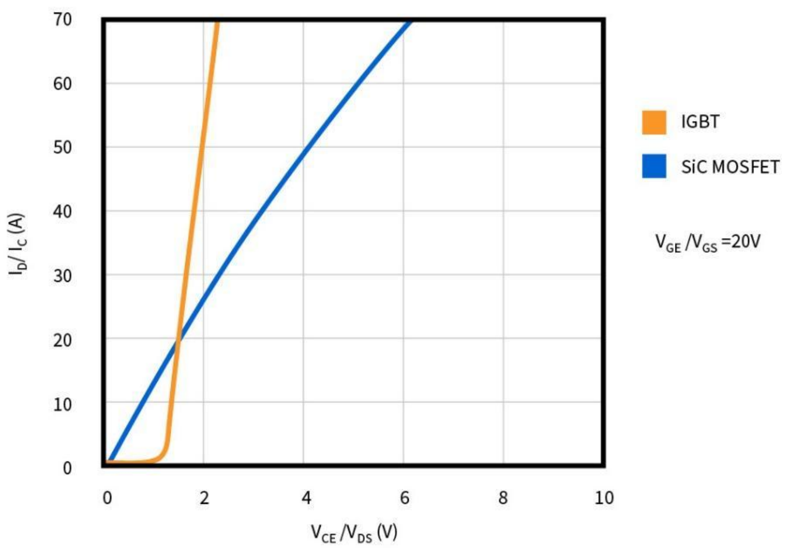

Figure 2: Conduction losses for a SiC MOSFET are lower than an equivalent IGBT at lower drain/collector voltages (< 1.5V).

IGBT-based switching converters are typically operated at around 15 – 20kHz. This is another parameter where SiC MOSFETs offer an advantage, operating comfortably at between 50kHz and 200kHz in commercial designs. Their aim is to reduce the size of the supporting passive components.

For example, the DC link capacitance of an inverter is dependent on the switching frequency squared in the denominator. Bearing in mind that this component alone can consume 20% to 50% of the volume of your inverter, even a modest increase in switching frequency can deliver a huge improvement on the design. Further benefits arise from the reduced cost of the components (lower system bill of material costs) and reduced overall weight.

Thermal considerations are important in motor drives, and IGBTs are susceptible to thermal runaway. This can be challenging as applications are pushing designers to build more compact, lighter inverters that may also require integration with the motor. SiC MOSFETs have a higher thermal conductivity, making them better suited to compact, highly integrated designs that place fewer demands, or even negate the need for, a cooling system.

Building SiC MOSFET drive circuitry

For those experienced in the design of power converters, many of the principles of operation remain the same when switching from IGBTs to SiC MOSFETs. However, the higher switching frequencies may require gate drivers different from those used for IGBT designs. Luckily, the industry has mostly standardised its pinout for such devices, meaning that testing using an existing PCB or comparing drivers on a new design is relatively straightforward.

Along with higher switching frequencies come more demanding requirements for slew rates and higher sink/source currents. Propagation delay requirements are also lower and must be consistent across devices to keep channel skew to a minimum. With their use in bridge architectures, isolated supply gate drivers with high input-to-output isolation are a must. Finally, an eye must be cast over the safety features that help respond to failures and incorrect operation.

When using gate drivers with one output, often two opposing diodes with resistors are integrated in the gate path (Figure 3). This allows the turn-on and turn-off slope to be controlled separately. The use of a SiC MOSFET with a Kelvin pin, an additional source pin that avoids the impact of the inductance of the source load path, helps to ensure that the switch turns off at a V_{GS} of 0V. It also establishes complete turn-on by avoiding a reduced V_{GS} as can occur when using three-pin devices. The resistor-capacitor to ground helps to reduce the risk of parasitic turn-on caused by the gate-drain capacitance.

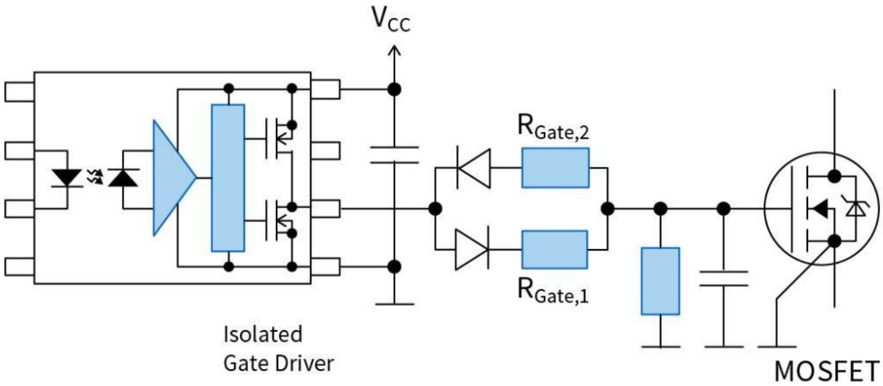

Figure 3: Basic design of a gate circuit for a SiC MOSFET driver.

Isolated gate driver families like the TLP570x family, a non-rail-to-rail design that designers may have used in IGBT designs, offer versions that match the needs of SiC MOSFETs. Because, due to their internal design, they don't operate rail-to-rail, a high output voltage drop of around 1.5V must be factored in. The TLP5702H and TLP5705H are both high-temperature types (Figure 4), suited for operation at up to 125°C, and support a peak output current of 2.5A and 5.0A, respectively.

Their supply voltage range is 15V to 30V (3mA supply), and the maximum propagation delay is 200ns. It is also critical to review the common mode transient immunity (CMTI), the maximum rise/fall of the common mode voltage the driver can sustain with the output in its logic low/high state. For these devices, a minimum value of ±50kV/µs and a typical value of ±100kV/µs is given, making it suitable for the high switching speeds attainable using a SiC MOSFET. The six-pin SO6L package offers a creepage distance of 8mm and an isolation voltage (BV_S) of $5000V_{rms}$.

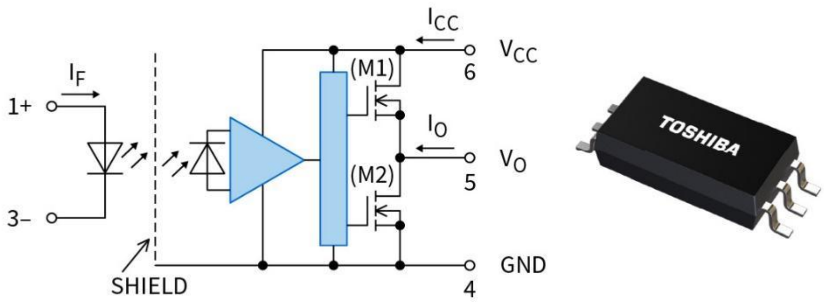

Figure 4: The non-rail-to-rail, isolated TLP5702H and TLP5705H are ideal for use in the gate driver of a SiC MOSFET.

If rail-to-rail outputs are desired, the isolated TLP57xx series should be considered. Operating from -40°C to +110°C and +125°C for the H variant, they also include an undervoltage lockout (UVLO). The TLP5754H operates from a supply voltage of 15V to 30V with a UVLO maximum of 13.5V and outputs 4.0A. It is suitable for switching frequencies of up to 50kHz and has a propagation delay of 150ns. The TLP5774H widens the supply voltage to 10 V to 30 V and can operate at up to 150kHz, with a UVLO maximum of 9.5V. The SO6L package offers the same creepage and isolation voltage as the TLP570xH devices.

Alternatively, the isolated TLP52xx series are smart gate drivers that include desaturation (DESAT), leading edge blanking and mute time, Miller clamp, fault status feedback, and automatic fault status reset (Figure 5).

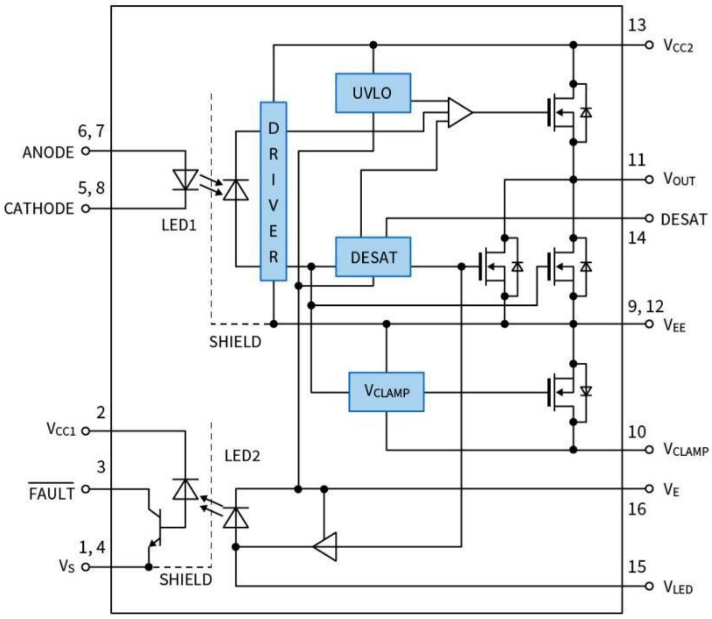

Figure 5: The isolated TLP5222 is a smart gate driver with Miller clamp, DESAT, and fault status feedback.

3rd generation SiC MOSFETs

The performance of SiC MOSFETs continues to improve, with Toshiba now offering its third-generation devices. Building on experience deploying earlier product series, the latest devices are designed to provide improved switching performance and are simpler to design in.

The five key improvements are:

- Built-in Schottky barrier diode (SBD)
- Reduction in $R_{DS(ON)}$ change
- Low $R_{DS(ON)} \times Q_{gd}$
- Wide V_{GSS} rating
- High and narrow V_{th} window

All MOSFETs have a parasitic body diode due to their horizontal and vertical structure. Its parameters can vary widely between devices and the forward voltage, V_F, can be a few volts, depending on the process. Toshiba's latest SiC MOSFETs include Schottky barriers diodes (SBD) on the die beside the transistor. The SBD used has a low V_F of around 1.35V and is rated to the same current as the MOSFET.

Because reverse current flows through the SBD and not the MOSFET, the generation of crystal defects in the transistor area is suppressed. In turn, change in $R_{DS(ON)}$ is reduced during operation. In competitor devices, $R_{DS(ON)}$ could jump up to 150% of the rated value, dropping over many hours of operation. This has led to specifying SiC MOSFETs with a lower than required $R_{DS(ON)}$ to be on the safe side. Toshiba's third-generation devices no longer need to factor in such a change.

$R_{DS(ON)} \times Q_{gd}$ has also improved by 80% over the previous generation of devices. This reduces the current required to charge and discharge the gate, enabling shorter switching times and improved switching performance.

The final improvement is in the V_{GSS} rating, offering a wide -10V to +25V range. This makes the design of the gate driver simpler as the gate isn't so sensitive to small over- and undershoots. When coupled with the +3V to +5V threshold voltage (V_{th}), building a robust design that is less sensitive to false turn-on in a bridge leg and the issues caused by electrically noisy environments or Miller capacitance is easier.

In the third-generation 650V SiC MOSFET range (Figure 6), three-pin and four-pin devices are available with $R_{DS(ON)}$ covering 107 mΩ down to 15 mΩ. These are offered in TO-247 and TO-247-4L packages, respectively. Future packages, including TOLL and 8 × 8mm DFN, are also available. In the 1,200V range, three- and four-pin SiC MOSFETs are available with an $R_{DS(ON)}$ of 140 mΩ down to 15 mΩ. A channel temperature of up to 175°C is specified for both voltage classes.

V_{DSS}=650V

$R_{DS(ON)}$ Typ. (mΩ)	TO-247	TO-247-4L(X)	TOLL	DFN8x8
	3rd generation			
15	TW015N65C	TW015Z65C	-	-
27	TW027N65C	TW027Z65C	TW027U65C Mass Production 2025	TW031V65C
48	TW048N65C	TW048Z65C	TW048U65C Mass Production 2025	TW054V65C
83	TW083N65C	TW083Z65C	TW083U65C Mass Production 2025	TW092V65C
107	TW107N65C	TW107Z65C	-	TW123V65C

V_{DSS}=1200V

$R_{DS(ON)}$ Typ. (mΩ)	TO-247	TO-247-4L(X)
	3rd generation	
15	TW015N120C	TW015Z120C
30	TW030N120C	TW030Z120C
45	TW045N120C	TW045Z120C
60	TW060N120C	TW060Z120C
140	TW140N120C	TW140Z120C

Figure 6: Overview of the available and planned 3rd generation SiC MOSFETs with V_{DSS} of 650V and 1200V (mass production in 2025).

Applying SiC MOSFETs to an AC motor inverter

To put the third-generation SiC MOSFET family through its places, they were integrated into a 400V 3-phase motor inverter, an application traditionally implemented using IGBTs. The design, RD220[6], can use three- or four-pin

TW045x120C SiC MOSFETs and uses the optically isolated TLP5774H as the gate driver. For sensing motor phase currents and bus voltage, the isolated operation amplifier TLP7820 was selected.
The design consists of two boards (Figure 7). The first is an AC-DC board that generates a DC link voltage of up to 670V. The second is the inverter board that can generate three-phase 360VAC to 440VAC at up to 15A (Figure 8). It also includes fault detection for each motor phase (U, V, W), bus overvoltage and overcurrent conditions, and two channels of over-temperature monitoring using a TC75W95FU comparator. Both boards operate from a 20V control power supply and can use convection or forced air cooling.

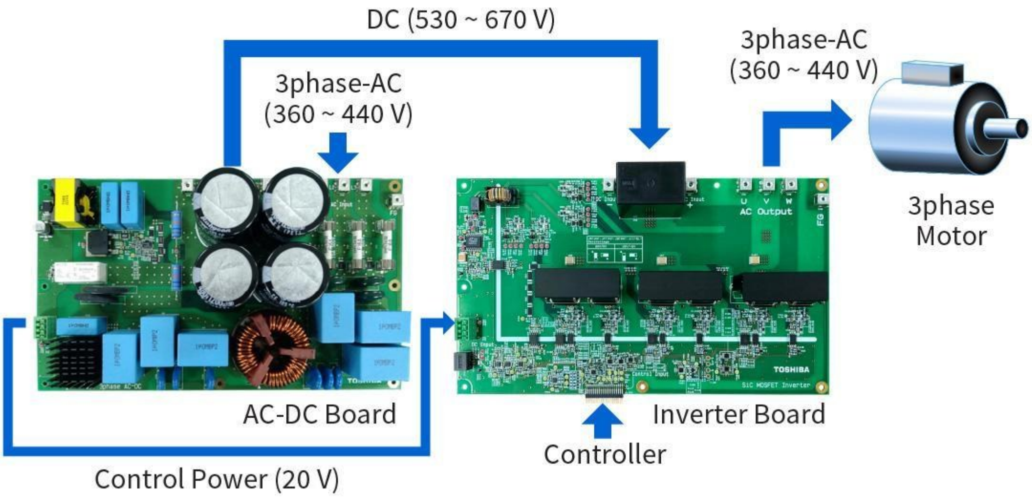

Figure 7: Overview of the complete RD220 SiC Motor Inverter Reference Design.

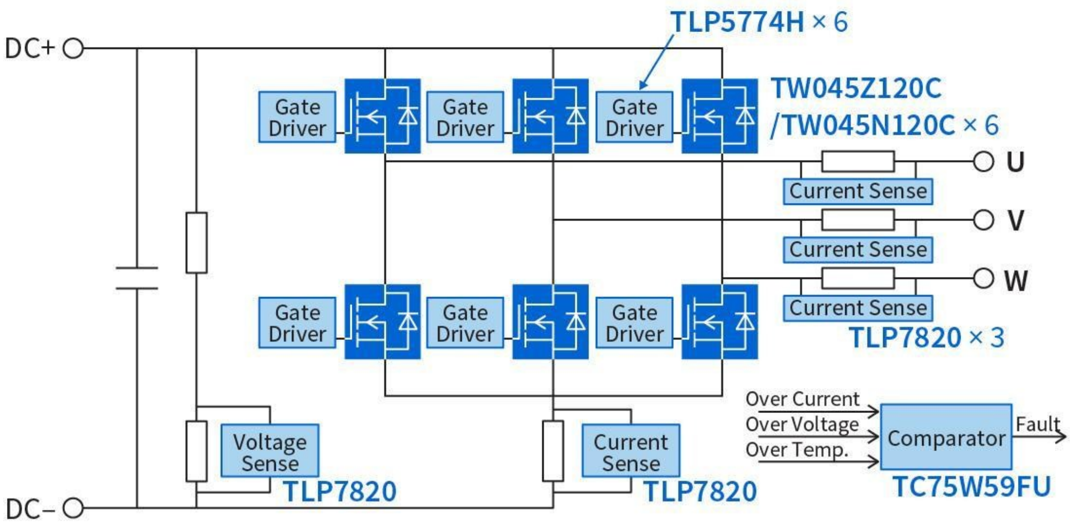

Figure 8: Block diagram of the 400V inverter featuring 3rd generation SiC MOSFETs and isolated gate drivers.

The inverter board generates four 20V isolated lines of power from the 20V supplied by the AC-DC board. This is implemented using a half-bridge gate driver that drives a half-bridge of MOSFETs (Figure 9). Switching frequency is defined by an RC oscillator device. The output voltage is fed into a transformer with four outputs. On the secondary side, a 2.0V Zener diode is used to create a -2V/+18V supply for the gate drivers and an LDO is used for a local 5V supply. Through the use of jumpers, the gate supply can be changed to 0V/+20V.

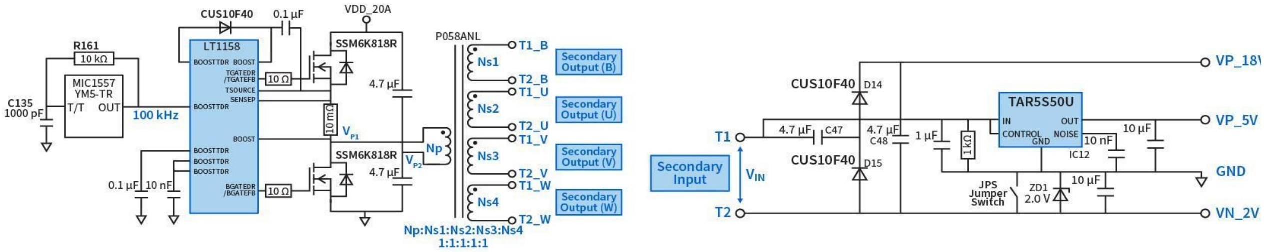

Figure 9: 20V supply and generation of isolated gate driver supply switchable between -2V/+ 18V and 0 V/+20V.

At the SiC MOSFET, the turn-on path uses just a 33Ω resistor, while the turn-off path is implemented with a single diode (Figure 10).

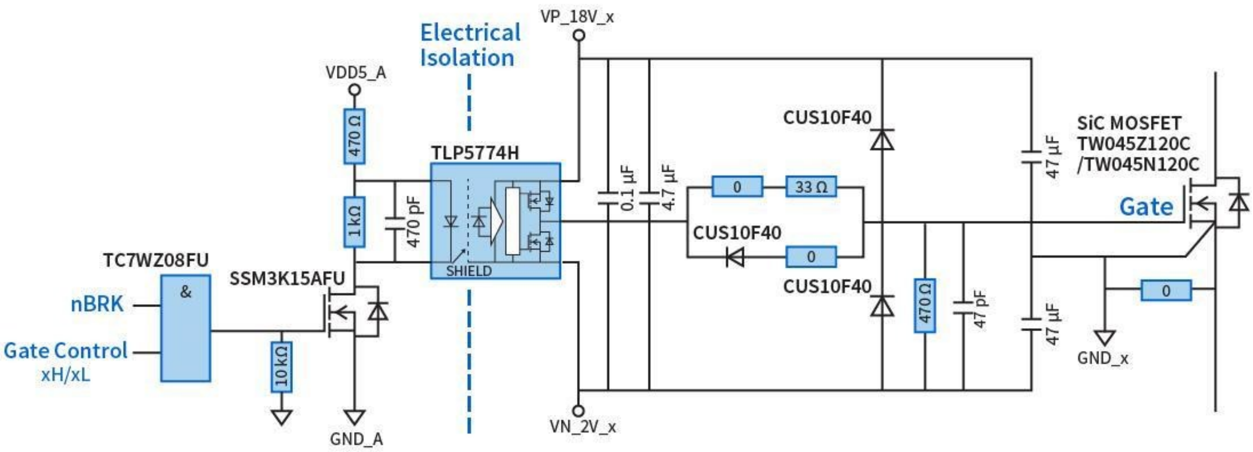

Figure 10: Implementation of the Sic MOSFET isolated gate driver circuit.

In operation, the inverter achieves an efficiency of 98.6% at maximum torque (11.6Nm) when driving a 2.2kW rated motor at a 5kHz switching frequency. More information on the design's implementation can be found in design guide[6] and reference manual[7] (Figure 11).

Figure 11: 400V motor inverter featuring four-pin TW045Z120C 3rd generation SiC MOSFETs.

Summary

While IGBTs will continue to be used for some time to come, SiC MOSFETs offer advantages for those looking to push the boundaries in inverter design to address new markets and show advancements in innovation. Thanks to their better thermal conductivity and higher upper operating temperature, SiC MOSFETs enable the more compact designs required for motors with integrated drives. They also offer an approach for inverters where forced cooling is not an option, such as in hermetically sealed designs. Compactness also comes about due to the higher possible switching frequencies, meaning the passives surrounding the switches can be smaller. This also has an impact on the BOM, lowering the system cost.

Toshiba's third-generation SiC MOSFETs are also easier to integrate into designs as a replacement for IGBTs. Packaging options with a fourth Kelvin source pin simplify the gate driver design in the presence of inductive loads. In some cases, the IGBT gate driver design can be reused. Alternatively, Toshiba's range of isolated gate drivers meets SiC's slew rate and propagation delay requirements while keeping channel skew to a minimum.

Reference designs like the RD220 400V, 3-phase motor inverter provide engineers with an excellent starting point, allowing space to test both 3-pin and 4-pin SiC MOSFETs and, thanks to the standardised pinout, different gate drivers.

References

1. https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en
2. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/
3. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en
4. https://theramreview.com/in-perspective-usdoes-study-of-electric-motor-systems-2021-edition-part-ii/
5. https://www.iea.org/reports/energy-efficiency-2020/industry
6. https://toshiba.semicon-storage.com/eu/semiconductor/design-development/referencedesign/detail.RD220.html
7. https://toshiba.semicon-storage.com/info/RD220-DGUIDE-02_E.pdf?did=153897
8. https://toshiba.semicon-storage.com/info/RD220-RGUIDE-02_E.pdf?did=153804

Restrictions On Product Use

Toshiba Corporation and its subsidiaries and affiliates are collectively referred to as “TOSHIBA”.
Hardware, software and systems described in this document are collectively referred to as “Product”.

- TOSHIBA reserves the right to make changes to the information in this document and related Product without notice.
- This document and any information herein may not be reproduced without prior written permission from TOSHIBA. Even with TOSHIBA’s written permission, reproduction is permissible only if reproduction is without alteration/omission.
- Though TOSHIBA works continually to improve Product’s quality and reliability, Product can malfunction or fail. Customers are responsible for complying with safety standards and for providing adequate designs and safeguards for their hardware, software and systems which minimise risk and avoid situations in which a malfunction or failure of Product could cause loss of human life, bodily injury or damage to property, including data loss or corruption. Before customers use the Product, create designs including the Product, or incorporate the Product into their own applications, customers must also refer to and comply with (a) the latest versions of all relevant TOSHIBA information, including without limitation, this document, the specifications, the data sheets and application notes for Product and the precautions and conditions set forth in the “TOSHIBA Semiconductor Reliability Handbook” and (b) the instructions for the application with which the Product will be used with or for. Customers are solely responsible for all aspects of their own product design or applications, including but not limited to (a) determining the appropriateness of the use of this Product in such design or applications; (b) evaluating and determining the applicability of any information contained in this document, or in charts, diagrams, programs, algorithms, sample application circuits, or any other referenced documents; and (c) validating all operating parameters for such designs and applications. TOSHIBA ASSUMES NO LIABILITY FOR CUSTOMERS’ PRODUCT DESIGN OR APPLICATIONS.
- PRODUCT IS NEITHER INTENDED NOR WARRANTED FOR USE IN EQUIPMENTS OR SYSTEMS THAT REQUIRE EXTRAORDINARILY HIGH LEVELS OF QUALITY AND/OR RELIABILITY, AND/OR A MALFUNCTION OR FAILURE OF WHICH MAY CAUSE LOSS OF HUMAN LIFE, BODILY INJURY, SERIOUS PROPERTY DAMAGE AND/OR SERIOUS PUBLIC IMPACT (“UNINTENDED USE”). Except for specific applications as expressly stated in this document, Unintended Use includes, without limitation, equipment used in nuclear facilities, equipment used in the aerospace industry, lifesaving and/or life supporting medical equipment, equipment used for automobiles, trains, ships and other transportation, traffic signalling equipment, equipment used to control combustions or explosions, safety devices, elevators and escalators, and devices related to power plant. IF YOU USE PRODUCT FOR UNINTENDED USE, TOSHIBA ASSUMES NO LIABILITY FOR PRODUCT. For details, please contact your TOSHIBA sales representative or contact as via our website.
- Do not disassemble, analyse, reverse-engineer, alter, modify, translate or copy Product, whether in whole or in part.
- Product shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable laws or regulations.
- The information contained herein is presented only as guidance for Product use. No responsibility is assumed by TOSHIBA for any infringement of patents or any other intellectual property rights of third parties that may result from the use of Product. No license to any intellectual property right is granted by this document, whether express or implied, by estoppel or otherwise.
- ABSENT A WRITTEN SIGNED AGREEMENT, EXCEPT AS PROVIDED IN THE RELEVANT TERMS AND CONDITIONS OF SALE FOR PRODUCT, AND TO THE MAXIMUM EXTENT ALLOWABLE BY LAW, TOSHIBA (1) ASSUMES NO LIABILITY WHATSOEVER, INCLUDING WITHOUT LIMITATION, INDIRECT, CONSEQUENTIAL, SPECIAL, OR INCIDENTAL DAMAGES OR LOSS, INCLUDING WITHOUT LIMITATION, LOSS OF PROFITS, LOSS OF OPPORTUNITIES, BUSINESS INTERRUPTION AND LOSS OF DATA, AND (2) DISCLAIMS ANY AND ALL EXPRESS OR IMPLIED WARRANTIES AND CONDITIONS RELATED TO SALE, USE OF PRODUCT, OR INFORMATION, INCLUDING WARRANTIES OR CONDITIONS OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, ACCURACY OF INFORMATION, OR NONINFRINGEMENT.