650V CoolSiC™ Hybrid Discretes

Optimizing the cost-performance ratio

About this document

Scope and purpose

This application note introduces 650 V CoolSiC™ Hybrid Discretes. It explains the product-level features, translates those features into system-level benefits and highlights potential use cases.

650 V CoolSiC™ Hybrid Discretes are a combination of two established, best-in-class semiconductor technologies: TRENCHSTOP™ 5 IGBTs and CoolSiC™ Schottky diodes G6. The result is an ease-of-use product with optimized cost-performance ratio and a proven track record.

Intended audience

This document addresses power electronic engineers with a basic knowledge of state-of-the-art discrete IGBTs.

Table of contents

1 Introduction

Most grid tied, power electronic systems in the low power range are based on semiconductor switches with a blocking voltage of 600 V or 650 V. Thus it is no surprise that many device concepts and technologies were developed for that voltage class [2]-[5]. For hard-switched converters that require robust free-wheeling diodes, IGBTs have undoubtedly become the most popular type of device. While wide-bandgap switches might be suitable replacements from a purely technical perspective, the cost-performance ratio as well as the proven track-record of IGBTs is quite remarkable. This is particularly true for the IGBTs used in CoolSiC™ Hybrid Discretes [1].

650 V CoolSiC™ Hybrid Discretes are a combination of two established, best-in-class semiconductor technologies: TRENCHSTOP™ 5 IGBTs and CoolSiC™ Schottky diodes G6. This combination offers two main advantages over conventional duo-pack products with silicon freewheeling diodes: drastically reduced switching losses and improved electromagnetic compatibility (EMC). Its ease-of-use nature is an additional advantage: a plug and play replacement of traditional TRENCHSTOP™ 5 IGBTs is possible.

The remainder of this section offers a brief introduction to the CoolSiC™ Hybrid Discretes concept and the portfolio. A more detailed explanation of the product features is provided in Section 2. Section 3 focuses on the application, and translates the product features into system-level improvements.

1.1 Positioning

The positioning of IGBTs is often illustrated using so-called trade-off charts. Such charts illustrate the loss characteristics of a certain device – in other words, whether it is optimized for low conduction or for low switching losses. Figure 1a) shows a trade-off chart with the IGBT forward voltage drop V_{CEsat} on the x-axis and the total switching energy (E_{on}+E_{off}) on the y-axis. The improvement from TRENCHSTOP™ IGBTs to CoolSiC™ Hybrid Discretes is clearly visible: a drastic reduction of the switching energies. Depending on the gate resistor selection, a switching loss reduction of 50% is realistic.

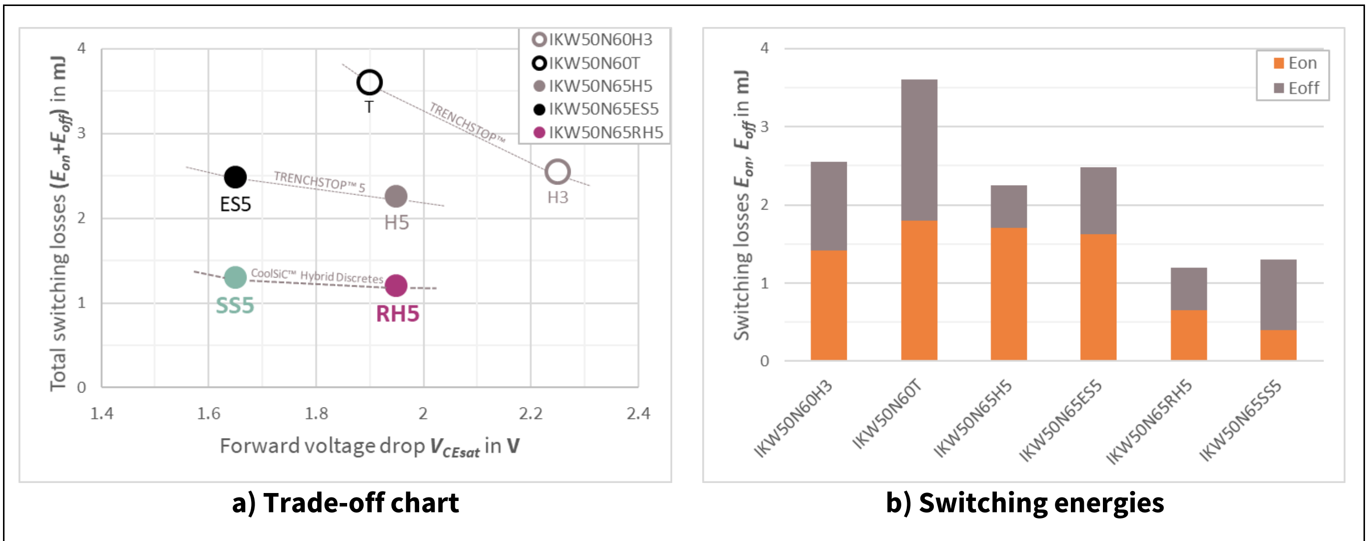


Figure 1 Conduction and switching losses of 600 V TRENCHSTOP™, 650 V TRENCHSTOP™ 5 and 650 V CoolSiC™ Hybrid Discretes based on the data sheet specifications at nominal current and maximum temperature: a) trade-off chart b) break-down of the switching energies.

Historically, conduction losses have been represented by the forward voltage drop V_{CEsat} and the switching losses by the turn-off switching energy E_{off}. The turn-on switching energy E_{on} has been ignored for two reasons: first, because the switching energy depends heavily on the diode and second, because the turn-off switching energy used to dominate the switching losses. However, according to Figure 1 b), the latter statement is not valid for modern 650 V-IGBTs anymore: due to the reverse recovery of silicon freewheeling diodes, turn-on energies clearly dominate. It is therefore obvious that a significant improvement of the switching losses requires a reduction of the reverse recovery charge. With CoolSiC™ Hybrid Discretes, this aspect is considered in a very consistent manner: the 6th generation CoolSiC™ diodes eliminate reverse recovery completely. This minimizes the switching losses without sacrificing electromagnetic compatibility, for instance via steeper switching slopes.

1.2 Product offering

The potential applications of CoolSiC™ Hybrid Discretes are manifold and so is the portfolio. In short, the offering contains products with different trade-off optimizations, different current ratings and different packages. An up-to-date overview of the portfolio is available online [1].

Figure 2 explains the naming of CoolSiC™ Hybrid Discretes. It is worth noting that the nomenclature is consistent with TRENCHSTOP™ 5 IGBTs. Each part number consists of eight blocks, where block number seven describes the type of free-wheeling diode as well as its current rating. The letters “R” and “S” indicate the application of half- and full-rated silicon carbide Schottky barrier diodes, respectively.

The nominal current of a co-packed diode is usually specified relative to the IGBT. A full-rated diode has a similar current rating as the IGBT, a half-rated diode around fifty percent of it. Figure 3 visualizes the relative diode ratings of CoolSiC™ Hybrid Discretes using the example of two 50 A devices. Further comments on the current ratings are provided in Section 2.4.1.

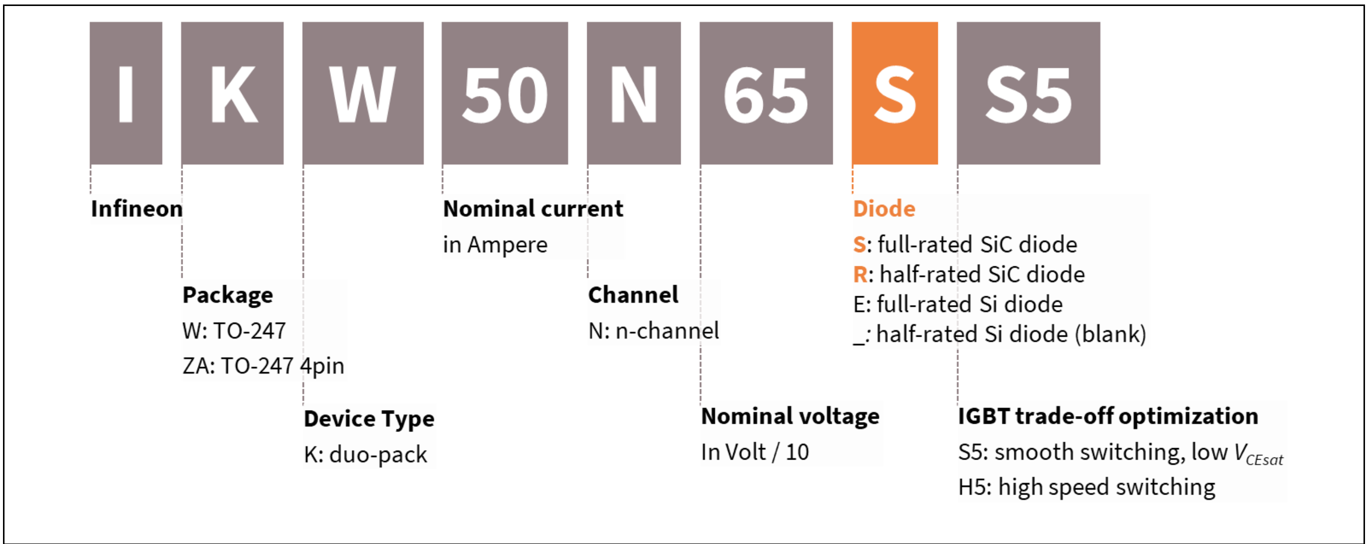


Figure 2 Nomenclature for CoolSiC™ Hybrid Discretes: part numbers are consistent with traditional TRENCHSTOP™ 5 IGBTs; the seventh block describes the applied free-wheeling diode.

Figure 3 Diode current ratings using the example of two 50A devices: a) IKW50N65SS5 with full-rated diode, b) IKW50N65RH5 with half-rated diode.

2 Product features

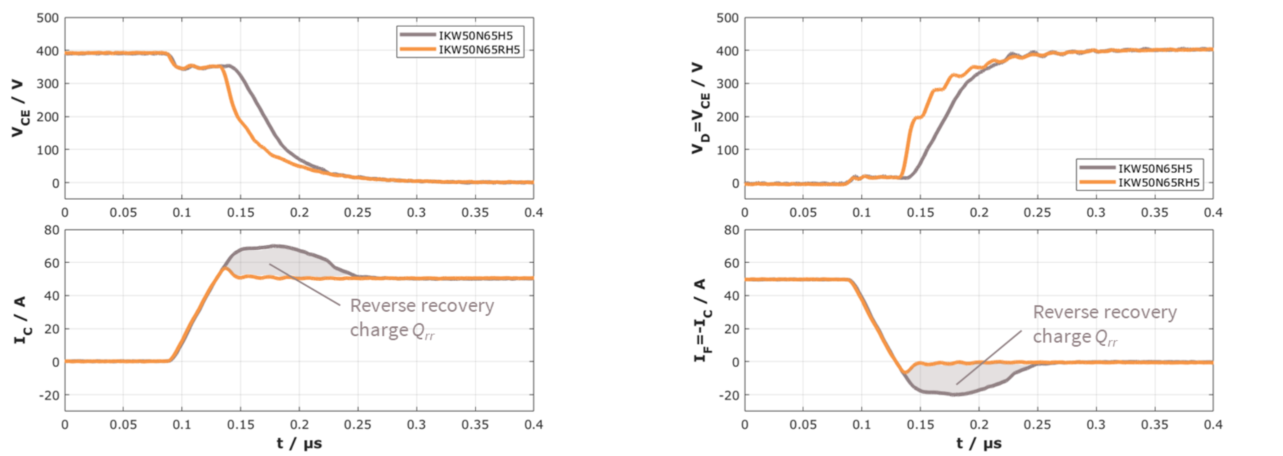
This section introduces the features of CoolSiC™ Hybrid Discretes. It highlights how the conduction and switching behavior as well as the data sheets differ from traditional TRENCHSTOP™ 5 duo-packs.

2.1 About reverse recovery

PN junction diodes cannot change from the on-state to the off-state immediately. They need to undergo reverse recovery during the transition phase: the rising blocking voltage of the diode extracts the electron-hole plasma which has accumulated in the diode chip during the conduction period. This extracted plasma is referred to as reverse recovery charge and causes switching losses.

Figure 4a) and b) show exemplary switching transients acquired during the turn-on of an IGBT. In order to accentuate the reverse recovery effect, a direct comparison of the waveforms obtained with a silicon PN junction diode (gray) and the waveforms obtained with a silicon carbide Schottky barrier diode (orange) is depicted. The waveforms are identical until the load current has fully commutated to the IGBT. Then, the respective diode is not forward biased anymore and can start to block a voltage. On the silicon carbide Schottky barrier diode, the voltage rises immediately. With the PN junction diode it takes a bit longer since the blocking voltage needs to extract the electron-hole plasma, typically referred to as reverse recovery charge, out of the diode.

Apparently, reverse recovery causes losses on both, the IGBT and the diode. Part of the losses can directly be attributed to the reverse recovery charge through ($Q_{rr} \cdot V_{bus}$); the rest is due to reduced steepness of the voltage slope. Since silicon carbide Schottky barrier diodes are not flooded with charge carriers during the conduction phase, they do not need to undergo reverse recovery. Compared to silicon PN junction diodes, this leads to a substantial reduction of switching losses.



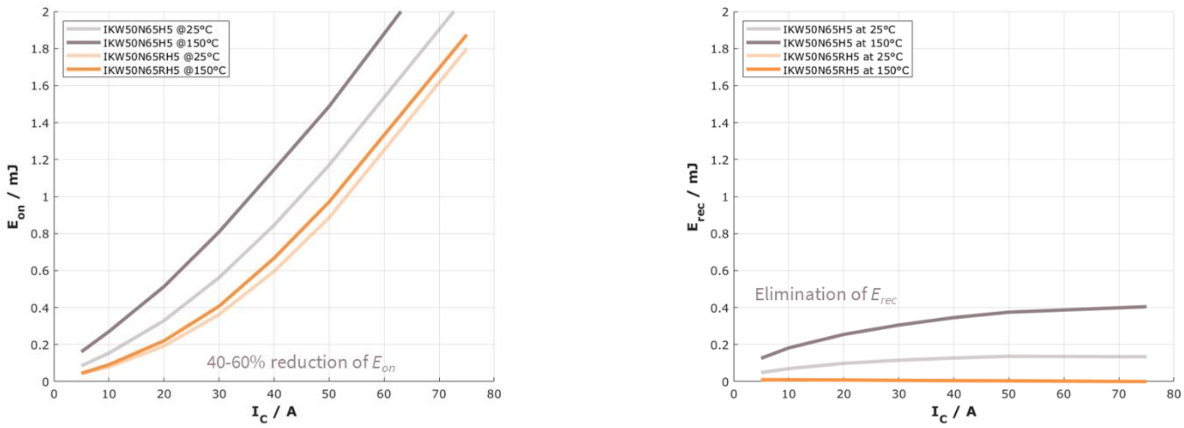
a) IGBT waveforms b) Diode waveforms

Figure 4 Exemplary waveforms of a current commutation in a half bridge after the turn-on of an IGBT at 400V, 50A and 150°C; the orange waveforms were obtained with a silicon carbide diode, the gray waveforms with a silicon PN diode; the impact of reverse recovery on a) the IGBT and b) the diode is clearly visible.

2.2 Switching losses and behavior

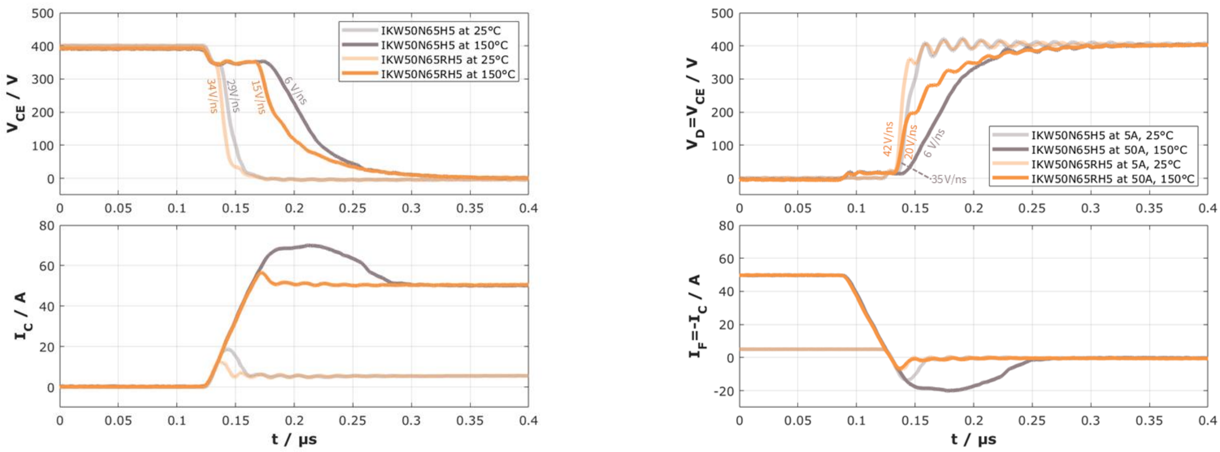
As explained above, CoolSiC™ Hybrid Discretes with its silicon carbide Schottky barrier diodes have drastically lower switching losses compared to traditional TRENCHSTOP™ 5 duo-packs with silicon diodes. While the turn-off switching energy E_{off} is essentially unchanged, the turn-on switching energy E_{on} is reduced significantly and the diode recovery energy E_{rec} is eliminated completely. Furthermore, the turn-on energies and switching slopes become virtually independent of the temperature. The exemplary measurement data provided in Figure 5 indicates that even a halving of the total switching energy (E_{on}+E_{off}+E_{rec}) is realistic. However, the relative reduction depends on the respective operation conditions: the lower the load current, the higher the switching speed and the higher the temperature, the more significant is the loss reduction.

Besides the well-known loss reduction potential, there is another interesting aspect of CoolSiC™ Hybrid Discretes. Its performance improvement does not come with adverse effects. While a reduction of the switching losses with classical means often goes hand in hand with more aggressive switching transients – switching slopes get steeper and over-voltages higher – this does not really happen when applying silicon carbide Schottky barrier diodes. CoolSiC™ Hybrid Discretes can even help to improve electromagnetic compatibility and system reliability.



a) Turn-on energy of the IGBT b) Reverse recovery energy of the diode

Figure 5 Switching energies related to the turn-on of the IGBT: a) turn-on energy dissipated on the IGBT, b) reverse recovery energy dissipated on the diode; the energy values are presented as a function of the load current and were obtained at a bus voltage 400 V, temperatures of 25°C and 150°C, with a gate voltage of 15 V and a gate resistance of 10 Ω.



a) Turn-on waveforms of the IGBT b) Turn-off waveforms of the diode

Figure 6 Switching waveforms of a) an IGBT and b) a freewheeling diode acquired during the same switching transient; the comparison illustrates the switching behavior at low and high load conditions and was obtained using a gate voltage of 15 V and a gate resistance of 10 Ω.

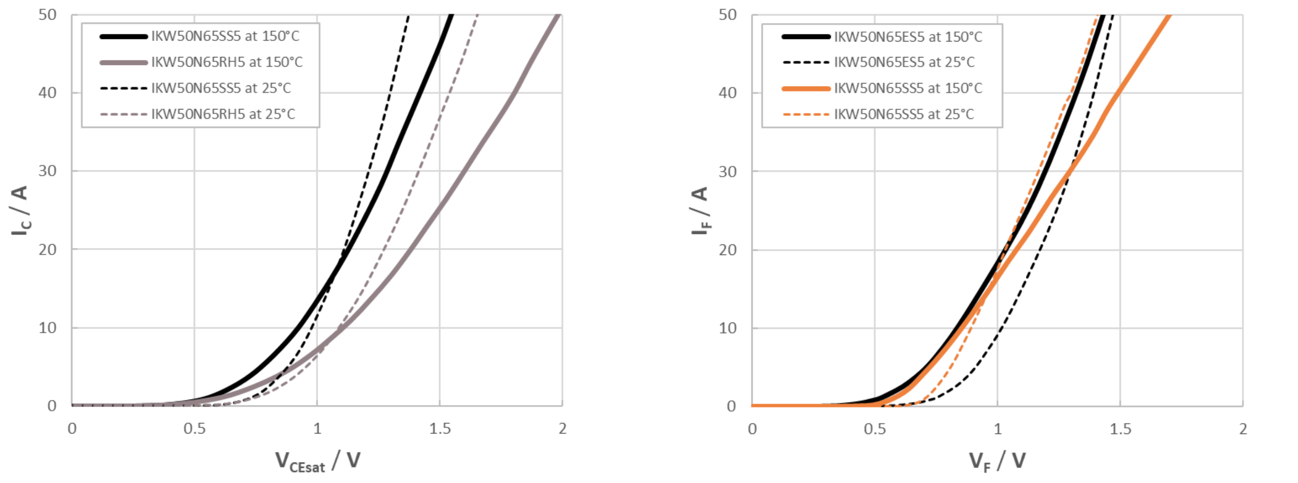
Indeed, silicon carbide Schottky barrier diodes bring an increased steepness of the turn-on voltage slope at high temperature and current levels. At such conditions, though, the steepness values are far from their maximum values. Steep turn-on voltage slopes occur at low current and temperature values. And for those conditions, TRENCHSTOP™ 5 IGBTs and CoolSiC™ Hybrid Discretes behave very similarly, as Figure 6 clearly shows. In short, CoolSiC™ Hybrid Discretes do not increase the worst-case *dv/dt*. Instead, they minimize the slow-down of the switching speed at high current and temperature levels.

Finally, CoolSiC™ Hybrid Discretes also have an advantage over conventional duo-packs with respect to snappiness. Many silicon PN junction diodes tend to get "snappy" at elevated bus voltages. This potentially leads to high over-voltages, severe oscillations and an increased risk of parasitic turn-on. Due to the unipolar nature of Schottky barrier diodes, there is no plasma-supported reverse current which can suddenly snap off.

2.3 Conduction losses

Due to the re-application of the IGBT technology, CoolSiC™ Hybrid Discretes and TRENCHSTOP™ 5 duo-packs have the same output characteristics and thus the same conduction losses in forward direction. The difference between the known IGBT trade-off variants S5 and H5 are indicated in Figure 7a).

In reverse direction, where it is the diode that matters, there is a slight difference, according to Figure 7b). While the Schottky barrier diode of CoolSiC™ Hybrid Discretes are advantageous at lower temperature and current values, the silicon diodes of TRENCHSTOP™ 5 duo-packs are beneficial at higher current and temperature values.



a) Output characteristic of IGBT trade-off variants b) Forward characteristic of diode

Figure 7 Voltage drop in a) forward and b) reverse direction.

2.4 Data sheet specifics

In order to allow a fast comparison of device features and parameters, the data sheets of CoolSiC™ Hybrid Discretes were kept as consistent as possible with TRENCHSTOP™ 5 data sheets. Nevertheless, as explained in the remainder of this section, a few differences were unavoidable.

2.4.1 Diode current ratings

The silicon carbide Schottky barrier diodes assembled in CoolSiC™ Hybrid Discretes boost the performance of the duo-pack drastically. However, at present, silicon carbide chips are still comparably expensive. Hence, to reach a good balance of cost and performance, the diodes must not be overdesigned. This implies a slight reduction of the DC and the pulse current ratings compared to the diodes of conventional TRENCHSTOP™ 5 duo-packs. Since Schottky diodes are free of switching losses, the reduced diode ratings are typically well compensated by the drastic loss reduction.

As visualized in Figure 3, the DC current ratings of the silicon carbide diodes assembled in CoolSiC™ Hybrid Discretes are around twenty percent smaller compared to the silicon diodes which are used in traditional TRENCHSTOP™ 5 duo-packs. The pulse-current limits scale linearly with the diode rating and are consistent with the surge and pulse-current specifications of the standalone CoolSiC™ diodes. At the same time, they are lower compared to traditional TRENCHSTOP™ 5 duo-packs. So, in order to allow designers to maximize the utilization of the diodes, an additional diagram is provided in the data sheet. It specifies the allowed pulse-current value as a function of the junction temperature. An example is provided in Figure 8.

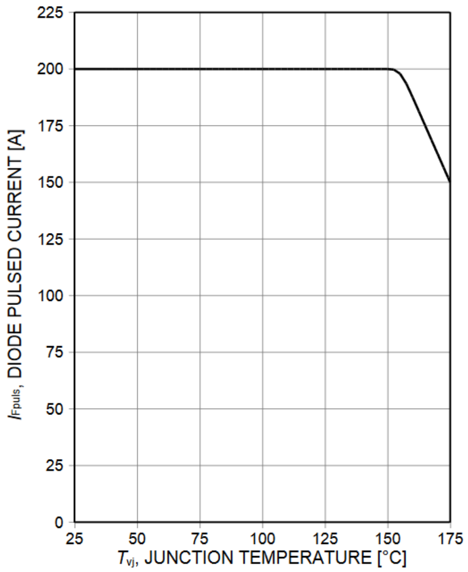


Figure 20. **Maximum pulse current as a function of junction temperature**

Figure 8 **Exemplary pulse-current chart: it was newly introduced for the CoolSiC™ Hybrid Discrete data sheets, and describes the maximum pulse current of the diode as a function of the junction temperature; the chart shown here belongs to the IKW50N65SS5**

2.4.2 Diode switching characteristics

Due to their operation principle, silicon carbide Schottky barrier diodes do not undergo reverse recovery during the commutation. Essentially, this means that they are free of reverse-recovery charge. The charge, which is visible during commutation of a Schottky diode, is of capacitive nature and orders of magnitudes smaller compared to the reverse recovery charge of typical silicon free-wheeling diodes. Consequently, the data sheets of CoolSiC™ Hybrid Discretes do not contain any specification of the reverse recovery charge Q_{rr}, reverse recovery time t_{rr} or the peak reverse recovery current I_{rrm}.

3 Improvements on system-level

This section describes selected use cases for 650 V CoolSiC™ Hybrid Discretes and translates the above-mentioned product-level features into system-level benefits.

3.1 General considerations

One of the most interesting features of 650 V CoolSiC™ Hybrid Discretes is the possibility to go for a plug-and-play design approach. By directly replacing classic TRENCHSTOP™ 5 duo-packs with CoolSiC™ Hybrid Discretes, a drastic increase of system performance is possible. Since drivers, supplies, gate voltages as well as gate resistances can remain unchanged, the design-in effort is practically zero.

Ideally, 650 V CoolSiC™ Hybrid Discretes are applied selectively. The guideline is simple: use silicon carbide diodes in circuit positions, where a hard commutation occurs in every switching period. In such cases, the one-to-one replacement of 650 V TRENCHSTOP™ 5 duo-packs by 650 V CoolSiC™ Hybrid Discretes leads to an efficiency increase of around 0.1 % for each 10 kHz switching frequency. For an exemplary system operating at 30 kHz, the efficiency increases by around 0.3 %. While it is straightforward to determine this rule of thumb analytically via ($Q_{rr} \cdot V_{bus}$), an empiric demonstration is found in [6]. It should be noted though, that this rule of thumb holds for the situation of one hard commutation per switching period and assumes a bus voltage of around 350-400 V.

Of course, the reduction of switching losses might also be used to increase the switching frequency. With unchanged output power requirements, the potential switching frequency increase can be estimated using total switching losses ($E_{on}+E_{off}+E_{rec}$). As mentioned in Section 2.2, the total switching losses might even be halved. In theory, this would allow a doubling of the switching frequency.

3.2 Potential applications

While there are systems that can benefit greatly from the application of 650 V CoolSiC™ Hybrid Discretes, the latter do not pay off in each and every circuit. This section lists and explains selected application examples.

3.2.1 Clamping path of three-level inverters

In Section 3.1 it was mentioned that 650 V CoolSiC™ Hybrid Discretes should be applied selectively in order to optimize the cost-performance ratio. This is particularly true for three-level inverters which create an additional output voltage level of 0 V to reduce the stress on the filter inductors. This 0 V-level is often obtained using a dedicated clamping path. Interestingly, at a power factor of one, only the freewheeling diodes in that clamping path undergo hard commutation. Hence, the application of 650 V CoolSiC™ Hybrid Discretes in three-level inverters can and should be limited to the clamping path.

Figure 9 provides an overview of three-level topologies which are commonly used to realize single-phase solar string inverters. The circuit positions highlighted in orange serve as clamping path and are ideally implemented using SS5 devices, i.e. CoolSiC™ Hybrid Discretes with an S5 IGBT trade-off.

The improvement potential and optimization possibilities obtained through the application of CoolSiC™ Hybrid Discretes are explained using the chart in Figure 10. It shows a calculation of the maximum achievable output current of a HERIC converter for two different clamping leg implementations. The black line represents an implementation with traditional TRENCHSTOP™ 5 IGBTs, the orange line with CoolSiC™ Hybrid Discretes. By using CoolSiC™ Hybrid Discretes both the switching frequency and output power can be increased. While the chart only shows the extreme cases – either a 20% output power increase at 30 kHz or a doubling of the switching frequency – all kinds of compromises between those corner points are possible.

Note that while the calculation is based on the HERIC topology, the statements also hold for single-phase inverter implementations based on the H5 and H6 topology families as well as three-phase inverters based on the three-level T-type topology [6]. The fundamental operation principle of those inverters is similar.

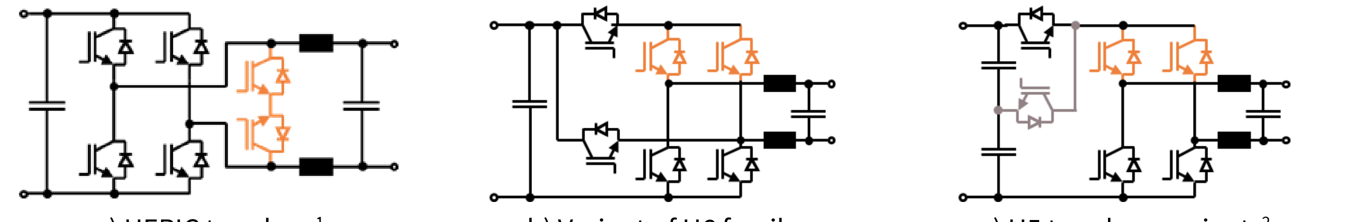


Figure 9 Common single-phase three-level inverters: a) HERIC, b) one variant of the H6 topology family and c) variants of the H5 topology; components highlighted in orange serve as clamping path, and are ideally implemented using SS5.

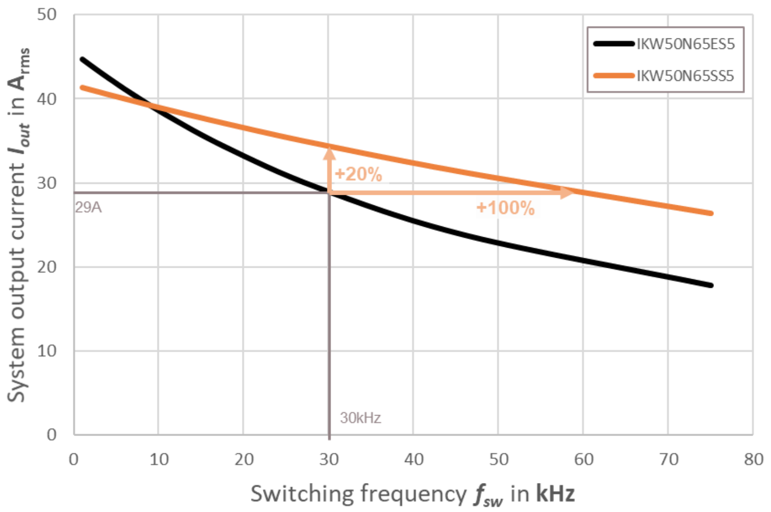


Figure 10 Comparison of the maximum achievable output current of a HERIC converter at different switching frequency values: The bridges are implemented using IKW50N65H5, the clamping path using IKW50N65ES5 (black) and IKW50N65SS5 (orange); all IGBTs are assembled on the same heat sink; conditions: heat sink with 0.6 K/W total, Al_2O_3 ceramic insulators with 0.4 K/W per package, T_{amb}=50°C, $T_{vj,max}$=150°C, V_{bus}=550 V, V_{out}=230 V, cos(ϕ)=0.9, V_{GE}=15/0 V, R_G=10 Ω.

3.2.2 High-speed leg of totem-pole PFC circuits

The most widespread single-phase active rectification solution is probably the boost PFC shown in Figure 11a). It is simple to build, simple to control, and implemented with one switch, only. However, it requires a bridge rectifier at the input. Considering that two rectifier diodes are in the current path at all points in time and each diode causes a voltage drop of around 1 V, close to 1% of the efficiency is lost on the bridge rectifier at high line. Naturally, this figure gets even higher at low input voltage. Thus it is no surprise that many bridgeless PFC topologies have been suggested as alternatives. While some require a second boost inductor or result in severe

[1] Topology may, in some jurisdictions, be subject to intellectual property rights, e.g. EP 1 369 985 B1, and accordingly, usage thereof may be subject to approval by the respective owner.

[2] At least one topology variant may, in some jurisdictions, be subject to intellectual property rights, e.g. EP 2 290 797 B1, and accordingly, usage thereof may be subject to approval by the respective owner.

EMC challenges, the so-called totem-pole PFC depicted in Figure 11b) and c) is free of those side effects. It consists of a high-speed half bridge leg and a line frequency rectification leg. RH5 devices are ideal candidates for the high-speed leg.

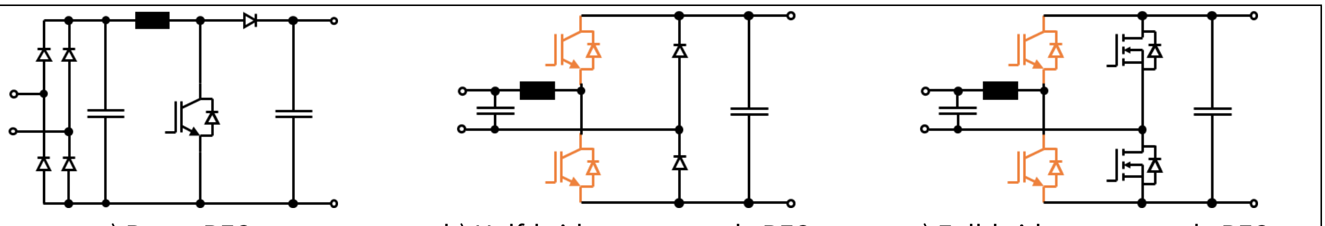


Figure 11 Single-phase PFC solutions: a) boost PFC, b) half-bridge totem-pole PFC and c) full-bridge totem-pole PFC; components highlighted in orange are ideally implemented using RH5.

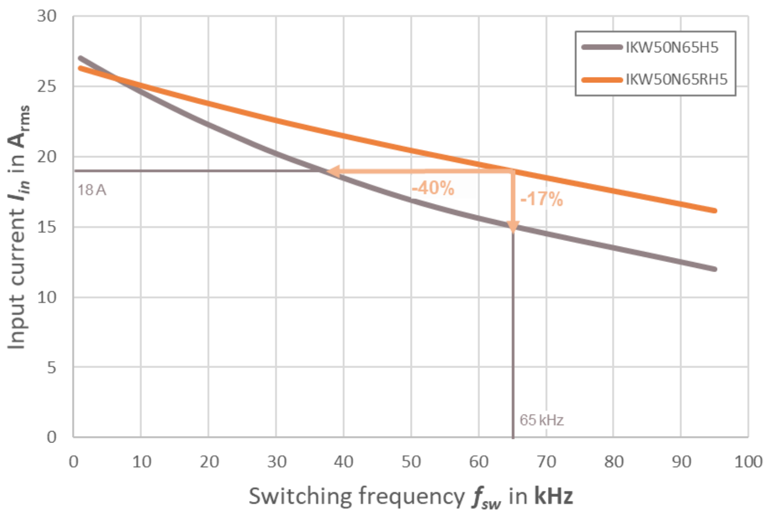


Figure 12 Comparison of the maximum achievable output current of a half-bridge totem pole PFC at different switching frequencies: the high-speed leg is implemented using IKW50N65H5 (black) and IKW50N65RH5 (orange); conditions: heat sink with 1.1 K/W total, polyimide-based insulation foil with 0.6 K/W per package, T_{amb}=50°C, $T_{vj,max}$=150°C, V_{bus}=400 V, V_{in}=230 V · 0.8=184 V, V_{GE}=15/0 V, R_G=5 Ω.

Figure 12 gives an impression of the output current capability of such a device. A 50 A device can be operated at a switching frequency of 65 kHz, and process 3.3 kW. Since both the switching frequency and the power rating are commonly seen in high-performance PFCs, highly optimized and cost-efficient passives are available off-the-shelf. With respect to performance, TRENCHSTOP™ 5 IGBTs cannot really compete at 65 kHz. First, the efficiency would be around 0.6% lower. And second, either a reduced power rating of around 2.8 kW or a larger heat sink needs to be accepted.

3.2.3 Half-bridge converters

CoolSiC™ Hybrid Discretes might be applied in all hard-switching half-bridge converters that require bi-directional power flow capability. While the selection of the IGBT trade-off is quite straightforward for the above-mentioned use cases, here the decision depends on the specific design goal.

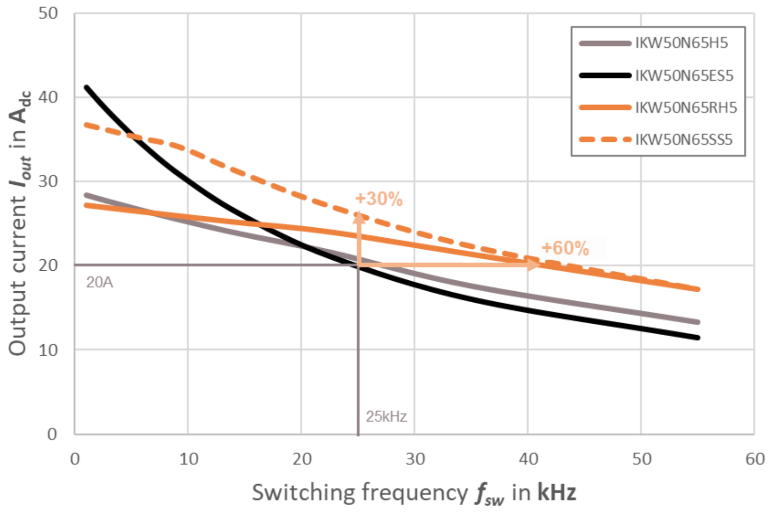


Figure 13 Comparison of the maximum achievable output current of a half-bridge operating as buck converter: the circuit is implemented using IKW50N65H5 (gray), IKW50N65ES5 (black), IKW50N65RH5 (solid orange) and IKW50N65SS5 (dashed orange); the IGBTs are assembled on the same heat sink; conditions: heat sink with 1.1 K/W total, polyimide-based insulation foil with 0.6 K/W, T_{amb}=50°C, $T_{vj,max}$=150°C, V_{bus}=400 V, V_{out}=200 V, V_{GE}=15/0 V, R_G=10 Ω.

An example calculation is provided in Figure 13. It assumes that a state-of-the-art system with traditional TRENCHSTOP™ 5 duo-packs is operated at a frequency of 25 kHz. From a pure performance perspective, the following rules can be formulated:

1. Select SS5 devices if a pure output power increase is desired. Due to the low switching frequency, the load current and thus the conduction losses on the semiconductors tend to get higher. Thus, a full diode rating is reasonable.
2. Select RH5 devices if a pure switching frequency increase is desired. Due to the high frequency, the dominant losses on the IGBT are switching losses. Consequently, the load current tends to be comparably low. The half-rated diode might be fully utilized but is usually sufficient, and avoids expensive over-engineering.
3. A further option in the example calculation shown in Figure 13 would be to use an IKW75N65RH5 instead of the IKW50N65SS5.

4 Summary

CoolSiC™ Hybrid Discretes are a combination of two established, best-in-class semiconductor technologies: TRENCHSTOP™ 5 IGBTs and CoolSiC™ Schottky diodes G6. The resulting products have a performance similar to silicon carbide switches but come for lower cost.

Since CoolSiC™ Hybrid Discretes are based on the widely used TRENCHSTOP™ 5 IGBT technology, the design-in is straightforward: gate drivers, supplies and gate voltages can remain untouched. In the special case of replacing TRENCHSTOP™ 5 IGBTs directly, even the gate resistances can be kept the same.

Despite the effortless design-in, the performance improvement achievable with CoolSiC™ Hybrid Discretes is remarkable. The switching loss reduction compared to TRENCHSTOP™ 5 brings a significant efficiency increase. A simple rule of thumb which works for many applications is that the efficiency increases by around 0.1% for each 10 kHz switching frequency. Naturally, this is an enabler for increasing the output power, reducing the cooling effort or increasing the switching frequency.

Last but not least, CoolSiC™ Hybrid Discretes might also help to improve the situation with electromagnetic compatibility. Due to the unipolar nature of Schottky barrier diodes, there is no plasma-supported reverse current which can suddenly snap off and cause overvoltages and excessive ringing.

CoolSiC™ Hybrid Discretes can be used in many different applications such as three-level converters or totem-pole PFC circuits, to name just a few. Ideally, the devices are applied selectively – in circuit positions, where the diode undergoes a hard commutation in every switching period. This is where the diode displays its strength.

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