Breaking barriers: Optimizing power technology for efficient traction inverters

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1 Introduction

Efficient traction inverters have the ability to unleash the full potential of electric vehicles. The optimal technology will strike the right balance between power, efficiency, and material utilization. Different semiconductor materials offer different performance benefits: Overall, silicon carbide (SiC) takes center stage, offering superior performance and efficiency. However, it is subject to complex production processes and is the more expensive option. Fusion technology traction inverters combine silicon (Si) and SiC power switches to hit the sweet spot between efficiency, cost, and sustainability.

Infineon Technologies offers a comprehensive product portfolio for advanced traction inverter designs. These devices give customers the opportunity to join the movement towards greener transportation and a circular economy, prioritizing energy efficiency and local sourcing. This article explores how innovative inverter technologies from Infineon are paving the way for a sustainable and electrifying ride.

By Dirk Geiger and Christoph Bauer, Infineon Technologies

2 Efficiency by design: Fusion technology for traction inverters

2.1 Moving beyond single material designs towards fusion technology

Power semiconductor technologies such as Si IGBTs or wide-bandgap (WBG) semiconductors have different performance characteristics suited to different target applications. The choice of semiconductor material is not only dictated by factors such as the need to reduce cost or downsize an application. Increasingly, designers are looking to use and combine semiconductor materials in creative ways to reduce material requirements.

Innovative approaches challenge the previously established notion that certain applications are locked into specific uniform semiconductor materials. In the past, for instance, it was assumed that inverter power stages must be designed with the same semiconductor material. Now, fusion technology is paving the way for new design possibilities. However, this calls for an in-depth understanding of electric drivetrains and different automotive application requirements. Technology leader Infineon is pioneering the innovative combination of semiconductor materials for new inverter designs that strike a market-driven balance for both cost and performance optimization.

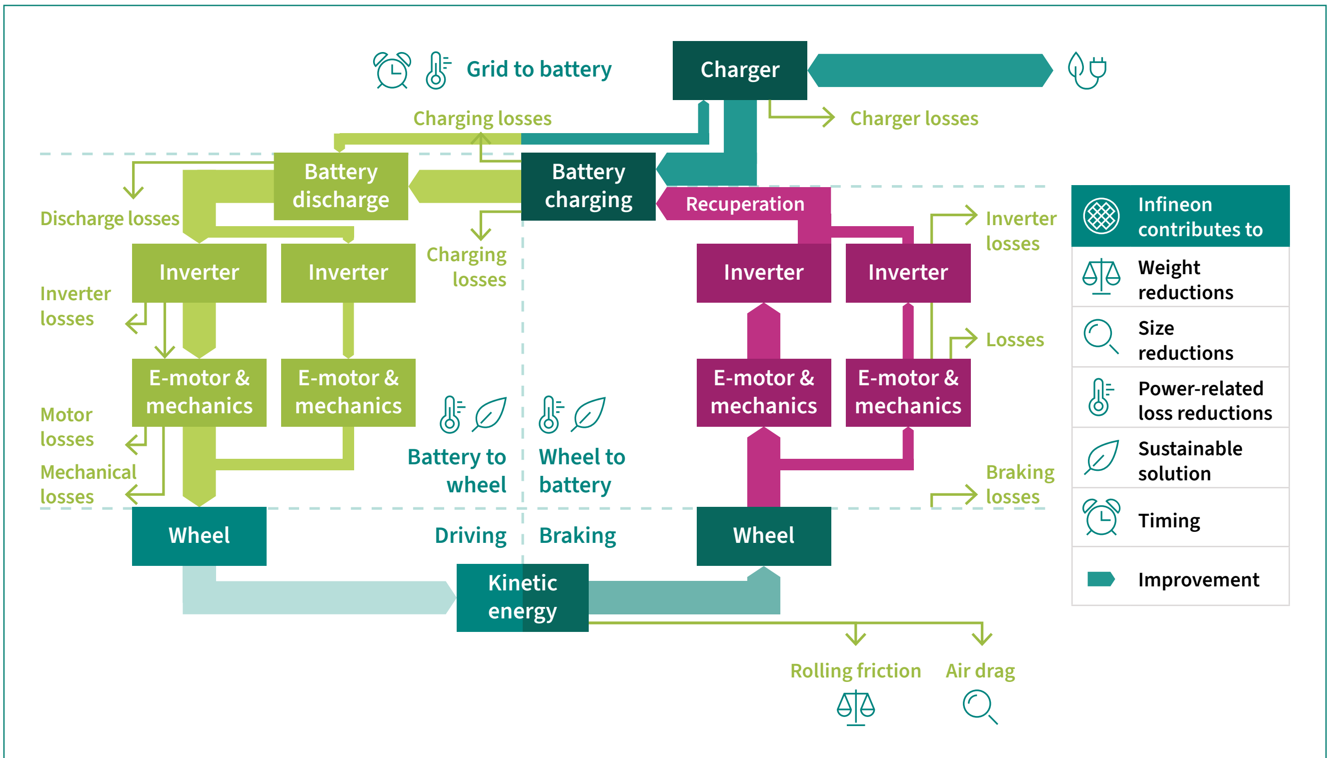


Figure 1 Power flow diagram for a two-eAxle electric vehicle (EV)

2.2 Closer look at energy flow in an EV

The power flow diagram (Figure 1) highlights where energy is consumed, lost and harvested in an electric vehicle (EV) drivetrain. On the left side, you can see the propulsion cycle and, on the right, the braking and recuperation cycle. This illustration shows a vehicle with two electric axles – one on the front and one on the rear with a single motor each. That raises the question: “What is the purpose of each axle?”. In the following sections, we will define the respective requirements and solutions.

Looking at an electric vehicle with two eAxles, OEMs and system developers have a series of choices to make to address efficiency requirements, cost considerations, sustainability, and the availability of materials.

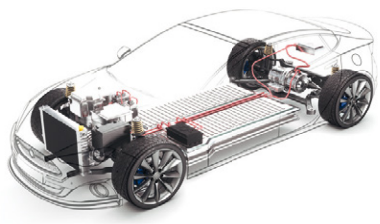
3 Key roles of traction inverters

3.1 Key component supporting multiple functions

In simple terms, all you need is a charger, a battery, a traction inverter, and a motor to get an electric vehicle in motion. On closer inspection, the traction inverter and motor are not only responsible for propulsion, but also work as a generator during deceleration to recover energy and feed it back into the main HV battery. The traction inverter and motor perform some secondary functions, like hill hold and battery preconditioning. The system also supports related functions, like torque management, steering, and vehicle stability (Figure 2).

1 Primary Functions

Motor control
- Forward/backward
- Hill hold
- Generator (regenerative braking)
- Enables car to respond safety



2 Secondary Functions

Battery warm-up/ pre-conditioning
- Start-up in cold conditions
- Energy transfer inverter/battery

Torque vectoring actuation
- Front/rear & right/left (differential)

Battery charging
- DC-DC charging 400 V – 800 V

Discharging the DC link
- After battery turn-off

3 Related Functions

Vehicle stability system
- Motion control (VCU)
- Synergies:
  - Motors
  - Braking
  - Steering
  - Suspension

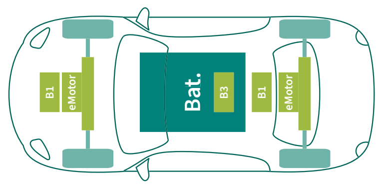


Figure 2 Multiple functions supported by a traction inverter

3.2 Measuring EV efficiency using the standardized drive cycle (WLTP) vs. peak performance

The Worldwide harmonized Light vehicles Test Procedure (WLTP) drive cycle reflects a near real-world drive mission. Being standardized, it gives OEMs and consumers a reference value to compare the efficiency of different vehicles. For EVs, it is expressed in consumption of energy over a distance, like 10 kWh for 100 km, or as “miles per gallon of gasoline-equivalent” (MPGe), an indicator that also allows comparisons with conventional combustion engine vehicles.

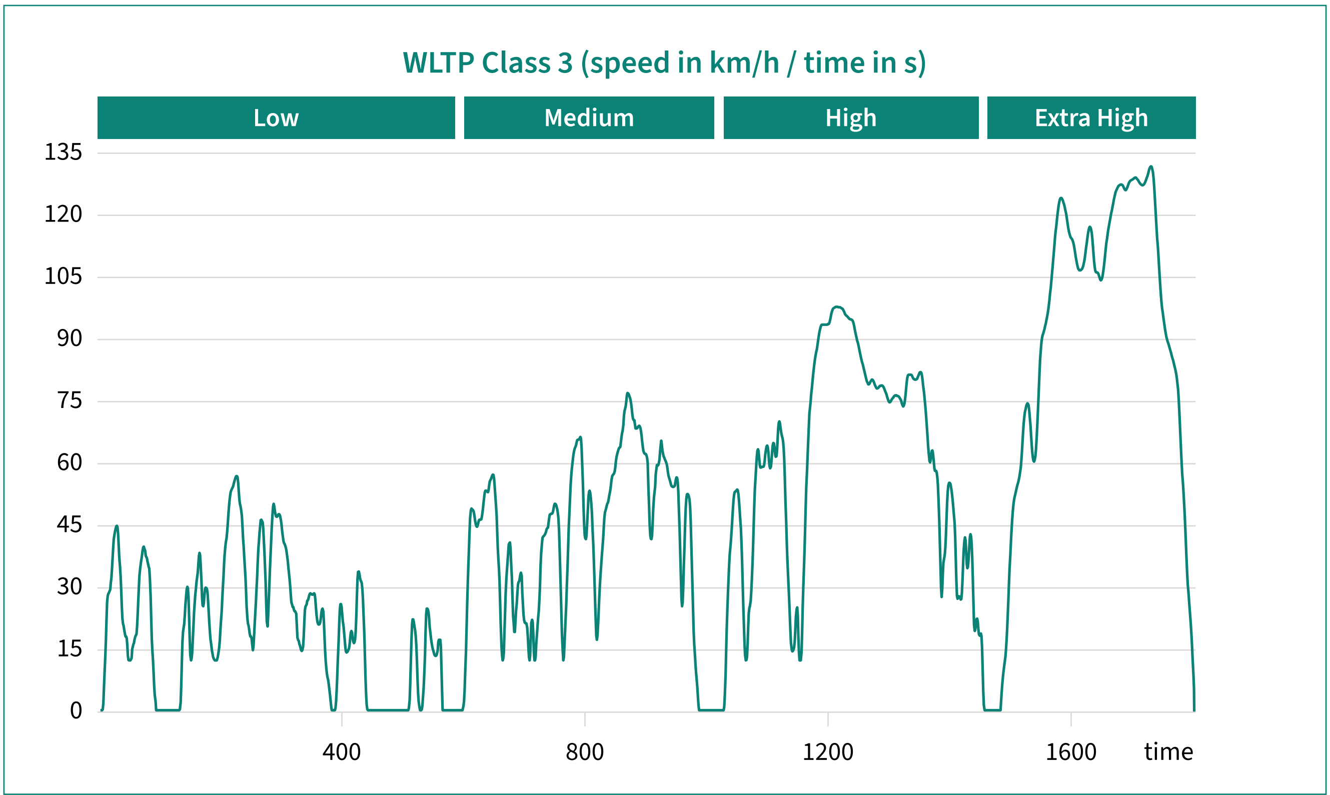


Figure 3 Worldwide harmonized Light vehicles Test Procedure (WLTP) represents a typical drive profile

The WLTP drive cycle (Figure 3), comparable to any other mission profile, consists of various accelerations, decelerations, and performance periods within a 23.3 km distance for 1800 seconds. There are different opinions as to whether the WLTP reflects real-world driving given the variations in driving styles. But it is suitable as a basis for rating the efficiency of a car. The WLTP mission profile allows OEMs to calculate the required minimum motor performance for a given vehicle and its key parameters, like weight, wind resistance, driving efficiency, acceleration, and recuperation.

Taking the example of a car weighing 1500 kg, the values were calculated and plotted in a histogram (Figure 4). This chart shows that the output power of the traction inverter to satisfy the WLTP drive cycle needs to be ~50 kW. That is surprisingly little power to accelerate, reach peak speed, and recuperate an EV for this mission profile. In generator mode (see purple bars in Figure 4), the maximum power is ~28 kW.

For the next chapters 80 kW is defined as the reference value for the maximum output power to allow for heavier vehicles, stronger wind resistance, and the possibility of higher demands during other driving cycles.

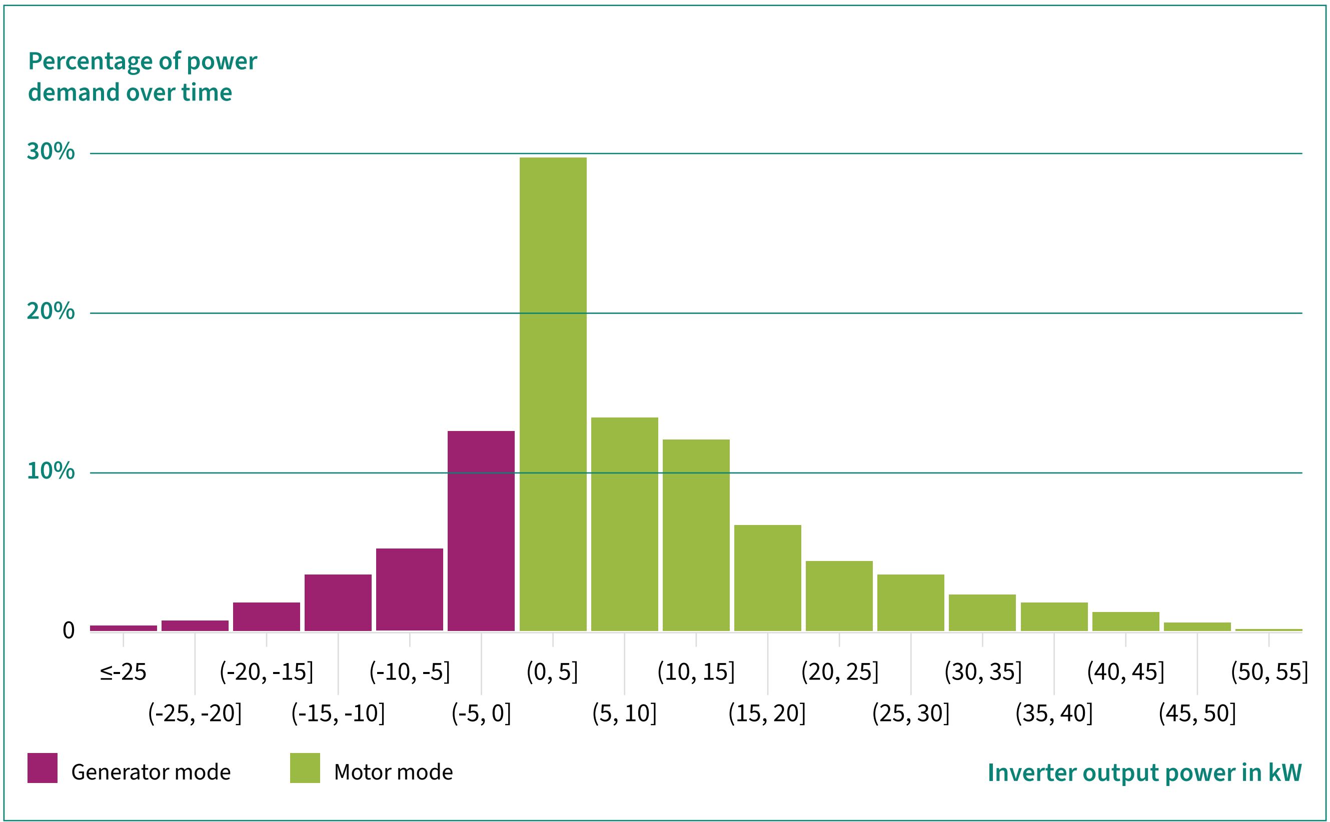


Figure 4 Traction inverter output power over time within the WLTP cycle

4 Build more with less: Overcoming supply limitations through innovation

4.1 Need for new supply chains

Decarbonization is accelerating the replacement of conventional combustion vehicles with electrified options. We estimate that every second car sold (Figure 5) will be electrified by 2030 (or that about 40-50 million vehicles sold in 2030 will be electrified). That is an enormous technology shift, calling for the fast ramp-up of new vehicle technologies. This, in turn, means that new value chains need to be established. In this early stage, the industry is driven by innovation, with a strong focus on optimizing energy efficiency and the usage of raw materials.

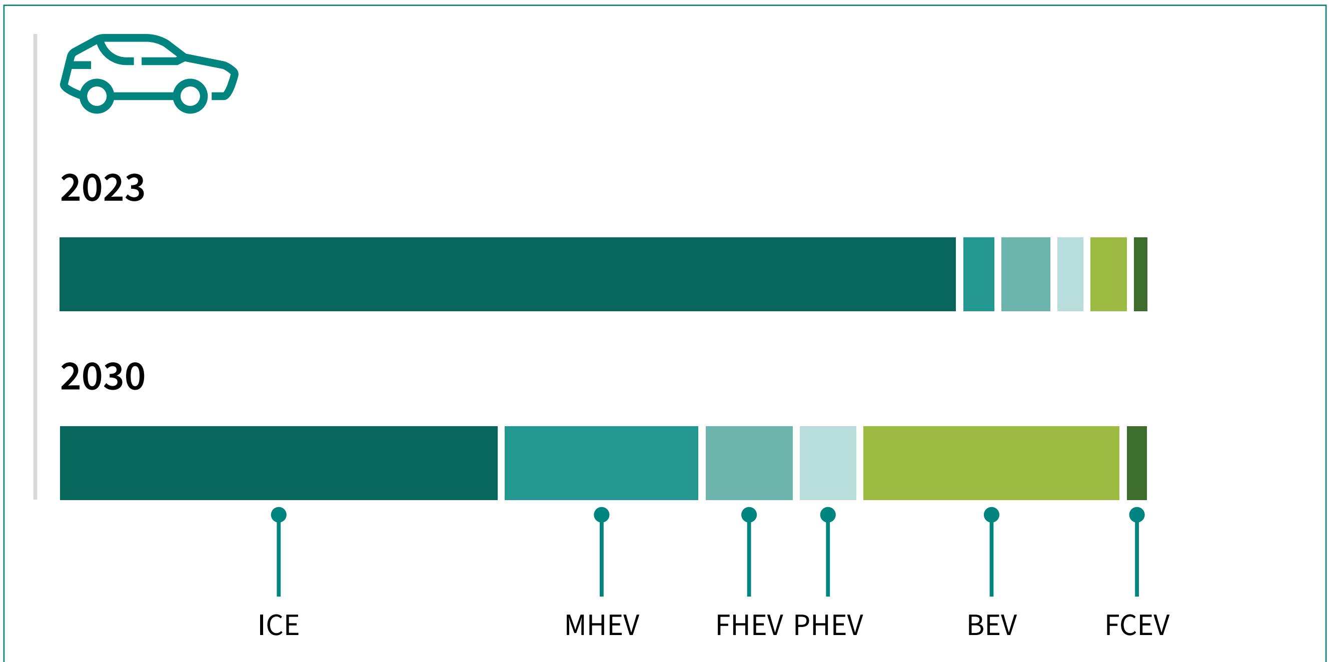


Figure 5 Every second car sold will be electrified by 2030 (according to Infineon's market study)

The EV supply chain is highly complex, expensive, and exposed to risk. EV makers are shifting from global to local sourcing to enable simpler, faster, and cheaper supply chains.

The rapid growth in EV uptake needs to be enabled by a supply chain that can deliver the required materials for motors and batteries, as well as aluminum, steel, and semiconductors. To make the supply chain as sustainable as possible, a circular economy is also needed. In other words, end-of-life materials are reused in the production of new vehicles. EV batteries in particular must be given a second life in industrial or consumer applications.

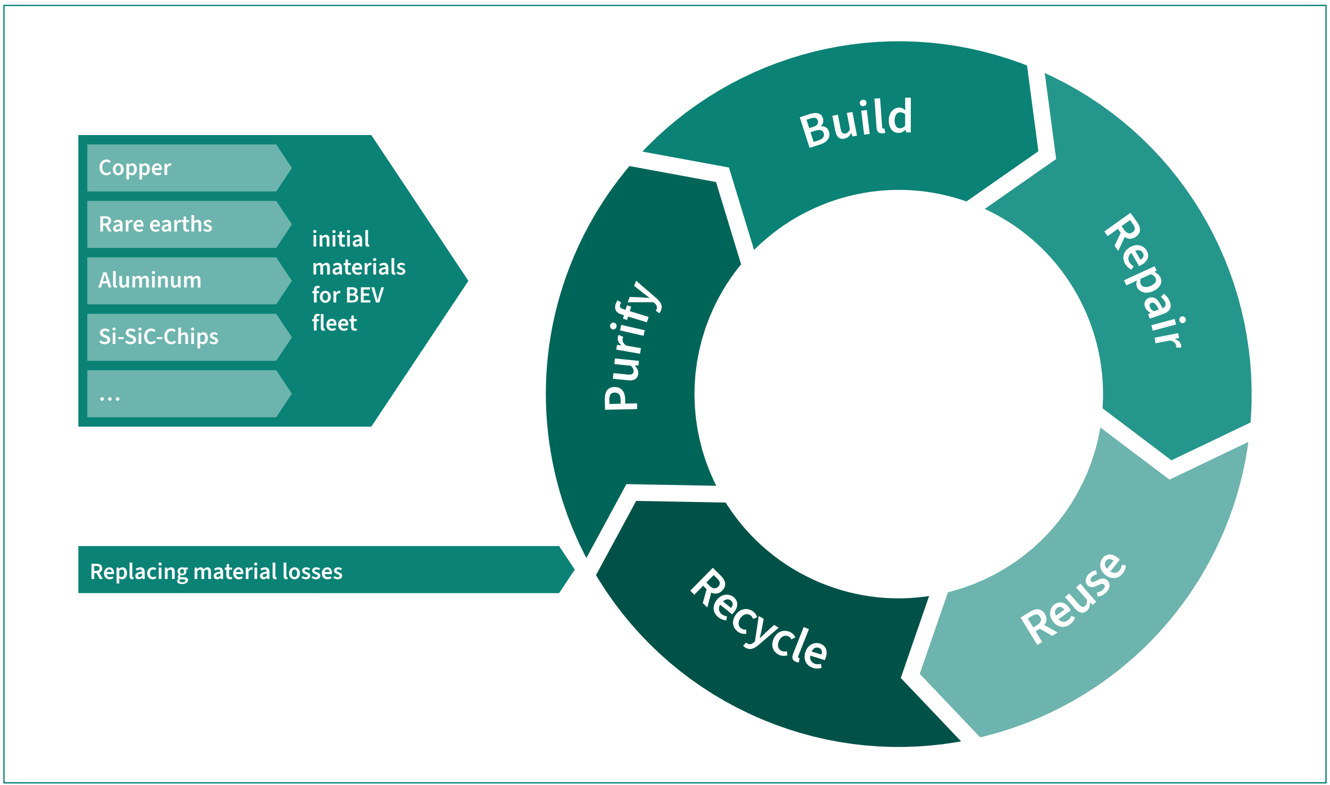


Figure 6 Thoughtful use of raw materials is crucial at the early planning phase for a circular EV economy

4.2 Building out the BEV supply chain

We are still in the early stages of the mobility electrification movement. Currently, the market for battery electric vehicles (BEVs) is still in its infancy. This means that the materials to build a BEV fleet have to be sourced, and this process is currently challenged by the existence of certain availability constraints (see Figure 6, left, for a list of potentially constrained materials). Assuming the majority of all cars are BEVs, these materials would ideally then be utilized in a circular BEV economy and only the lost materials (due to recycling rates below 100% or materials that are not entirely recyclable) have to be replaced. The target is to build vehicles that function extremely efficiently under most driving profiles, but that nonetheless optimize consumption of the materials available. This would allow OEMs to maximize the electrification rate within the constraints of supply limitations and gain cost advantages.

5 SiC for the traction inverter

One of the materials subject to supply constraints is SiC. This is a key material in high end traction inverter designs. And as we know, the traction inverter plays a defining role in EV performance and efficiency overall.

Looking more closely at inverter designs for EVs targeting the mass market, criteria such as cost-effectiveness and a reasonable power rating combined with a reasonable level of efficiency are key success factors. This is not as straight-forward as it sounds and warrants a closer look at the role of SiC.

Let us examine the electric vehicle as a whole and simply think about motor performance and performance distribution. At that level, in simple terms we now evaluate minimum performance for the drive mission profile and the desired peak performance. Those insights will tell us which semiconductor power technology – Si or WBG – is best suited to each particular use case..

5.1 Performance versus cost

In the previous example, an 80 kW motor was sufficient to perform the standardized WLTP drive cycle and consequently support most driving requirements. If SiC is used to increase the vehicle's power rating, the excess power will be "unused" most of the time. In some cases, however, 80 kW may not be enough for a "fun" (sporty) driving experience. So some silicon can be added to increase the vehicle peak performance. For example, a Si part capable of delivering an additional 160 kW. This would result in a very sporty car. At the other end of the spectrum, these values could be scaled back to 40 kW SiC and 80 kW Si to achieve an entry-level EV power of 120 kW.

It's up to the vehicle designer to decide how to distribute the Si and SiC chip parts within the car. Given the range of options, it makes sense to take a deeper look at the electric drivetrain configuration.

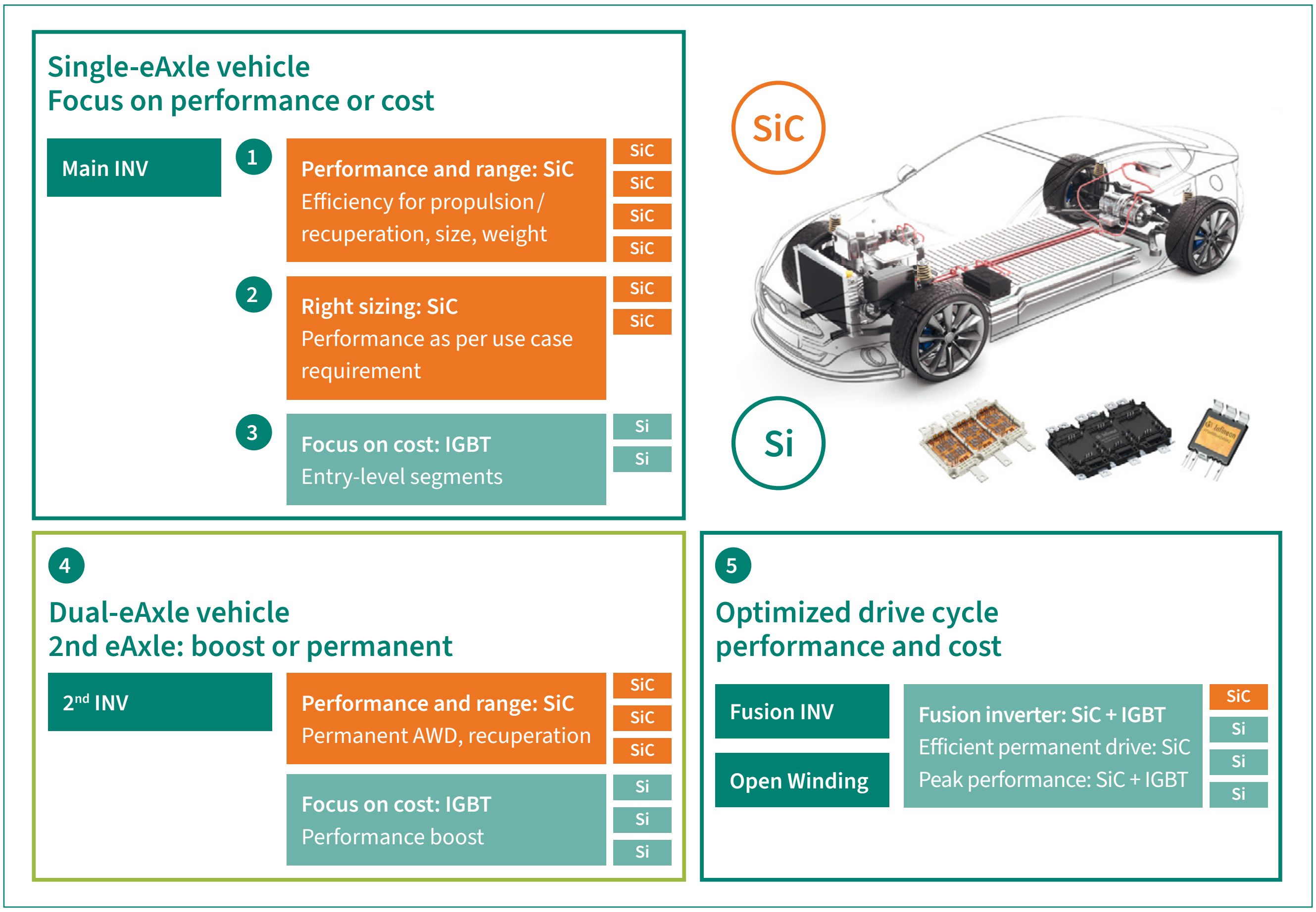


Figure 7 Technology options for electric drivetrains suited to different use cases

5.2 Electric drivetrain configurations

For the drivetrain, and especially for the traction inverter, different technology approaches offer different efficiency, performance, and cost advantages (Figure 7). Designers can achieve their goals by simply evolving to next-generation SiC (1), right-sizing vehicle performance (2), implementing cost-optimized solutions (3), deploying Si or SiC on a secondary eAxle (4), or combining technologies within one traction inverter (5). That is a broad solution space and it can be hard for designers to make the right choices given that efficiency is not only required for propulsion but also for recuperation.

The benefits of a secondary eAxle (4) are well-known and are summarized in Figure 8. With this car configuration (config. 2 combined with config. 4 in Figure 7), both Si and SiC technologies are also used but deployed on different axles

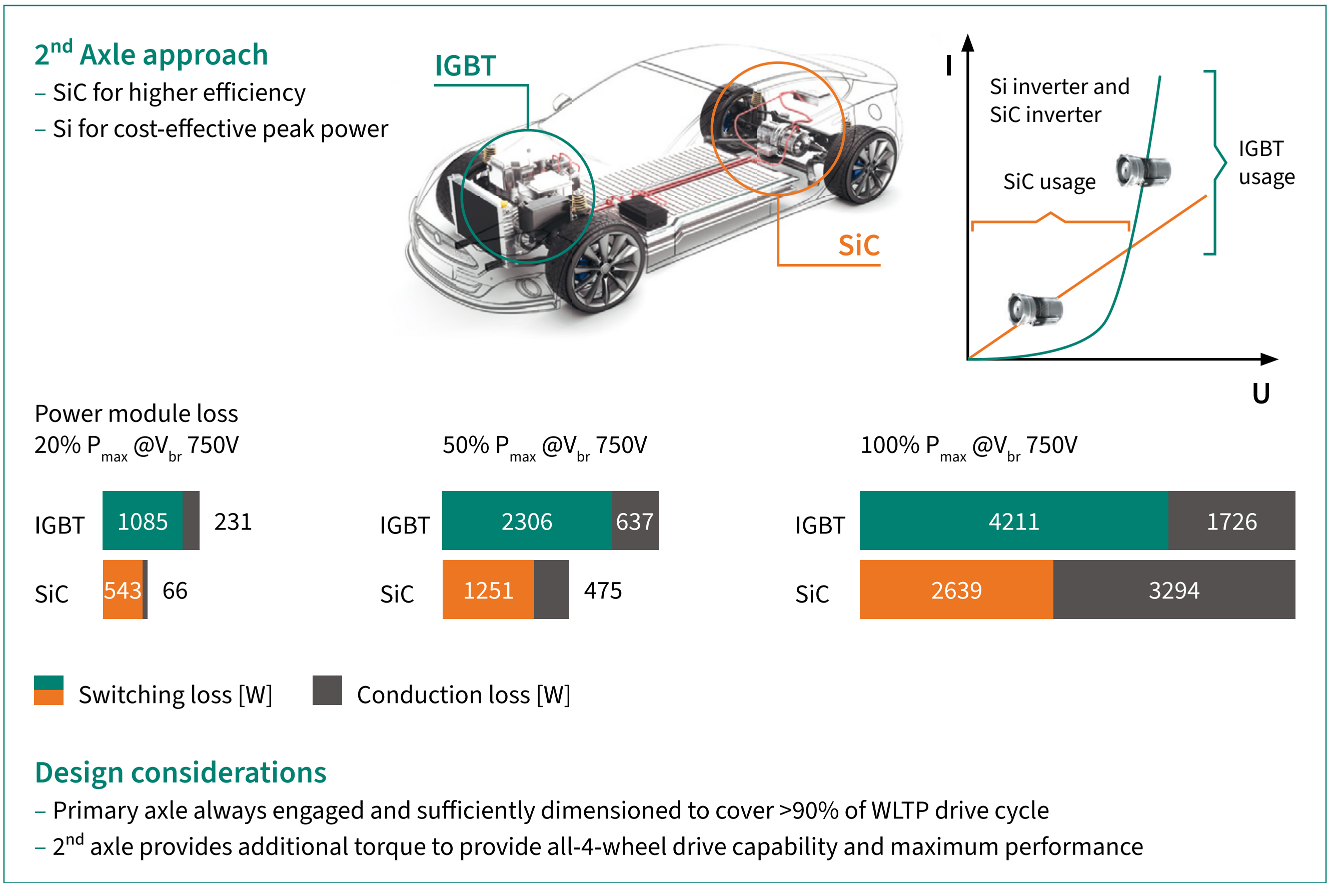


Figure 8 Technology options for electric drivetrains suited to different use cases

For all of the options shown in Figure 7, the target mission profile, such as the WLTP drive cycle, should be considered to achieve the targeted vehicle use cases with the desired customer value. OEMs need to decide how to position the vehicle in the marketplace and where to add value to their target customers typical use cases. The WLTP drive cycle can act as a reference to compare different options.

5.3 Arranging the Si and SiC layouts within the traction inverter of a drivetrain

There are various options to distribute performance within an EV. The most obvious is to split it between the main and the secondary drive axle. In our example (Figure 9), configurations 1 and 2 use the full SiC content either on the rear or the front axle, which is a typical set-up found in today's electric vehicles. Configurations 3 and 4 show fusion technology traction inverters. These options strike a good compromise between efficiency and cost. With fusion technology, Si and SiC chips operate in parallel within the same traction inverter. To understand why fusion technology traction inverters offer efficiency gains relative to the other configurations, let us take a more in-depth look at different driving scenarios.

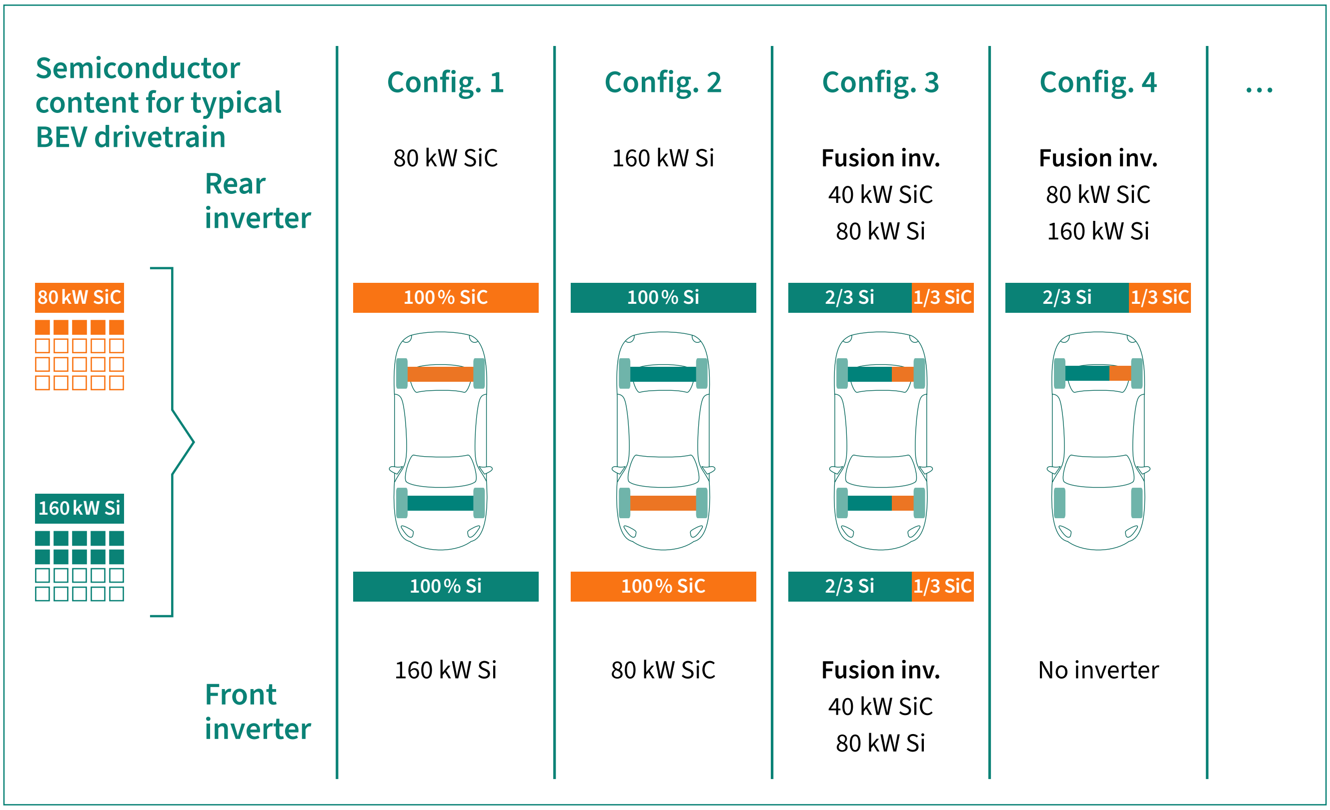


Figure 9 Four sample configurations with fusion technology traction inverters offering efficiency gains for propulsion and recuperation along with peak performance

5.4 Striking the right SiC/Si balance

Diving deeper into the energy flow diagram illustrated in Figure 1, we can take a closer look at the energy flow within fusion technology traction inverters (Figure 10). Under standard load, the SiC on the rear axle is used to accelerate, and the SiC on the front and rear axles (66% to 33% share) is used to smoothly decelerate the car. For this load situation, which is comparable to most driving conditions and the WLTP test conditions, the acceleration and recuperation can be managed entirely by the SiC and on the desired axles. To increase the power up to peak level, additional Si is used for acceleration. Only Si is used here for recuperation, as it offers better efficiency at high loads. To summarize: fusion technology traction inverters capitalize most effectively on the different benefits of different semiconductor power switches, thus making a valuable contribution to efficient and affordable eMobility.

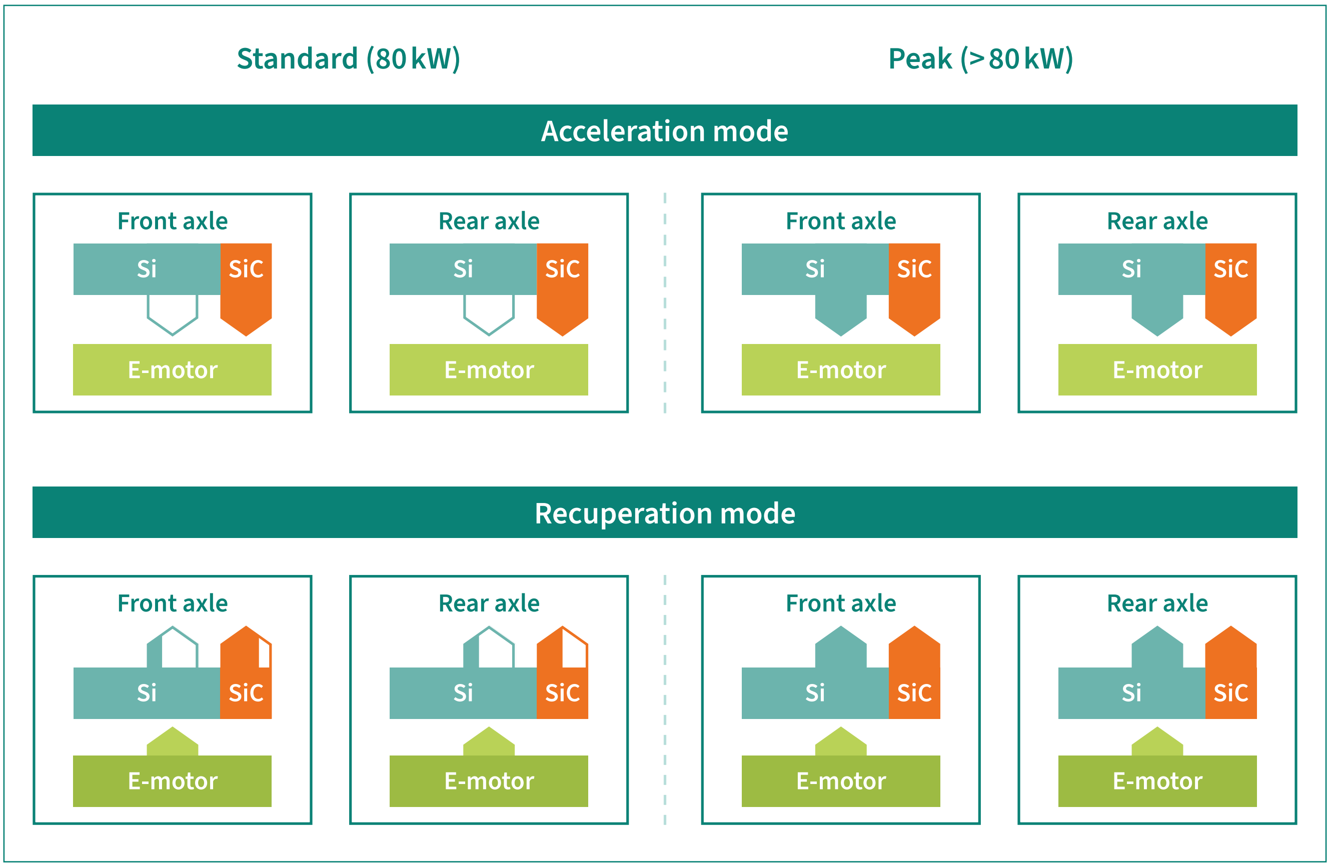


Figure 10 Efficient drive profile with SiC and peak performance enabled by Si

The 33% share of SiC and 66% share of silicon outlined above are suggested by way of example but nonetheless provide a very good starting point for the SiC vs. Si discussion. To work out the specific ratio best suited to each customer and use case, we need to take a close look at various physical parameters (such as vehicle mass, air drag, voltage class, etc.). In addition, the drive cycle/s must be defined (WLTP, Artemis Highway, target value for kWh/100 km, etc.). Last but not least, the target price of the inverter, the HV battery, and the drivetrain must be factored into the equation. Based on all of these parameters, it is possible to define the precise SiC/Si ratio.

As the thermal limits of Si and SiC must never be exceeded, it is important that the temperature thresholds are observed in any ratio simulations carried out. The exemplary 3D graphs below from the simulations we carried out here at Infineon (Figures 11 and 12; exclusive switching) show the interplay between SiC area, the load current, and the SiC/Si die temperatures. An “AA SiC in p. u.” equal to 0 means that the active area (AA) of silicon carbide in the inverter (p.u.) is 0 and the silicon active area is increased to handle the full power. Consequently, “AA SiC in p.u.” equal to 0 is a full silicon inverter and a value of 4 represents a full SiC inverter. For proper dimensioning, both technologies must utilize their maximum temperature at maximum load. The graphs show that the correlations are far from linear and consequently simulations need to be carried out.

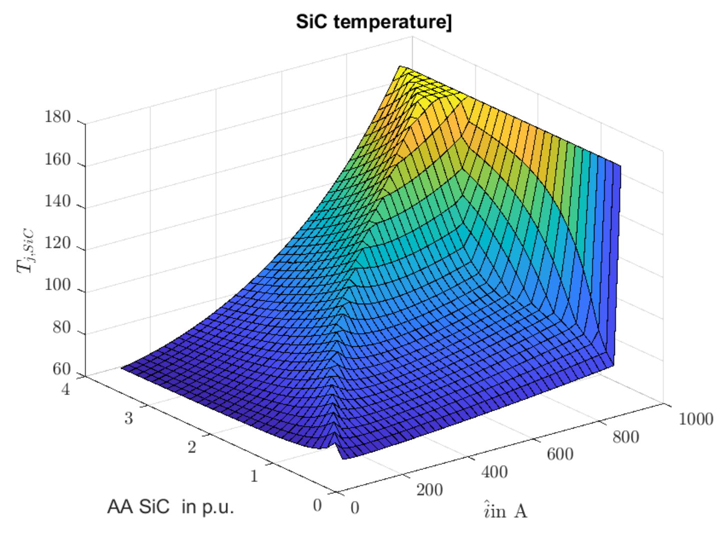


Figure 11 SiC die temperature as a function of phase current and active area (during exclusive switching)

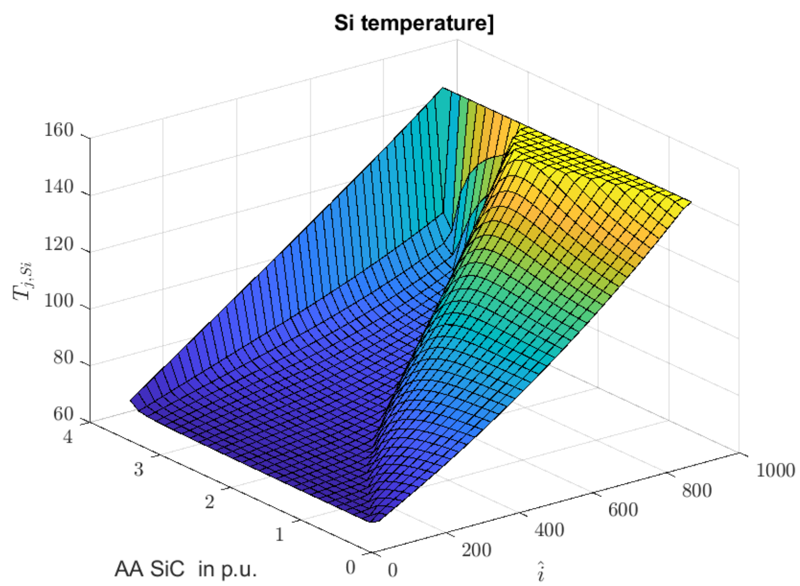


Figure 12 Si die temperature as a function of phase current and SiC active area (during exclusive switching)

In addition, the targeted efficiency within the desired drive cycle should be investigated across the different SiC/Si ratios. A pure SiC inverter would offer the highest efficiency but a silicon inverter would result in the lowest costs. This calls for a tradeoff between drive cycle efficiency and cost. Figure 13 shows this relation. Restricting the choice to SiC or Si will result in one of the two extremes (see yellow and green cross). Fusion strikes a compromise. In Figure 13, the example of 17% SiC AA (and 83% Si AA) is shown. This represents a 33% SiC current capability and a 66% Si share (as discussed above).

This calculated example shows that this ratio entails only a minor drop in efficiency (~97% down to ~96%) but a relevant decrease in the inverter BOM. A more detailed overview of costs and efficiency can be found in the summary chapter at the end of this document.

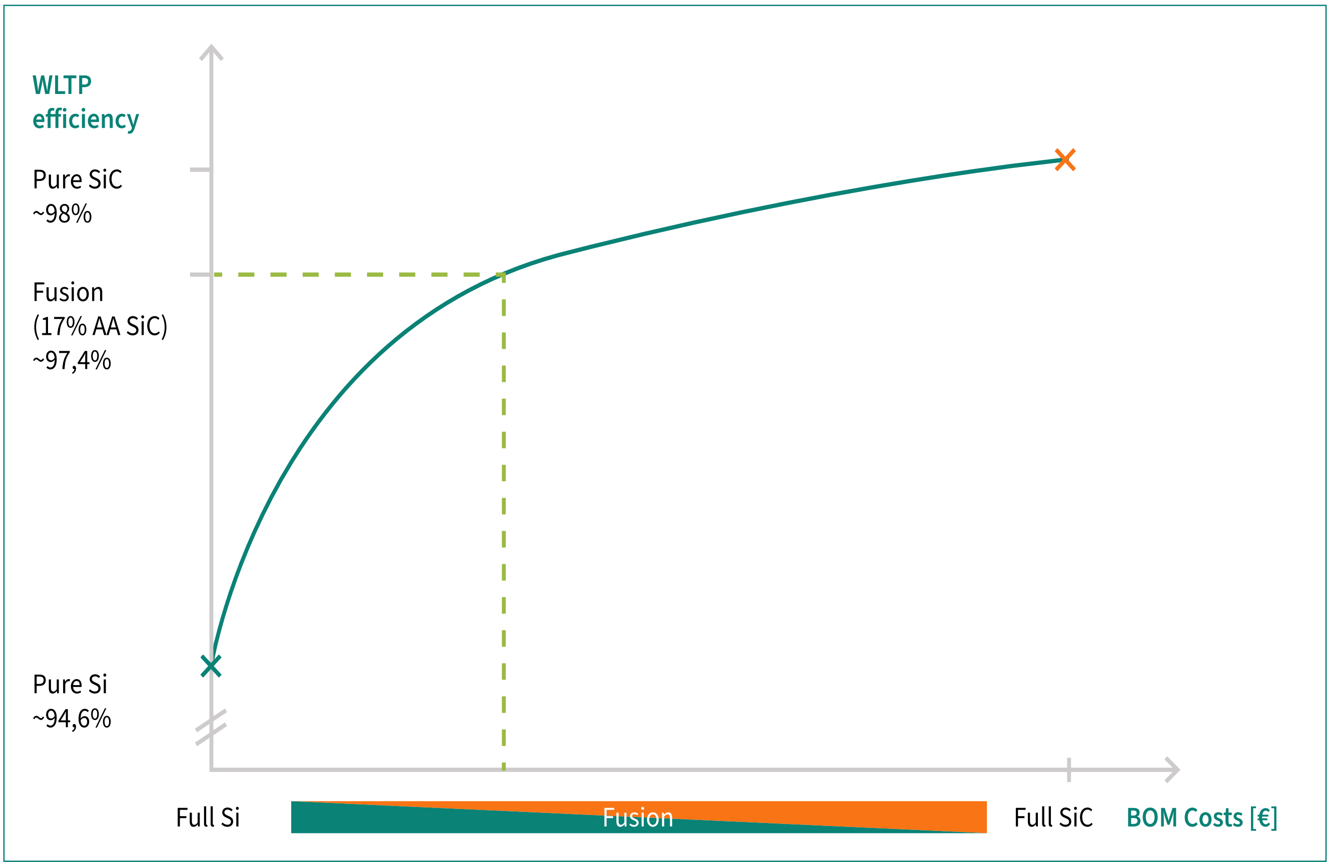


Figure 13 Fusion approach strikes a compromise between a pure SiC inverter (orange cross) and a pure Si inverter (green cross; much cheaper but less efficient)

6 Different fusion inverter operating modes

As explained above, Si and SiC can be combined in different ways to achieve different objectives. In a standard 2-level traction inverter, where just one semiconductor technology is used, there is no need for a strategy as only Si or SiC need to be switched.

But fusion technology traction inverters enable different strategies. Three different inverter operating modes are possible. The first is exclusive operation mode (Ex), where just one semiconductor technology (Si or SiC) is used. The second option is simultaneous switching (S), where Si and SiC are always used in parallel. And the third option entails operating both Si and SiC individually (In). Here, the inverter can seamlessly switch between exclusive and simultaneous modes, leveraging the benefits of fusion technology traction inverters in full. The fact that both technologies are connected physically in parallel does not automatically mean that they have to be operated simultaneously.

Each of the operation modes has its own pros and cons, based on the efficiency of the semiconductor material used and the effort of operating a fusion technology traction inverter in general.

The different operating modes for a fusion technology traction inverter are outlined and compared in Figure 14.

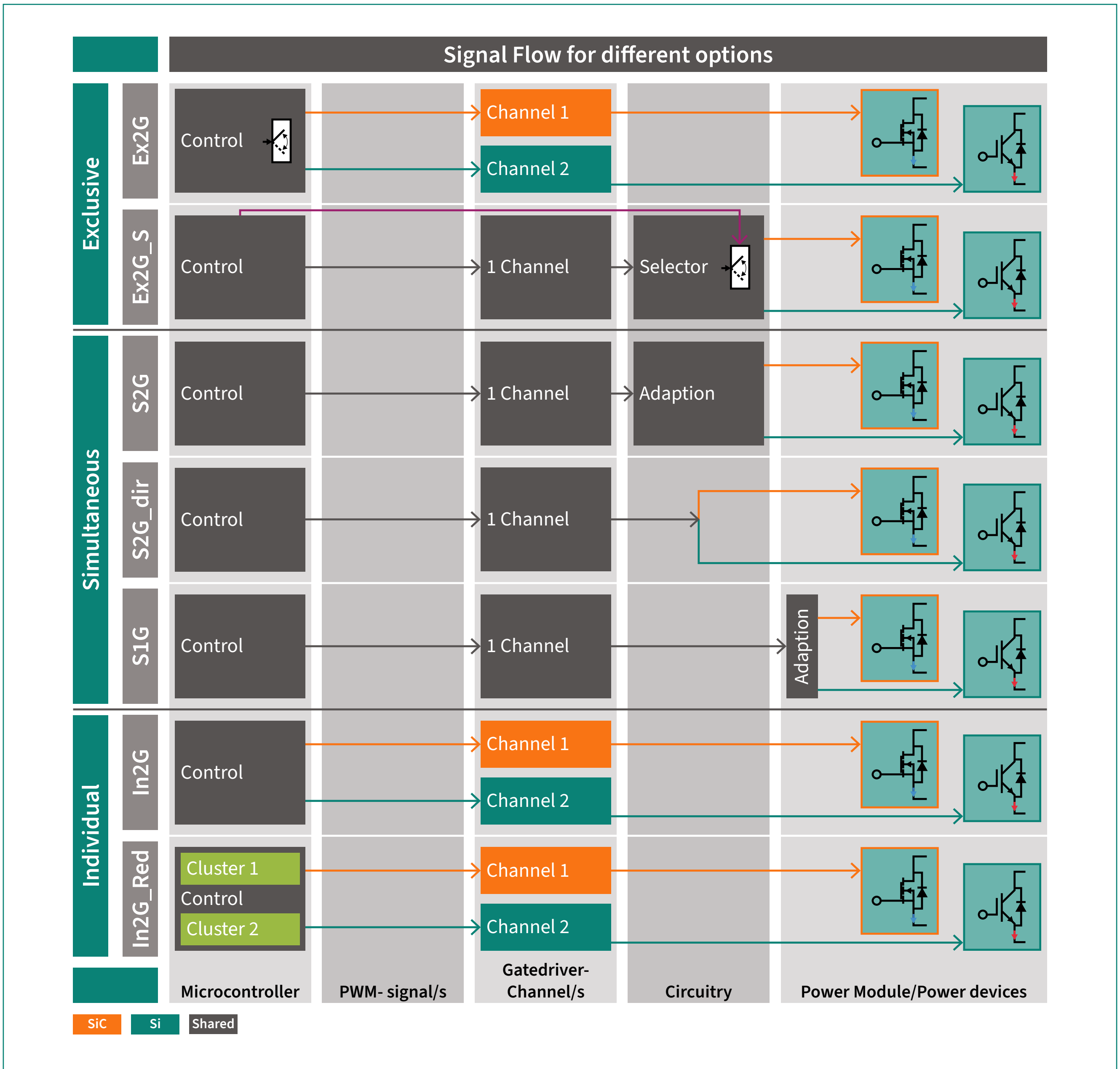


Figure 14 **Different options to control fusion technology traction inverters (Ex2G, Ex2G_S, S1G, S2G, S2G_dir, In2G and In2G_Red)**

The abbreviations for the different fusion approaches are compiled in the following manner:

- First letter/s: Type of switching
  - Ex: Exclusive control of Si and SiC
  - S: Simultaneous switching of Si and SiC
  - In: Individual control of Si and SiC
- Second part: Number of gates of the power module/power devices:
  - 1G: One gate contact
  - 2G: Two gate contacts
- Third part: Special parameters
  - _S: A selector is used
  - _dir: Direct connections of Si gate and SiC gate
  - _Red: Setup for increased redundancy

6.1 Selecting the best fusion technology approach

Figure 15 below summarizes the advantages and challenges of each implementation approach. As Figures 14 and 15 show, all of the variants have advantages for certain use cases. The availability of suitable products and engineering capabilities will often dictate implementation feasibility. Based on these boundary conditions, different fusion technology traction inverter approaches will prevail for different market segments.

Looking ahead, the benefits of fusion technology traction inverters extend beyond the initial and obvious cost and material availability benefits to offer answers to future automotive challenges.

How do the different implementation modes stack up?

	Exclusive (Ex2G)	Simultaneous (S1G & S2G)	Individual (In2G)
	– SiC is used below a certain current threshold. If a higher current is demanded, the SiC switches are turned off and just the IGBTs are in operation. Once the current falls below the threshold again, the SiC switches are reactivated – This transition between the technologies is executed four times within a sine-wave period (provided current amplitude is high enough) – Thermal capacity is utilized to achieve higher peak currents than those possible with IGBT-only designs – WLTP efficiency is dictated by SiC behavior	– SiC MOSFET and IGBT controlled by one common PWM signal – Currents creating V_{CE}/V_{GS} voltages of <0.7 V conducted by SiC only – Current sharing for voltage drops >0.7 V depends on device characteristics and sizing – Dynamic current sharing during switching is defined by device characteristics and parasitics in the communication loop – Adaptation circuit (gate resistance/capitance) is needed to tune switching behavior of each technology	– Current conduction on Si and SiC controlled individually – SiC only for lower power, Si only for medium power, both conducting for highest power – Change of current sharing during an on-state period is optional – Current sharing is adapted by shaping of PWM signals for SiC and Si. Current sharing in diode mode can be tuned with active rectification in SiC – Full flexibility in transitions during turn-on/turn-off
	– Single technology commutation – Adaptable during operation – Limp-home functionality/fail operational	– Simple implementation (S1G only) – Common PWM signal – No impact on control strategy	– Highest optimization potential – Limp-home functionality/fail operational
	– Potential of fusion inverter not fully utilized – Max. output power limited to chip size of one technology – 2 gate channel signals required	– Commutation across two technologies – Potential of fusion inverter not fully utilized	– Commutation across two technologies – 2 gate channels required – Complex control strategy

Figure 15 Summary and comparison of different fusion technology traction inverter implementations

6.2 Exclusive switching: Ex2G mode

As mentioned above, one design option is the exclusive operation mode, where just one semiconductor technology (Si or SiC) is used. Looking at the example above (Figure 9), the SiC area is used exclusively for all power demands below 80 kW. If the vehicle requests an output power higher than 80 kW from the traction inverter, SiC is used for phase currents up to the representing current value of 80 kW and all currents above this value are implemented by Si. The change-over between SiC and Si can happen even between different PWM cycles. This results in a maximum output power of 160 kW with this example (as Si and SiC are not used simultaneously). The fact that the SiC part of the inverter is not contributing to the maximum output is obviously the main disadvantage of this option. On the upside, this mode offers ease of control, as both technologies are not operated simultaneously. To implement the exclusive operation mode, two gate signals are needed ("Ex2G") to control both technologies independently.

6.2.1 Complementary solutions from Infineon

To create an ASIL-compliant, state-of-the-art inverter, however, designers also need the right gate drivers, microcontrollers, and power supply ICs. As outlined in the following, Infineon covers all of these building blocks with implementation concepts offering a variety of benefits.
traction inverters. These options strike a good compromise between efficiency and cost. With fusion technology, Si and SiC chips operate in parallel within the same traction inverter. To understand why fusion technology traction inverters offer efficiency gains relative to the other configurations, let us take a more in-depth look at different driving scenarios.

6.2.1.1 The microcontroller

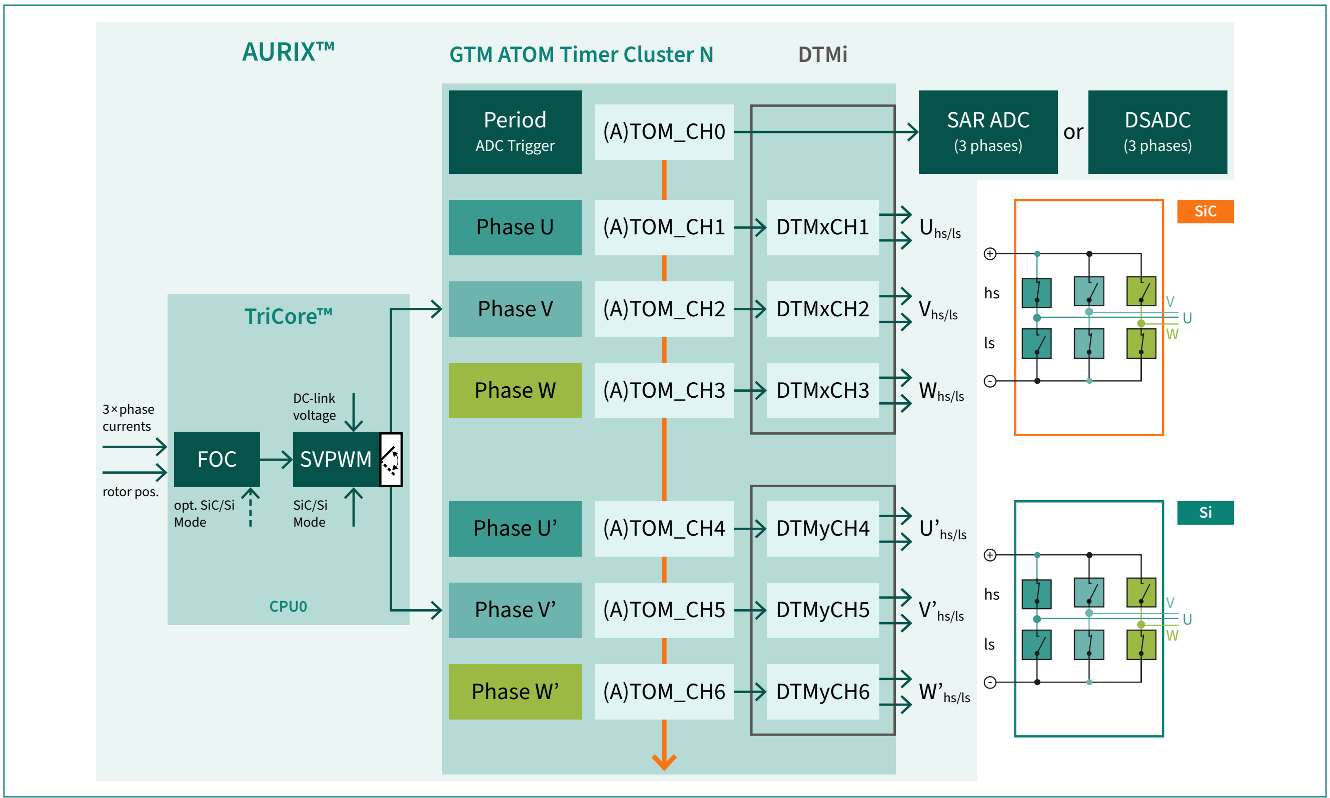


Figure 16 View inside the AURIX™ microcontroller showing how Ex2G can be implemented

The concept illustrated above is based on an AURIX™TC3xx microcontroller and offers a number of compelling benefits. The SiC/Si field-oriented control (FOC) calibration parameters and dead time modules (DTMs) can be individually configured to fine-tune the Si/SiC switching behavior. The space vector pulse width modulation (SVPWM) can also be adapted to the requirements of SiC/Si respectively on the software side. In addition, a smart timer (GTM)and ADC peripherals offload the main CPU to a significant extent. The GTM ATOM timer outputs with shadow-based compare register update contribute to glitch-free operation. Thanks to the best-in-class, field-proven safety performance of AURIX™ microcontrollers, however, this concept ensures that common CPU or timer cluster failures will immediately lead to shutdown into proper safe state.

Highlights of this concept include:

- TriCore™ CPU host with the following SW components:
  - FOC with 3-phase current sensors and one rotor angle with common SW functions for SiC/Si (with optional calibration parameter adaptation)
  - SVPWM with individual SW adaptations for SiC and Si mode (e.g. modulation scheme, dead time, PWM frequency, etc.)
- Generic Timer Module (GTM_ATOM_Timer_Cluster)
  - 1 period master and 2x3 ATOM channels used with coherent period and duty cycle update capability
  - 2 DTM clusters, each with 3-channel DTM with individual configurable rising/falling edge dead time insertion based on HW
  - 1 configurable ADC HW trigger signal synchronized with PWM pattern
- ADC
  - Current measurements: SAR/ DSADC:
    - Figure 16 shows implementation of 1x3 current measurements
    - Figure 17 illustrates how 2x3 current measurements could be utilized
  - Rotor position measurement: DSADC (e.g. for resolver sin/cos evaluation) or any other position sensor
  - Isolated DC link voltage measurement

6.2.1.2 The current sensor

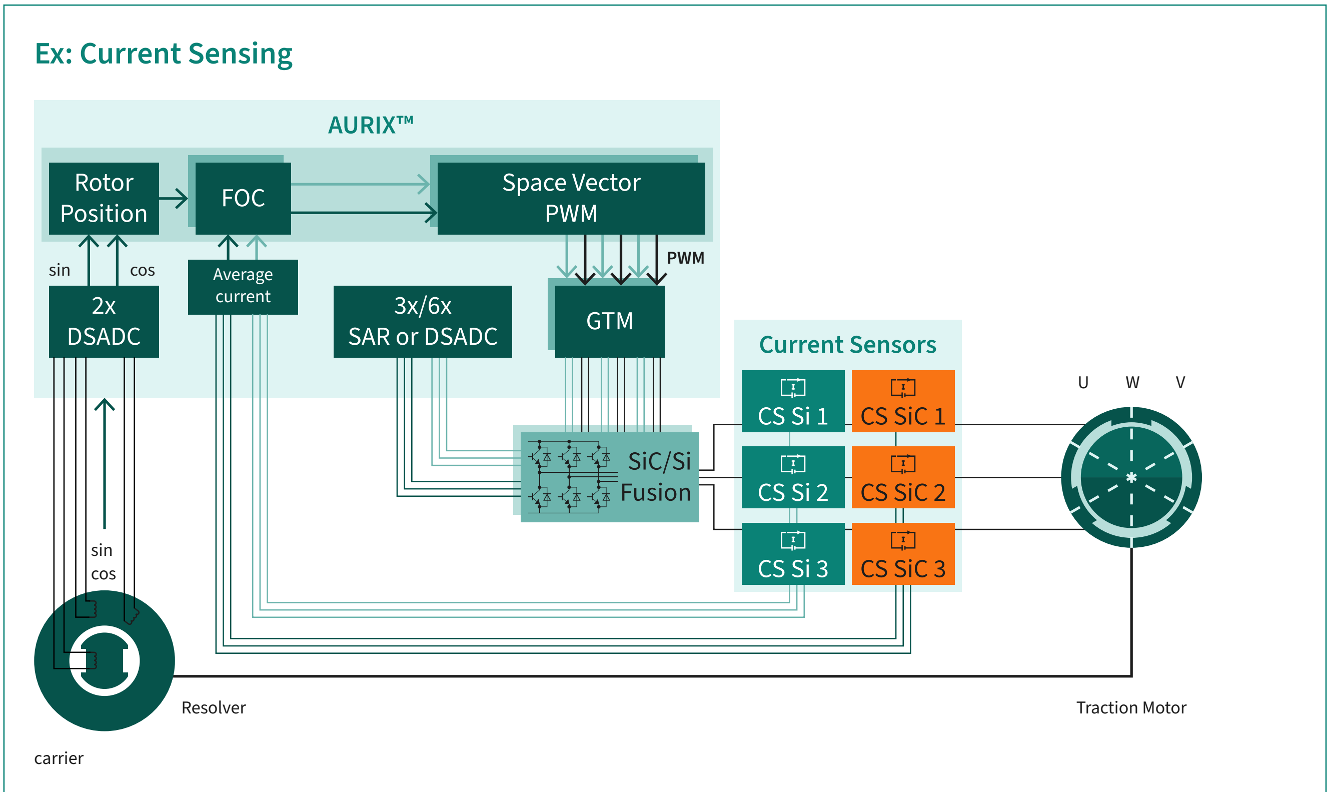


Figure 17 View of AURIX™ and current sensors

Current sensing can be challenging with exclusive switching: A normal current level in pure Si mode could be destructive if just SiC is utilized. Figure 16 and Figure 17 show the implementation of 3 current sensors and 6 current sensors. In the first place it seems to make sense to deploy two XENSIV® current sensors in parallel (see Figure 17). One is configured for the SiC measurement range and the overcurrent threshold; the other is calibrated to the Si values. But this leaves the challenge of masking overcurrent detection by the SiC current sensor if Si is fully utilized. Consequently, one current sensor per phase (see Figure 16) could be a valid solution, as the benefit of doubling them up is diminished by SiC overcurrent detection, which will be active during normal operation of Si.

6.2.1.3 The gate driver

Independent PWM signals and – by extension – two gate drivers are required to drive the IGBT and SiC independently in exclusive mode. This design offers complete flexibility to switch one of the two devices while at the same time providing independent diagnostic capabilities.
Infineon's EiceDRIVER™ 1EDI3025AS and EiceDRIVER™ 1EDI3035AS gate drivers are ideal for this task. Both devices offer a similar feature set, with DESAT and SOFTOFF capabilities, and are optimized for IGBT and SiC respectively. This combination enables IGBT and SiC to detect and respond to short circuits independently. We take a closer look at the capabilities of these devices in the following.

From the gate driver point of view, the exclusive Ex2G approach is similar to the individual In2G mode as shown in Figure 14 and described in detail below.

EiceDRIVER™ key features

The gate driver combination outlined above offers a few key advantages that make it a good choice for exclusive Ex2G mode:

– Independent diagnostic capabilities with minimal interference from the inactive gate driver
– Fast, accurate and well matched signal transmission of coreless transformer technology enables optimized timing between Si and SiC
– DESAT is activated by INP signals on the primary side so the DESAT threshold voltage of the second semiconductor device does not interfere if it is kept disabled when one power semiconductor device only is in use
– Independent gate drivers support limp-home mode if one power semiconductor device has failed

Turn-on and turn-off

The gate driver turn-on and turn-off behavior in exclusive Ex2G mode is similar to switching a typical IGBT or SiC inverter since only one power device is turned on or off at a time. The gate driver for the inactive power semiconductor can be kept disabled using the appropriate PWM inputs or by commanding the gate driver to a "PWM disabled" state. This will ensure that there is minimum interference to the gate driver that is actively switching the power device. When the gate driver is kept disabled, its diagnostics features have minimum to no interference on the actively switching gate driver. Figure 18 shows that if there is a gate-source fault on the SiC (4th diagram, red line, t= 1.5), it is commanded into safe state by its gate driver while the IGBT gate driver remains operational (2nd diagram, red line, t>1.5) in case the system safety concept requires limp-home capabilities.

Bridge short circuit (type 1)

Similar to the turn-on and turn-off behavior, a type 1 short circuit is comparable to a short circuit on a typical single device (IGBT or SiC inverter). The waveforms shown in Figure 19 and Figure 20 illustrate the ability to have different short-circuit detection and reaction mechanisms for IGBTs and SiCs in the same system without the other inactive gate driver interfering. Figure 19 shows the short-circuit detection (2nd diagram, red line, t> 1.051) and reaction of IGBTs (4th diagram, blue line, t= 1.07) where the SiC remains inactive. Notice that the DESAT threshold is higher than normal for SiC and that the system functions till IGBT DESAT is triggered without the SiC gate driver interfering. Figure 20 shows the short-circuit detection (2nd diagram, yellow line, t> 1.032) and reaction behavior for SiC (4th diagram, red line, t> 1.031) while IGBT remains inactive.

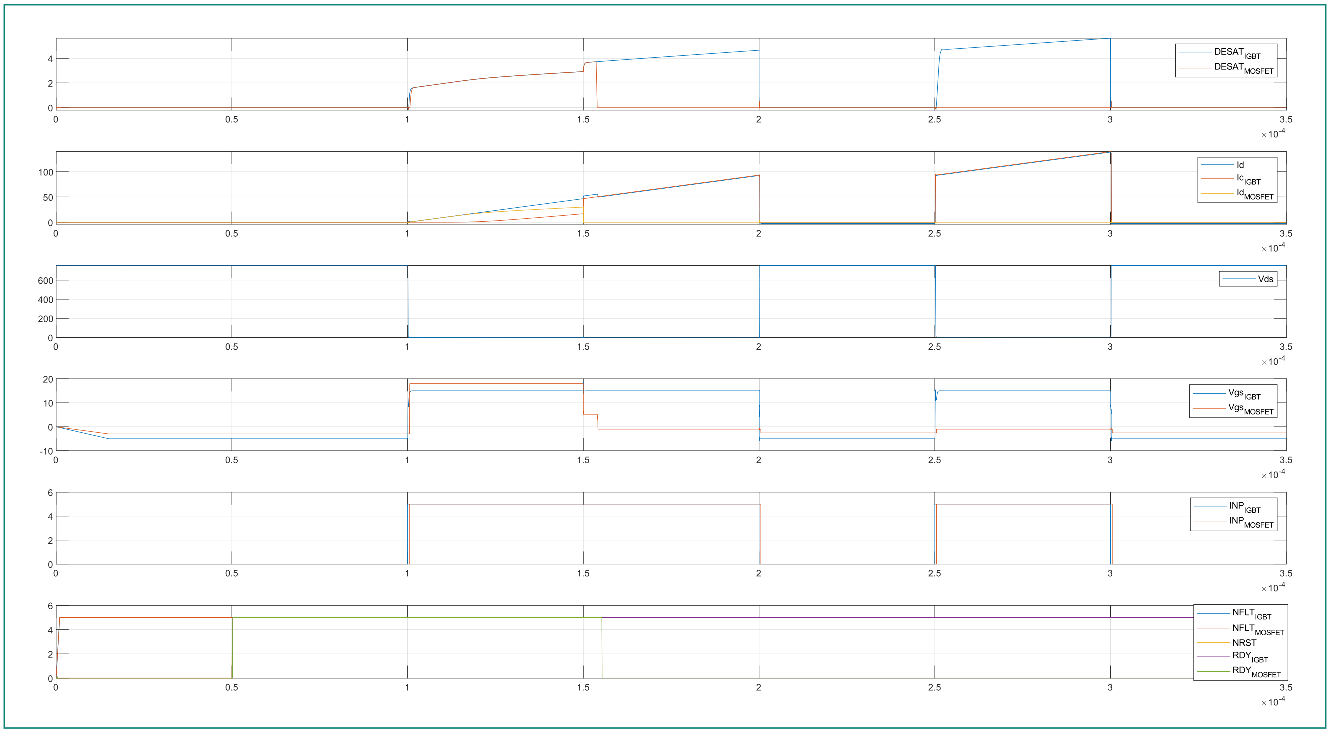


Figure 18 Example of limp-home mode with gate-source fault on SiC

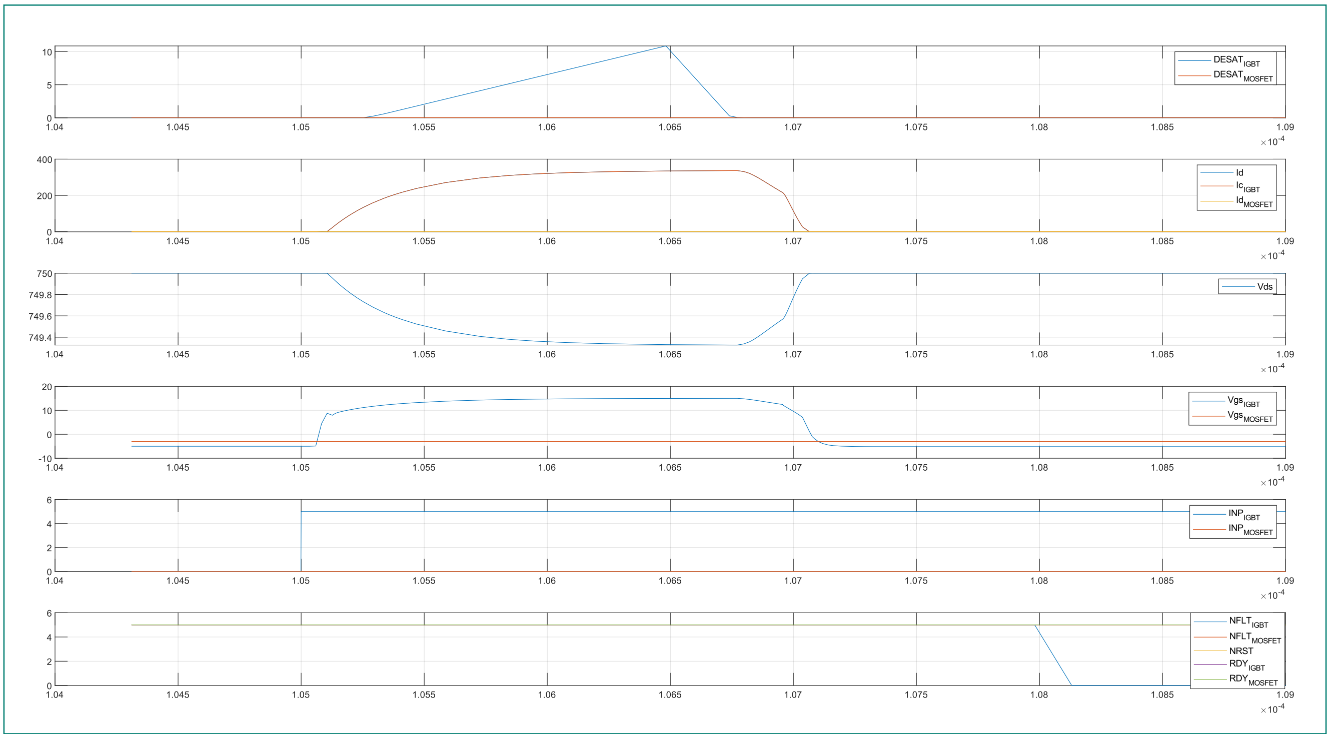


Figure 19 Short-circuit behavior with active EiceDRIVER™ 1EDI3025AS and inactive EiceDRIVER™ 1EDI3035AS gate drivers in exclusive Ex2G mode

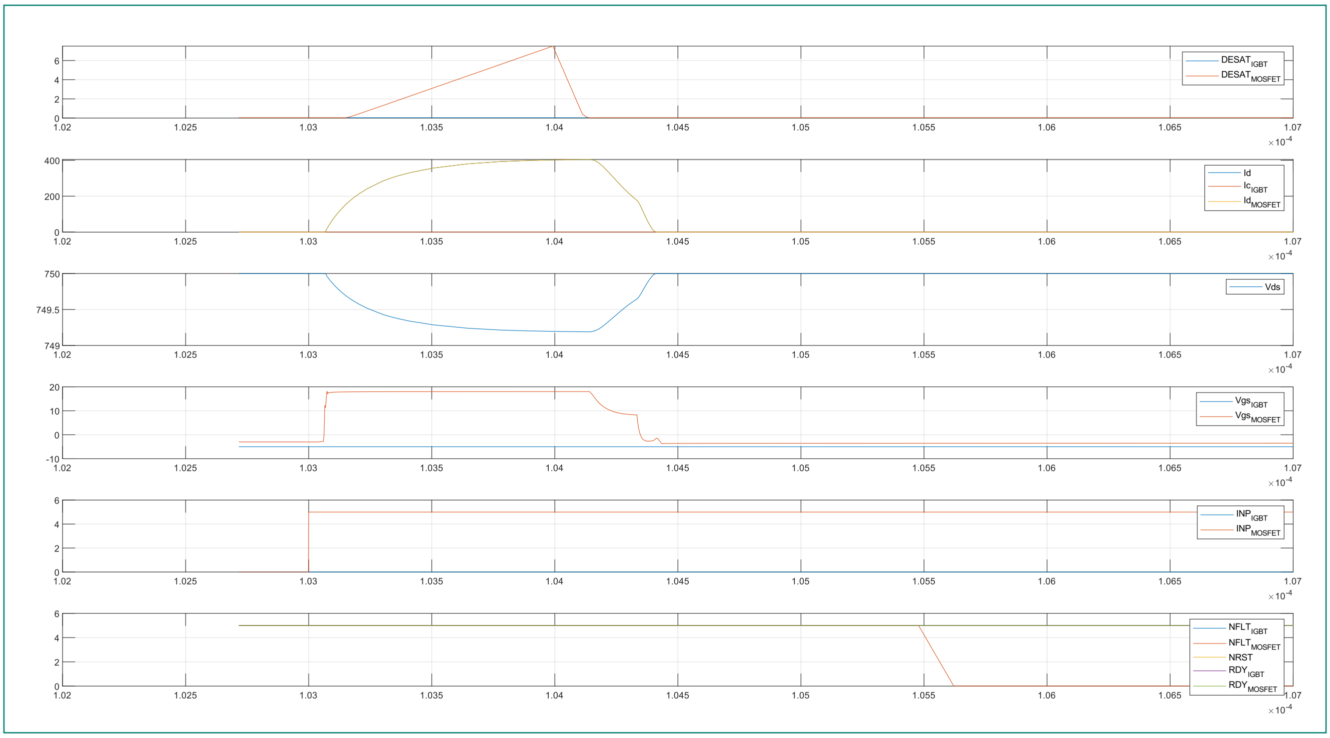


Figure 20 Short-circuit behavior with inactive EiceDRIVER™ 1EDI3025AS and active EiceDRIVER™ 1EDI3035AS gate drivers with each technology switched separately (see Ex- and In- mode)

6.3 Exclusive switching: Ex2G_S mode

Similar to the exclusive Ex2G switching mode, the exclusive Ex2G_S (S= external selector) mode means the system must select between the IGBT or the SiC for each switching cycle. The difference between Ex2G_S and Ex2G lies in how and where the SiC or IGBT is selected. With Ex2G, two separate gate drivers are used: one for SiC and one for IGBT. The SiC or IGBT is selected in the gate drivers by the microcontroller. With Ex2G_S, a single gate driver is used and the SiC or IGBT is selected in the gate driver path. For this selection to take place, separate circuitry is required on the gate driver path and a separate digital isolation channel is required between the microcontroller and gate driver path so the microcontroller can trigger the selection. This is shown in Figure 21.
Additional digital isolators and circuitry adaptations, such as separate booster stages, are required to enable the exclusive Ex2G_S approach. This makes it more complicated than Ex2G but more cost-effective. The circuitry adaptations also make some safety-critical features such as SOFTOFF more complicated. Additional circuitry to disconnect and reconnect safety-critical features between the SiC and IGBT are needed, and this can have an impact on safety and complexity. This additional complexity means that Ex2G is generally the recommended approach when choosing between the two exclusive modes. The advantages of Ex2G are mentioned above.

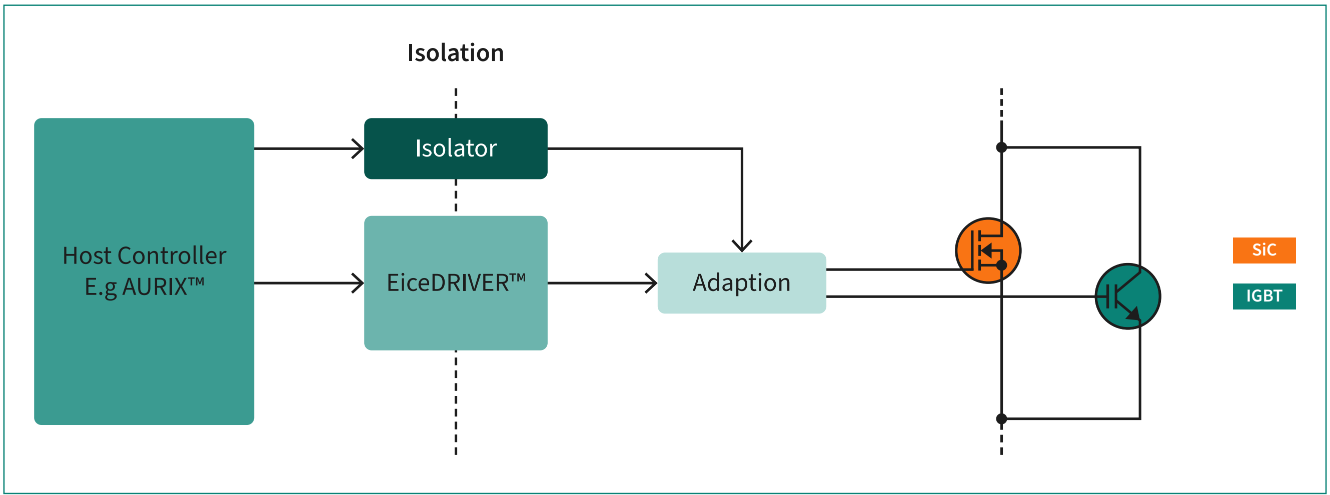


Figure 21 Implementation concept for Ex2G_S using one gate driver

6.4 Simultaneous switching: S1G, S2G & S2G_dir modes

The second switching option – simultaneous mode – is outlined in this chapter. Here, Si and SiC are always used simultaneously (excluding transients). This overcomes the downside of exclusive mode. One gate signal is used to toggle both technologies. Adaptations in the gate path can be used to match the turn-on and turn-off behaviors and enable proper transient behavior. Current sharing between all the individual switches must be ensured by design and by technology. However, with voltages below 0.7 V, for example, the SiC area will conduct most of the current and, above this limit, the Si will increase its share of the current. This is unavoidable in this mode. By dimensioning the chip areas within the setup, these values can be optimized to match efficiency and drive cycle goals.
There are two implementation options with simultaneous mode – a one-gate solution (S1G) or a two-gate solution (S2G). As both technologies are operated simultaneously, one gate contact would be sufficient. In adapting the technologies, the designer is free to either start with one PWM signal from the microcontroller and channel it via two gate drivers to the individual gates (S2G), or to just have one gate driver and one gate pin (S1G), where the signal is matched in the power module. The S1G option is quite a convenient solution for the designer, but offers less parameter configuration flexibility than S2G.

6.4.1 Complementary solutions from Infineon

Similar to exclusive mode outlined above, here also designers need the right gate drivers, microcontrollers and power supply ICs to create an ASIL-compliant, state-of-the-art inverter. As outlined in the following, Infineon covers all of these building blocks with implementation concepts offering a variety of benefits.

6.4.1.1 The microcontroller

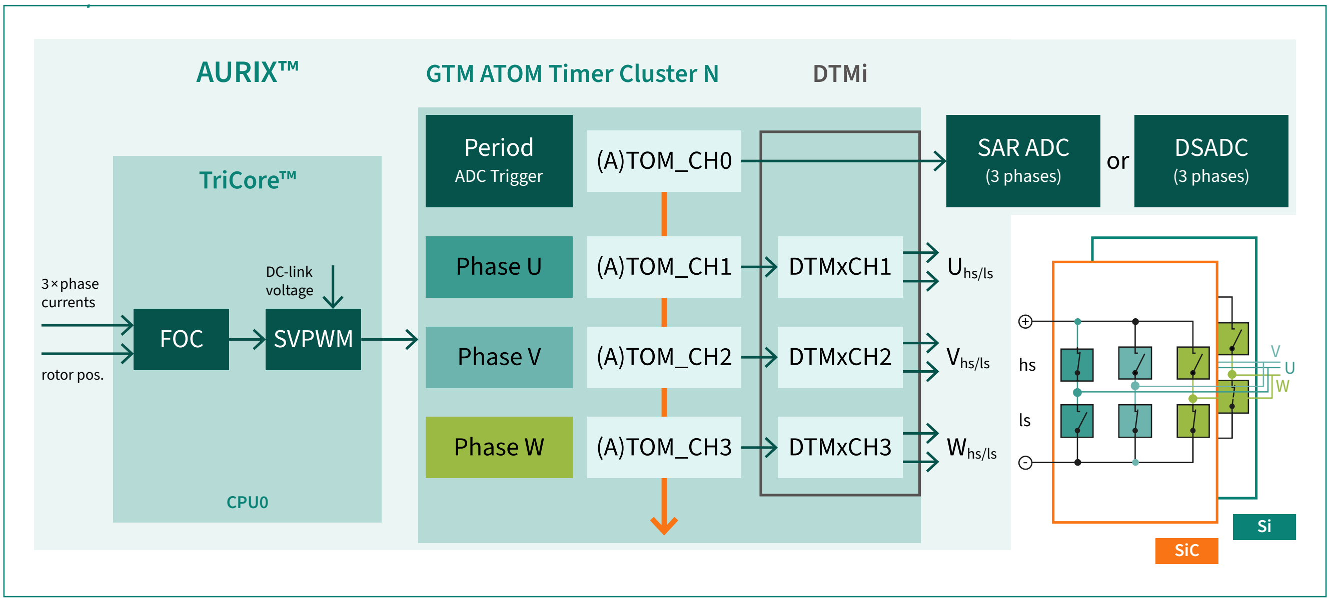


Figure 22 View inside the AURIX™ microcontroller for simultaneous switching

The AURIX™ TC3xx concept illustrated here (figure 22) offers the same features and benefits as the AURIX™ concept outlined for exclusive mode above but with a few key differences. One single inverter control scheme requires fewer hardware and software resources as no additional CPU performance is needed. In addition, the Generic Timer Module (GTM) has 1x period master and just 1x3 ATOM channels and the DTM module has only 1x3 channels.

It should be noted, however, that this concept does present some challenges. The calibration parameters for SiC/Si FOC cannot be individually set and therefore optimized. In addition, SiC-/Si-specific dead times cannot be individually configured as both technologies share the same SVPWM and Timer Output Module. This common SVPWM comes at the expense of efficiency gains that can normally be achieved by setting the dead times individually. Similar to exclusive mode, common CPU or timer cluster failures will immediately lead to shutdown into proper safe state.

6.4.1.2 The current sensor

If simultaneous mode is picked to implement the fusion technology, the current sensor requirements do not differ from those of a 3-phase SiC inverter. So, 3-phase current sensors are needed. Since Si and SiC are simultaneously on or off, the load current that can be handled by the power setup is always the same and no modifications are therefore needed.

6.4.1.3 The gate driver

As the name indicates, simultaneous switching means that both the IGBT and SiC can be driven with the same signal at least on the output of the gate driver and then appropriately adapted, if necessary, on the gate resistor circuitry (S2G) or inside the power module (S1G). From the gate driver point of view, this means that the topology requires only one gate driver output. The difference between S2G and S1G lies in where the start point of the gate signal of SiC and IGBT is located – either in the gate circuitry after the gate driver or in the power module.
Infineon's EiceDRIVER™ gate driver family includes two product families supporting simultaneous S2G and S1G modes:

- EiceDRIVER™ 1EDI3051AS with a single output stage and two independent diagnostic functions
- EiceDRIVER™ 1EDI302xAS/1EDI303xAS (x =5,6,8) with a single output and single diagnostic function

The following information on the gate driver implementation refers to both S2G and S1G.

Simultaneous switching using EiceDRIVER™ 1EDI3051AS

The EiceDRIVER™ gate driver 1EDI3051AS comes in a 36-pin DSO package with integrated SPI for advanced configurability that offers the highest degree of compatibility with the current-generation IGBT and SiC power technologies. This gate driver provides a second monitoring stage that allows independent gate monitoring, an active Miller clamp and overcurrent protection for IGBT and SiC. These features make it a good choice for the simultaneous S2G and S1G approaches. It also has an integrated flyback controller offering highly accurate control of the gate voltage. This helps to minimize conduction losses, especially in SiC.

A typical implementation of the simultaneous switching approach using the EiceDRIVER™ 1EDI3051AS gate driver is shown in Figure 23.

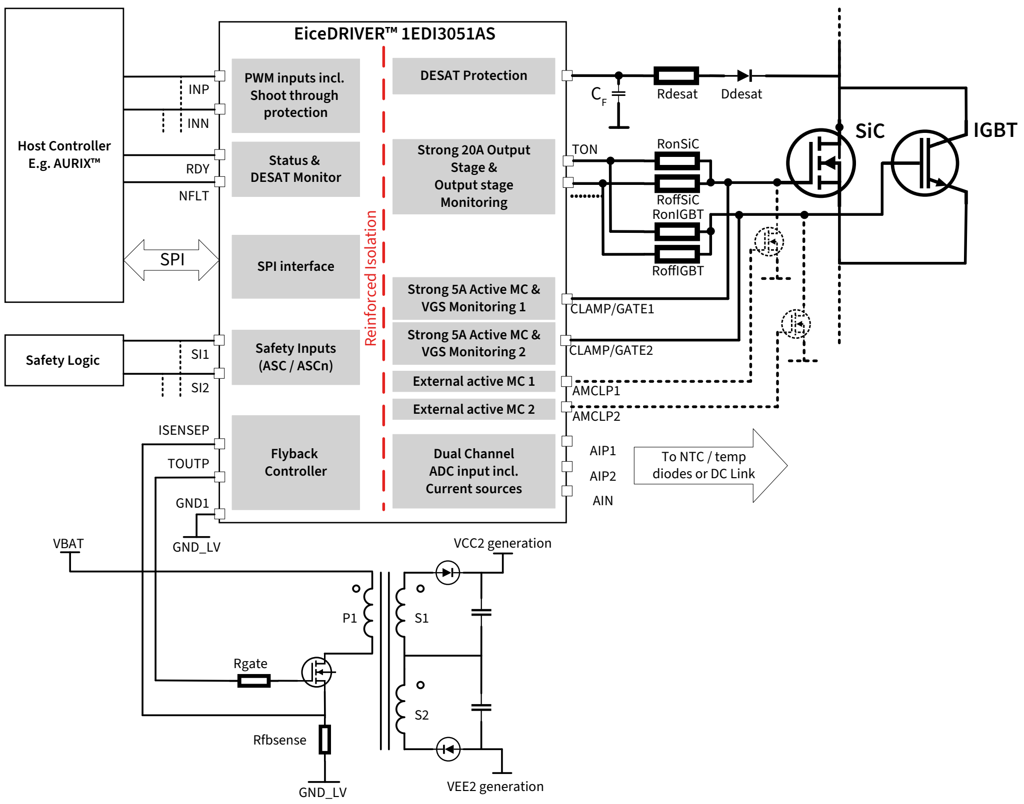


Figure 23 Simultaneous S1G and S2G approach using EiceDRIVER™ 1EDI3051AS (S2G shown here)

EiceDRIVER™ 1EDI3051AS key features

The EiceDRIVER™ 1EDI3051AS gate driver has a strong internal booster stage capable of peak currents of up to 20 A to drive modules with high gate charges. It also offers an accurate dual-channel 12-bit delta-sigma ADC with the ability to monitor two signals, such as the IGBT and SiC temperatures, using temperature diodes or NTCs placed close to the chips.

In addition to the above two features, this gate driver has further features that make it a good choice for simultaneous S1G and S2G modes:

- SPI-programmable DESAT threshold that provides complete flexibility to select the threshold such that a false DESAT is not triggered during normal operation but the threshold nonetheless prevents damage to the devices (SiC in particular) during high short-circuit currents
- SPI-programmable turn-off in the event of DESAT or overcurrent faults, providing complete flexibility for soft turn-off with a ramp or two-level plateau
- Separate internal active Miller clamp with gate monitoring for IGBT and SiC that allows individual fault detection in either of the power semiconductors
- Separate external active Miller clamp that provides flexibility to build in separate external clamping MOSFETs for IGBT and SiC
- Separate overcurrent protection that allows individual monitoring and protection for IGBT and SiC in the event that power semiconductor devices with current mirrors are used
- Common VCC2 and VEE2 power supply for both IGBT and SiC, minimizing the need for additional power supplies

Turn-on and turn-off

Depending on the adaption circuitry and the switching behavior, turn-on and turn-off could result in a mismatch between IGBT and SiC switching speeds. This could cause most of the load current to flow temporarily through one device (usually SiC during turn-on and IGBT during turn-off since SiC switches faster than IGBT). In such cases, a false DESAT trigger could be an issue. During turn-on, this problem is avoided by the DESAT filter time constant. During turn-off, the gate driver avoids this problem by setting internal DESAT clamping to low during the input PWM transition. Consequently, DESAT clamping becomes active before the switch is actually turned off, preventing a false DESAT trigger.

This scenario is simulated in Figure 24 (1st diagram, blue line, t= 2.002). Due to differences in switching speeds between IGBT and SiC, SiC turns off before the IGBT, so the entire load current flows temporarily through the IGBT. However, DESAT is clamped to low (0 V) during the INP transition (positive PWM input of the gate driver) and this prevents a false DESAT trigger.

Bridge short circuit (type 1)

The EiceDRIVER™ 1EDI3051AS gate driver allows fast detection and turn-off of both devices with a programmable DESAT threshold voltage and a programmable turn-off with a ramp or two-level plateau. For the gate driver, as simulated in Figure 25, detection of and response (4th diagram, t = 1.065) to the DESAT threshold is similar to the process involved in switching a single power semiconductor technology. Hence care needs to be taken by the system designers to ensure that the DESAT threshold chosen does not cause a false trigger under normal operating conditions while still being low enough to avoid compromising short-circuit times in the system that could damage the power semiconductors, especially the SiC MOSFET.

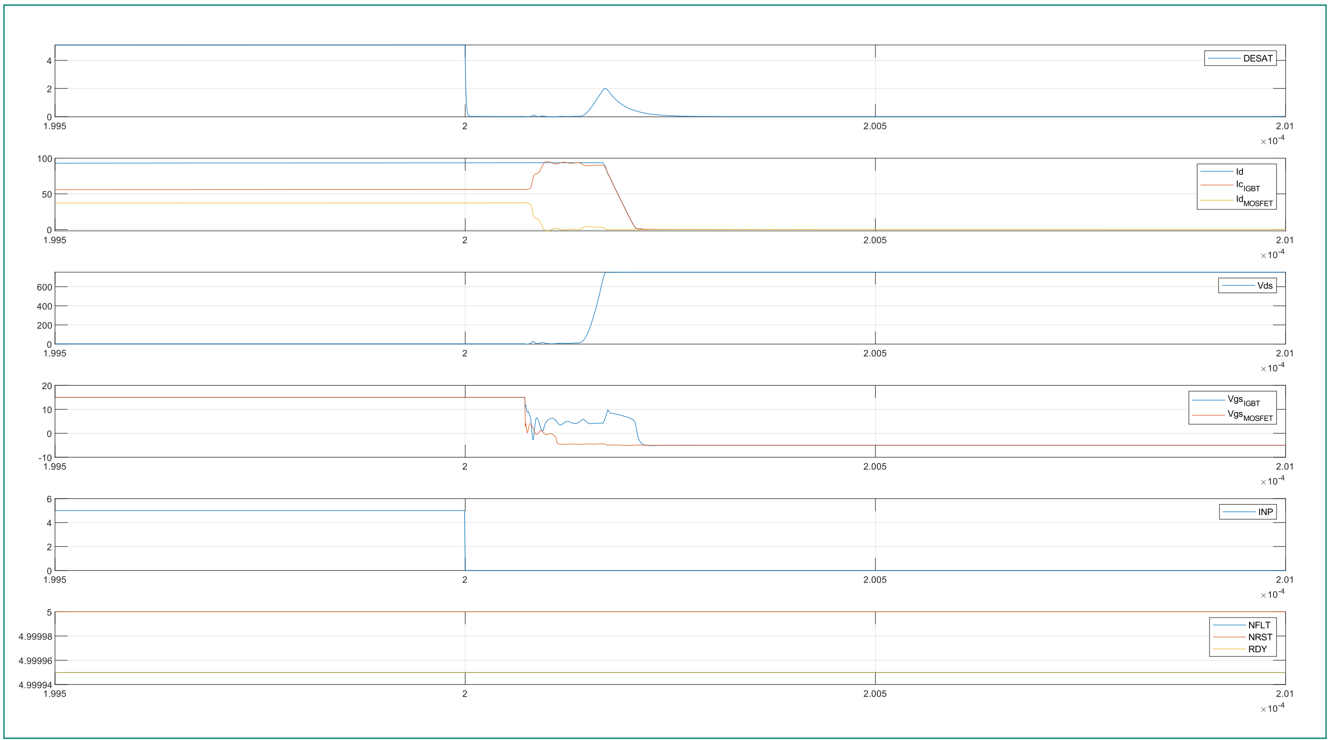


Figure 24 Turn-off behavior with EiceDRIVER™ 1EDI3051AS in simultaneous S1G and S2G modes

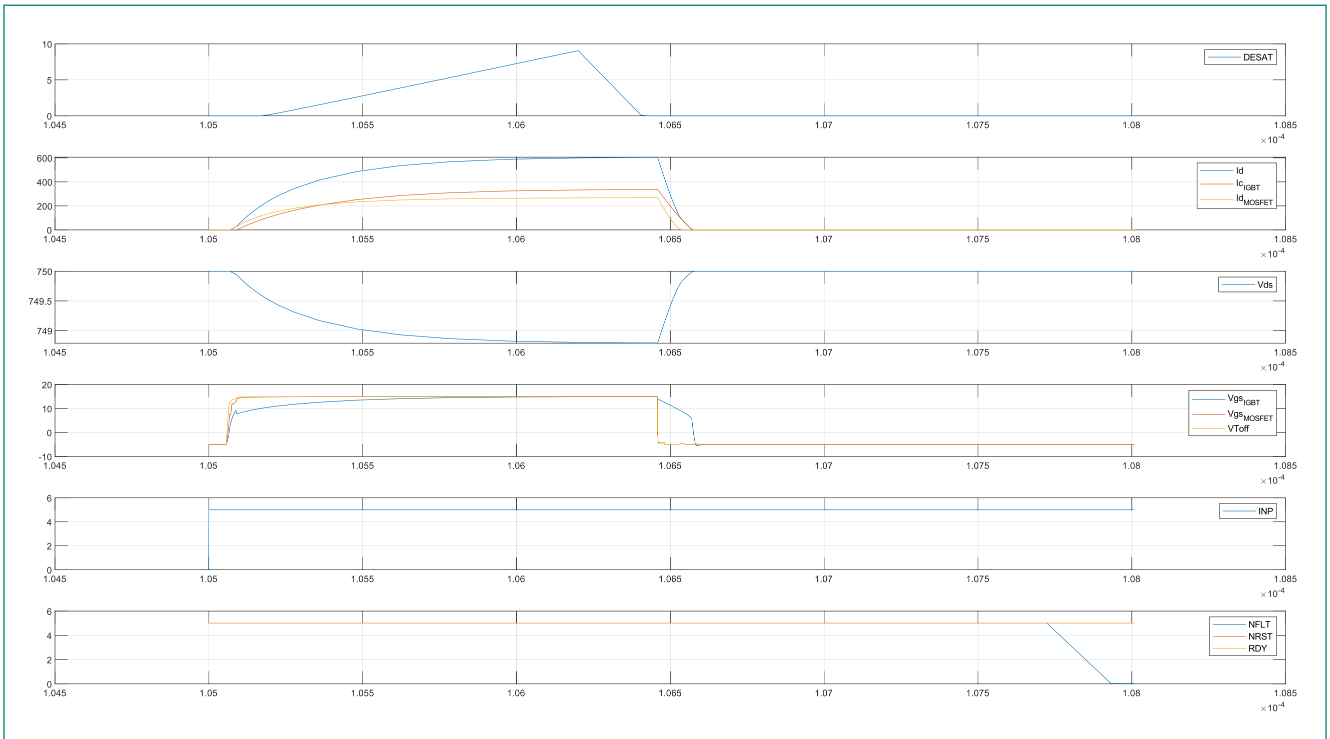


Figure 25 Short-circuit type 1 with EiceDRIVER™ 1EDI3051AS in simultaneous S1G and S2G modes

Simultaneous switching using EiceDRIVER™ 1EDI302xAS/1EDI303xAS (x = 5,6,8)

The EiceDRIVER™ gate driver family offers six devices in compact 20-pin DSO packages (1EDI3025AS, 1EDI3026AS, 1EDI3028AS, 1EDI3035AS, 1EDI3036AS, 1EDI3038AS), providing the highest degree of compatibility with the current generation of IGBT and SiC power technologies. Each of these devices implements a slightly different feature set to support individual system requirements and can be easily implemented without the user needing to master a complicated serial programming interface (SPI).

Table 1 shows the key product features per variant so designers can easily select the best fit for individual application needs.

Table 1 Overview of product variants

Type	AMCLP External active Miller clamp	SOFTOFF External soft off pin	OCP Overcurrent protection	DESAT Desaturation protection	OVLO3 VEE2 OVLO monitoring	ADC	Output stage rated current	Power switch target
1EDI3025AS		x		x	x		15 A	IGBT
1EDI3026AS		x	x		x			IGBT
1EDI3028AS		x		x		x	10 A	IGBT
1EDI3035AS		x		x	x		15 A	SiC
1EDI3036AS	x			x	x			SiC
1EDI3038AS		x		x			10 A	SiC

Short-circuit capabilities for fusion inverter applications are usually driven by SiC requirements and these tend to be more critical. Consequently, the EiceDRIVER™ 1EDI3035AS, which is optimized for SiC and offers a softoff feature, is often the best choice for simultaneous S1G and S2G implementations.

A typical EiceDRIVER™ 1EDI3035AS gate driver implementation is shown in Figure 26.

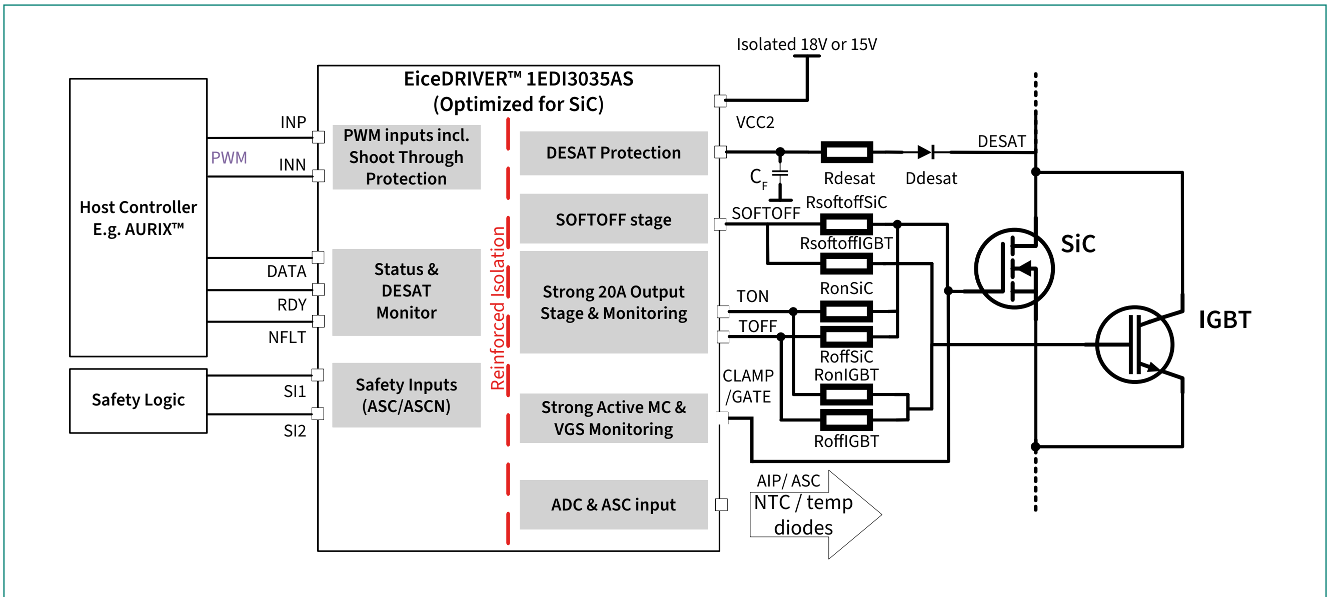


Figure 26 Simultaneous S1G and S2G implementation using EiceDRIVER™ 1EDI3035AS gate driver (S2G shown here)

EiceDRIVER™ 1EDI3035 key features

Turn-on and turn-off

The turn-on and turn-off behavior for simultaneous S1G and S2G modes using the EiceDRIVER™ 1EDI3035 gate driver is similar to that of the EiceDRIVER™ 1EDI3051AS, since the output stages are identical and the problem of false DESAT triggering as described in the general section “Turn-on and Turn-off” can be addressed in a similar way using the 1EDI3035 gate driver.

Bridge short circuit (type 1)

Similar to turn-on and turn-off, the short circuit behavior of the EiceDRIVER™ 1EDI3035AS is similar to that of the 1EDI-3051AS gate driver. However, faster DESAT detection and reaction times allow the gate driver to quickly sense and react to overcurrent situations. Similarly, the dedicated SOFTOFF pin allows the designer to set a separate optimized gate turn-off resistance to safely turn the device off in the event of overcurrent while keeping the switching losses optimized during regular turn-off conditions.

6.4.1.4 The power module

Feedback from the market shows that S2G_dir is gaining in traction relative to S1G or S2G, especially for the fusion inverter ramping phase.
With the S1G, S2G and S2G_dir methods, Si and SiC are always switched simultaneously (“S”). The S1G variant has an adaptation circuit internally in the power module, enabling just one gate (1G) to be addressed by the designer. The S2G variant still has two gates (2G: one gate for SiC and one for Si) and the circuit has to be adapted at PCB level. The beauty of S2G_dir is the fact that both technologies are matched. Si and SiC work so well together that no additional adaptation is required. The inverter designer just needs to short-circuit both gates at PCB level and no further tuning is required. For future developments, Si and SiC are still individually addressable, paving the way for In2G or In2G_red (see dedicated section).
This rising popularity of S2G_dir is due to a number of reasons. A one-gate solution as the control method for simultaneous mode offers various advantages. It also has the potential to leverage the Si IGBT platform in particular to improve inverter efficiency. Adding to its appeal is ease of implementation. S1G_dir comes with a low level of system complexity and requires no changes to the inverter system. We will take a closer look at the favorable switching behavior of S2G_dir in the following sections.
Measurements show that the switching characteristics change and that the simultaneous inverter fusion approach strikes a good balance between Si IGBT characteristics (see Figure 27, green graph) and SiC-only behavior (orange).

Figure 27 illustrates the conduction behavior both in the first quadrant (representing the acceleration phase) and the third quadrant (representing the deceleration/recuperation phase). As the graphs illustrate, the higher the SiC content in the switches, the closer the behavior to pure SiC curves. Conversely, the lower the SiC content implemented, the closer the curve moves to Si-only behavior.

These graphs clearly demonstrate that the fusion inverter gives designers an opportunity to implement the transfer characteristic best suited to the application in question in terms of performance and cost effectiveness. The graph on the left further illustrates the SiC/Si breakeven point (intersection between blue and yellow lines). SiC is more efficient at low loads (to the left of this intersection) and Si is more efficient at high loads (to the right of this intersection).

As discussed in earlier chapters of this paper, partial load plays an important role in the overall efficiency equation (e.g. according to WLTP). Especially for low currents, the fusion inverter shows a significant improvement relative to the pure Si variant.

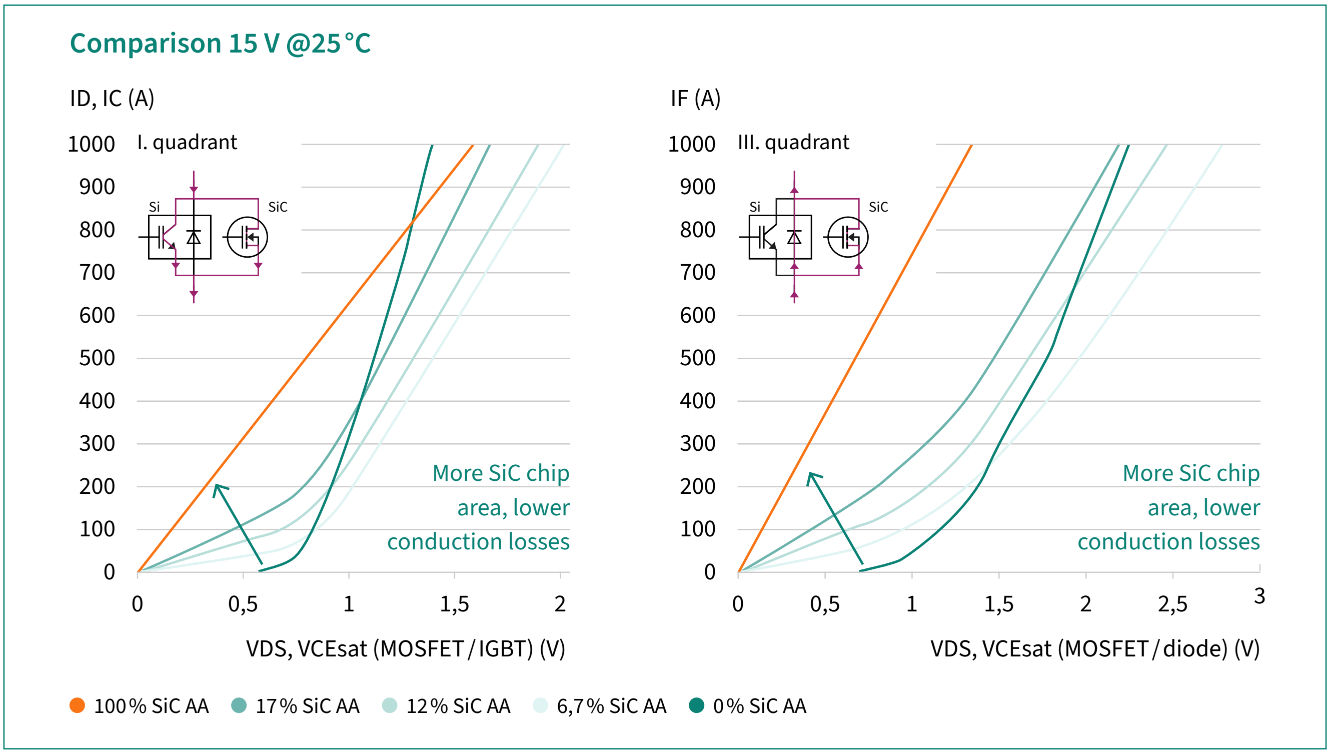


Figure 27 Transfer characteristics of S1G/ S2G with different SiC active areas (AA)

As Figure 27 describes the steady state losses of the combined fusion switch, the transient behavior of the parallelled switches is important for the efficiency as well. Figure 28 shows the comparison of the turn-off behavior for Si, SiC, and fusion switches.
It can be observed that the fusion switch has quite similar switching curves to those of the full Si version (left). The ringing, which is common with SiC switches (see right), does not appear. The oscillations are suppressed due to the IGBT tail current in combination with the low SiC AA of 17%, which results in a Si AA of 83%. As a result of this effect, the switching losses of SiC, in a fusion configuration, are lower than in a pure SiC power device.

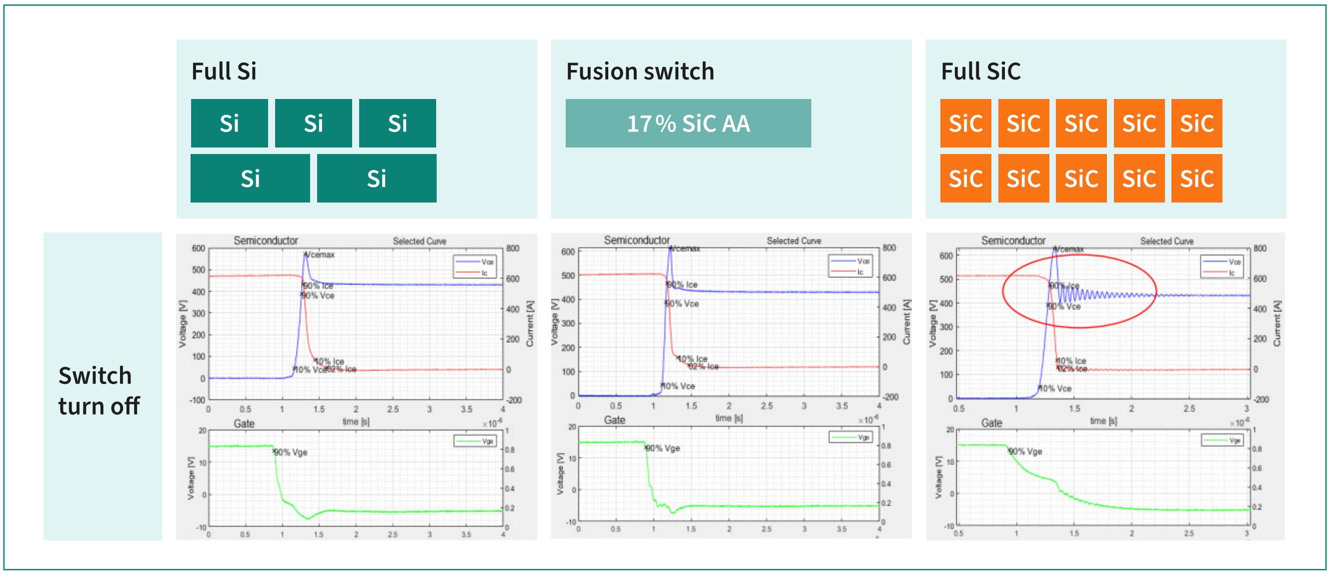


Figure 28 Comparison of switch-off behaviors of Si, SiC, and fusion switches

Even in special cases, such as short circuits, our measurements show stable short-circuit switching behavior (750 V technology under test).

6.5 Individual switching: In2G & In2G_Red modes

The third switching option entails operating both technologies independently. This requires two PWM signals per switch (so 12 per inverter). This mode has the advantage of optimal tuning for both switches and freedom to adapt the PWM pattern online within the control strategy. As SiC may switch faster than Si, the turn-on and turn-off edges can be shifted so as to optimize transient current sharing and minimize overload per technology. Depending on the use case, the resulting operation can seamlessly switch between exclusive and simultaneous modes. In the event of a failure, a kind of "limp home" mode could even be implemented, where one technology is switched off and the system operates via the remaining functional technology so it can limp home. Individual mode results in a more complex setup as it requires two gates (In2G) but – on the upside – it leverages the benefits of fusion technology traction inverters in full. It offers the bonus of redundancy between the two technologies (fail-over).
Individual switching offers the greatest potential for vehicle-level benefits, but requires a more complex control strategy. Taking a closer look, two different individual switching variants are conceivable. The first one (In2G) focuses on individual switching dynamics whereas the second one (In2G_Red) additionally can enable a major step in the direction of fail-operational systems.

6.5.1 Complementary solutions from Infineon

Similar to the exclusive and simultaneous modes outlined above, an ASIL-compliant, state-of-the-art individual mode inverter also calls for the right gate drivers, microcontrollers, and power supply ICs. As outlined in the following, Infineon's end-to-end offering spans all of these building blocks supporting different implementation concepts offering a variety of benefits.

6.5.1.1 The microcontroller in In2G mode

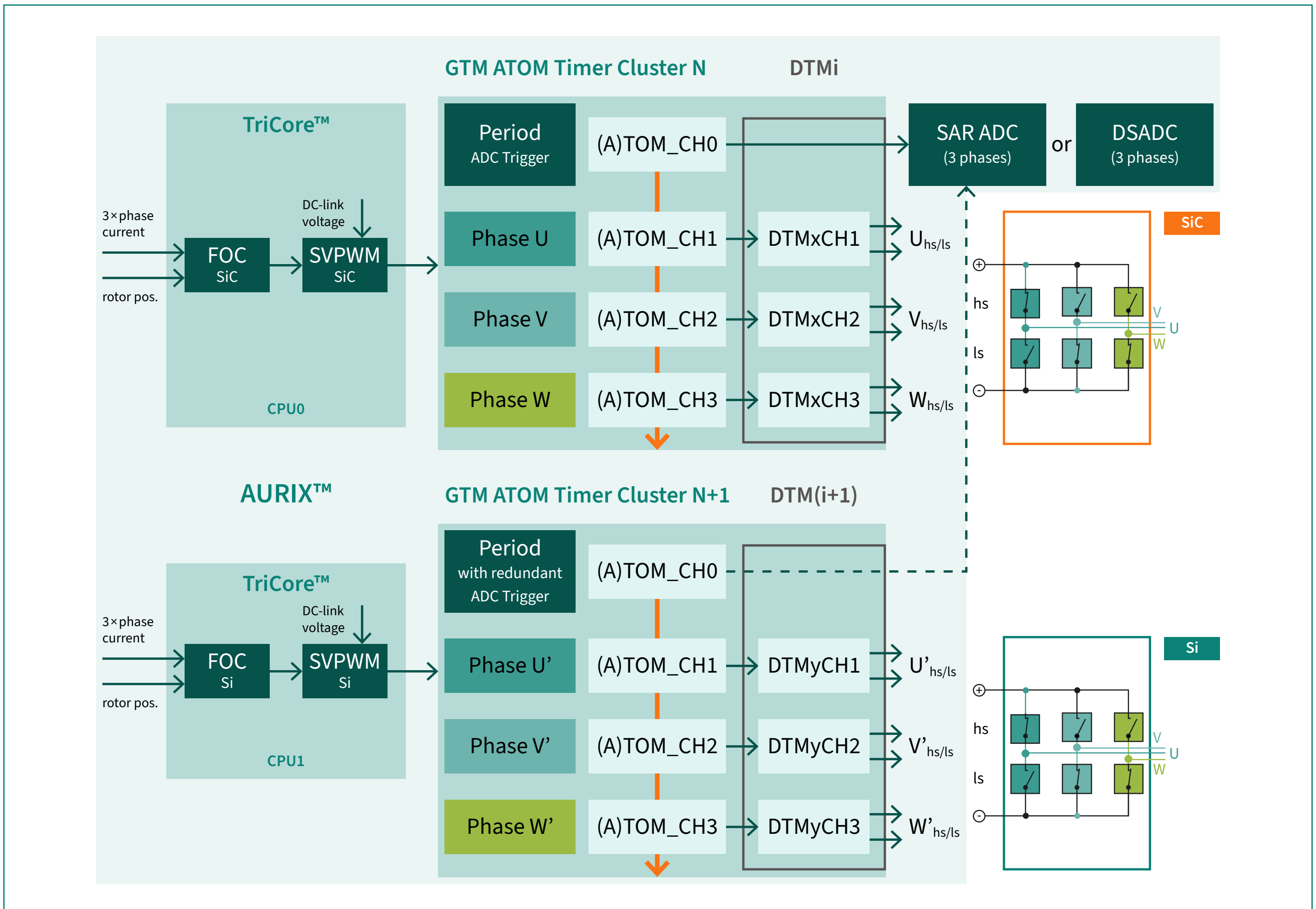


Figure 29 View inside the AURIX™ microcontroller in In2G mode using three current sensors

The AURIX™ concept illustrated in Figure 29 for In2G mode builds on the same field-proven safety performance of AURIX™ microcontrollers to offer a similar set of features and benefits to those outlined above for simultaneous and exclusive modes. There are, however, a few key differences to support the requirements of individual mode.

The TriCore™ host CPUs support individual software FOC functions for SiC and Si with the SVPWM also supporting individual adaptations for SiC and Si. The scalable CPU architecture with up to 6 cores in the AURIX™ TC3xx series allows for different functional partitioning inside the microcontroller. To support a limp-home feature, the Si and SiC software components can be implemented in different CPUs. In the event of a problem with one CPU, the other can still provide limp-home functionality. On the other hand, to save resources, the powerful TriCore™ CPUs may also support the calculation of the Si and SiC SW paths on one core. In addition, the Generic Timer Module has 2 period masters and 2x3 ATOM channels, and the DTM module has 2x3 channels. Furthermore, designers have the option of increasing availability by adding a second, redundant ADC hardware trigger (routed to the cluster n+1 period).

With this redundant design concept, these features combine to increase fusion inverter availability thanks to enhanced fail-operational capabilities. Limp-home mode works on both the Si and SiC switches to enable continued operation of the traction motor. In addition, the SiC/Si FOC calibration parameters can be set individually. Similar to exclusive mode, the SVPWM can also be adapted to the requirements of SiC/Si respectively. In addition, a smart timer and ADC peripherals offload the main CPU to a significant extent. ATOM timer channels with shadow-based compare register update mechanism contribute to glitch-free operation. And SiC-/Si-specific dead times contribute to efficiency gains.

This approach does have some downsides, however. It is the most resource-intensive design (at both a hardware and software level). In effect, it matches the resource requirements of dual inverter designs except it uses three phase current sensors instead of six.

6.5.1.2 The microcontroller in In2G_Red mode

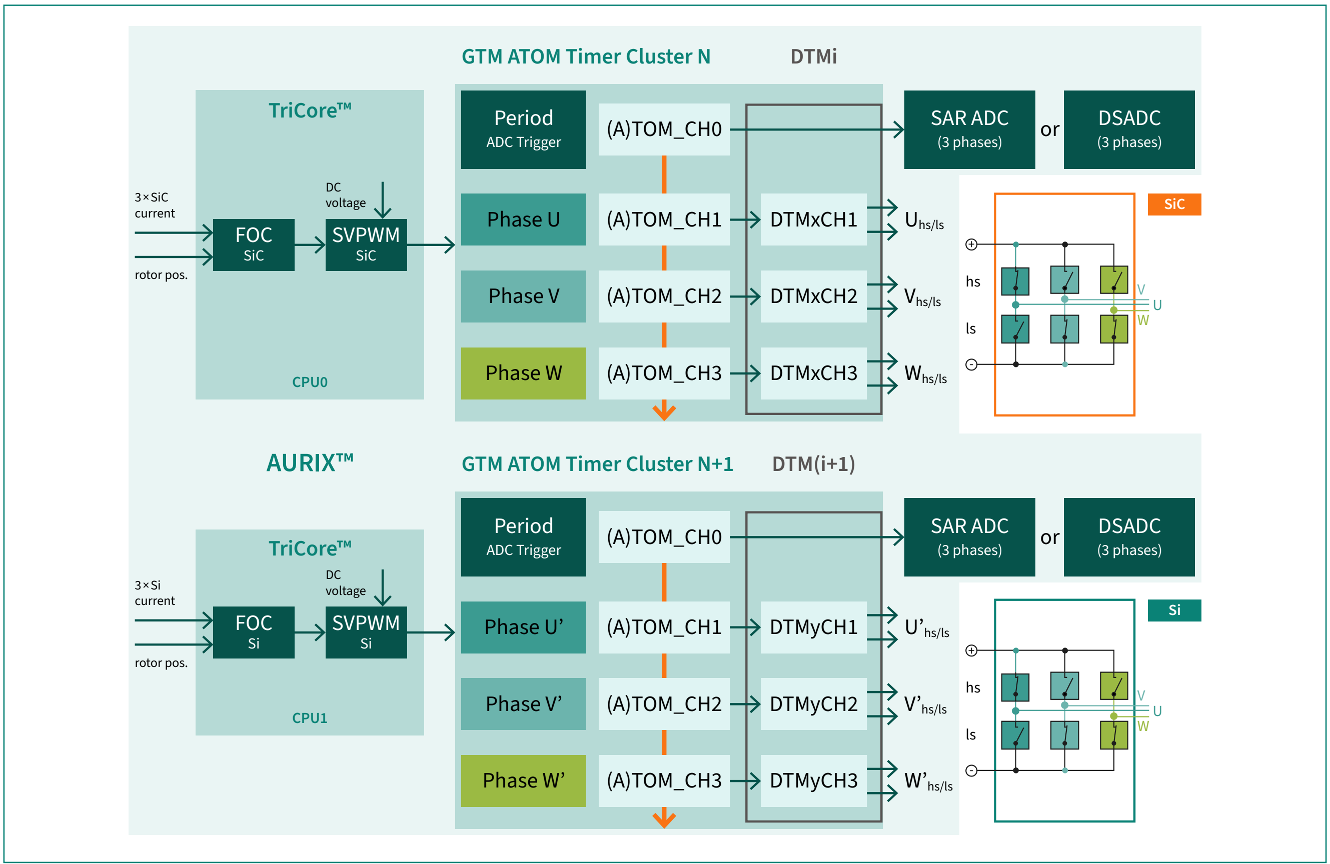


Figure 30 View inside the AURIX™ microcontroller in In2G_Red mode with two 3-phase current sensors

The AURIX™ concept (Figure 30) builds out the In2G scheme illustrated above to take redundancy to the next level. Six phase current sensors for individual Si/SiC current measurements further increase system availability. In addition, this design includes two configurable ADC HW trigger signals synchronized with the PWM pattern. Similar to In2G, the downside of this approach is that it is resource-intensive.

6.5.1.3 The current sensor

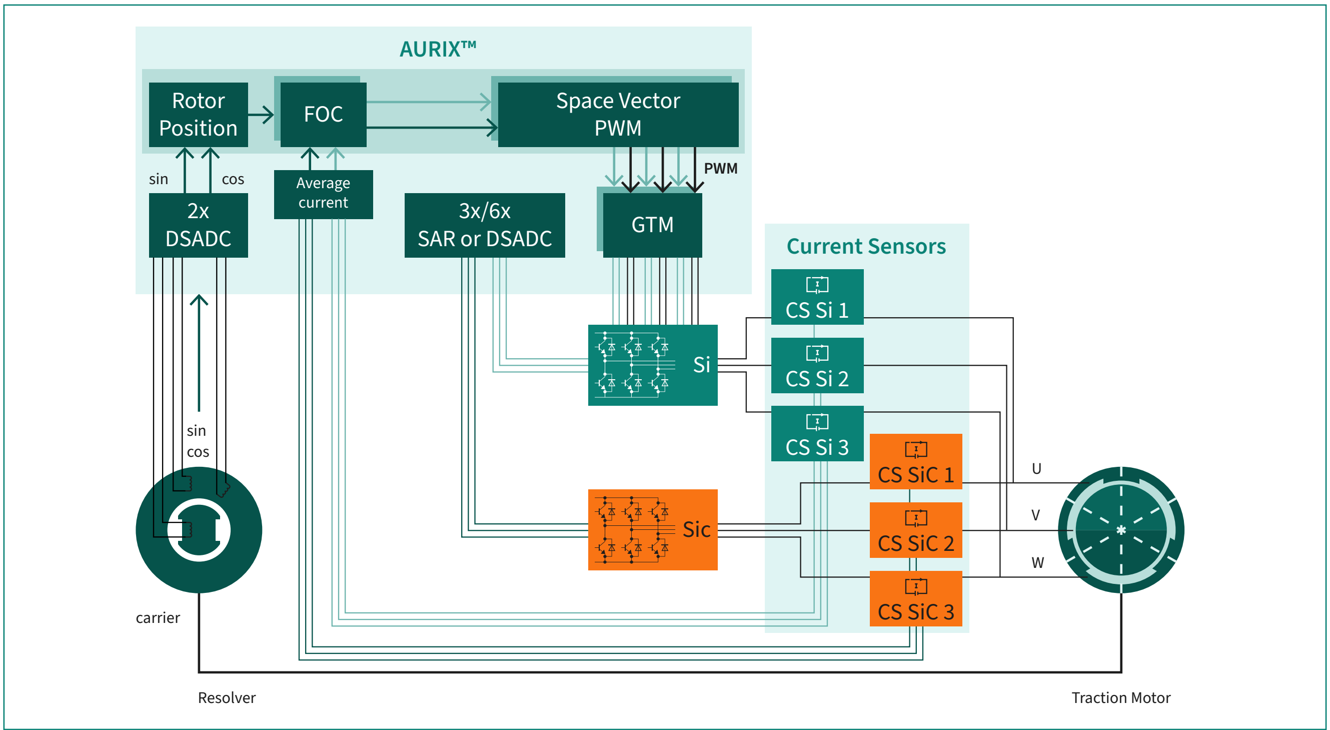


Figure 31 System overview of AURIX™ microcontroller in In2G- / In2G_Red mode with two sets of three phase current sensors

Figure 31 above illustrates how current sensors are positioned with this switching variant (In2G and In2G_Red). The benefits of this concept are the individual current measurement range and the individual fast overcurrent detection capabilities per technology. This arrangement helps to prevent technology overload – both in steady state and during transient events such as short circuits. Infineon's XENSIV™ coreless current sensors are compact, cost-effective solutions enabling designers to integrate six sensors per fusion inverter.

6.5.1.4 The gate driver

There is not much difference between In2G and In2G_Red at gate driver level, as each channel has its own gate driver. In2G and In2G_Red require independent PWM signals to drive the IGBT and SiC. This offers complete flexibility to optimize the switching behavior of the devices while at the same time providing independent diagnostic capabilities. From the gate driver point of view, this means that these topologies require two gate drivers.
As discussed in the section about simultaneous switching, the EiceDRIVER™ gate driver family offers six variants in compact 20-pin DSO packages (1EDI3025AS, 1EDI3026AS, 1EDI3028AS, 1EDI3035AS, 1EDI3036AS, 1EDI3038AS), providing the highest degree of compatibility with the current generation of IGBT and SiC power technologies. Each of these devices offers a different feature set to support individual system-level requirements.
The following section explores individual In2G and Ing2G_Red switching based on an EiceDRIVER™ 1EDI3025AS and EiceDRIVER™ 1EDI3035AS gate driver combination. Both of these drivers have a similar feature set with DESAT and SOFTOFF capabilities, and have been optimized for IGBT and SiC respectively. This combination of features enables the IGBT and SiC platforms to detect and respond to short circuits independently.

A typical implementation of the In2G switching mode is shown in Figure 32.

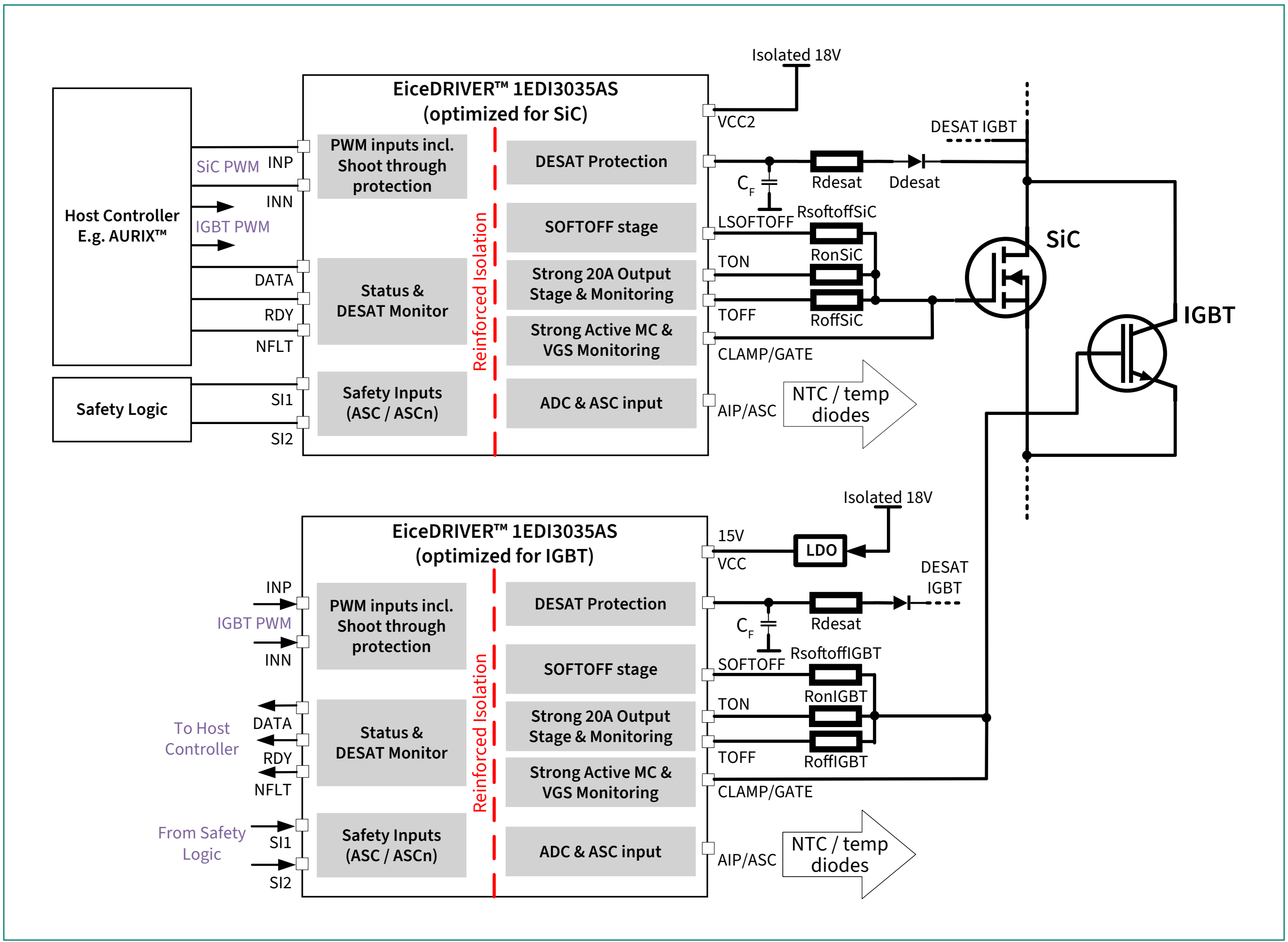


Figure 32 Individual In2G mode using EiceDRIVER™ 1EDI3025AS and EiceDRIVER™ 1EDI3035AS gate

EiceDRIVER™ key features

The combination of EiceDRIVER™ 1EDI3025AS and EiceDRIVER™1EDI3035AS gate drivers provides a strong internal booster stage capable of peak currents up to 20 A per gate driver to drive modules with high gate charges. It also offers independent 12-bit delta-sigma ADCs with the ability to monitor two signals, such as the IGBT and SiC temperatures using temperature diodes or NTCs placed close to the chips.

In addition to the two features outlined above, this gate driver combination has further features that make it a good choice for the individual In2G mode:

- Separate DESAT threshold voltages and filters for IGBT and SiC, providing complete flexibility to optimize DESAT detection and response
- Separate SOFTOFF providing independent fault reactions to overcurrent situations
- Separate VCC2 and VEE2 power supplies, minimizing conduction losses especially in SiC
- Separate strong internal active Miller clamp with gate monitoring for IGBT and SiC that allows individual fault detection in either of the power semiconductors
- Limp-home capability if one power semiconductor device fails
- Option of adapting to Ex2G approach so only one of the devices is switched

Turn-on and turn-off

Two separate gate drivers offer complete flexibility to turn on and turn off the power devices independently. They can be switched on and off with a delay to optimize the switching and conduction losses. Depending on how the respective power technologies behave and the influence of various parasitics in the system, different switching patterns can be implemented. Here, we will assume that Si turns on first and off last as SiC typically exhibits faster turn-on and turn-off behavior than IGBT. So SiC is turned on first and, after a delay, the IGBT is also turned on with zero voltage across it and hence achieving zero voltage switching (ZVS). Similarly, the IGBT is turned off first with ZVS and then SiC is turned off.
In this mode of operation, the entire load current flows through one device – SiC for the delay time during turn-on and turn-off. Since the DESAT threshold of the SiC gate driver is lower than that of the IGBT gate driver and since the voltage drop across SiC can be higher at higher currents due to the resistive nature of SiC, a false DESAT trigger could be an issue. During turn-on, this problem can be avoided by the DESAT filter time constant. During turn-off, specific care needs to be taken to prevent false triggering by adopting appropriate devices, DESAT delays, and filter times.
Turn-on behavior is simulated in Figure 33. Assuming the IGBT turns on 500 ns after the SiC, the entire load current flows through SiC for the 500 ns delay (2nd diagram, yellow line, t= 2.5). The impact on switching and conduction losses needs to be considered but it can be observed that due to the DESAT filter time constants, there is no false triggering during turn-on. If the IGBT turn-on delay is significantly longer, it is important to note that there could be a false DESAT trigger.
Turn-off behavior is also simulated in Figure 34. As the graph illustrates, the entire load current flows through the SiC for 500 ns after the IGBT turns off (2nd diagram, yellow line, t= 2.002). This causes the drain-source voltage across the SiC to increase and hence causes the DESAT voltage to rise (1st diagram, red line, t=2.005), finally reaching the trigger threshold and hence triggering a fault. But by reducing the delay time to below 500 ns or by dimensioning the SiC appropriately for the desired load current, this false DESAT trigger can be avoided. Depending on the power technology deployed in the IGBT, the effect of the IGBT tail current on switching losses requires further analysis.

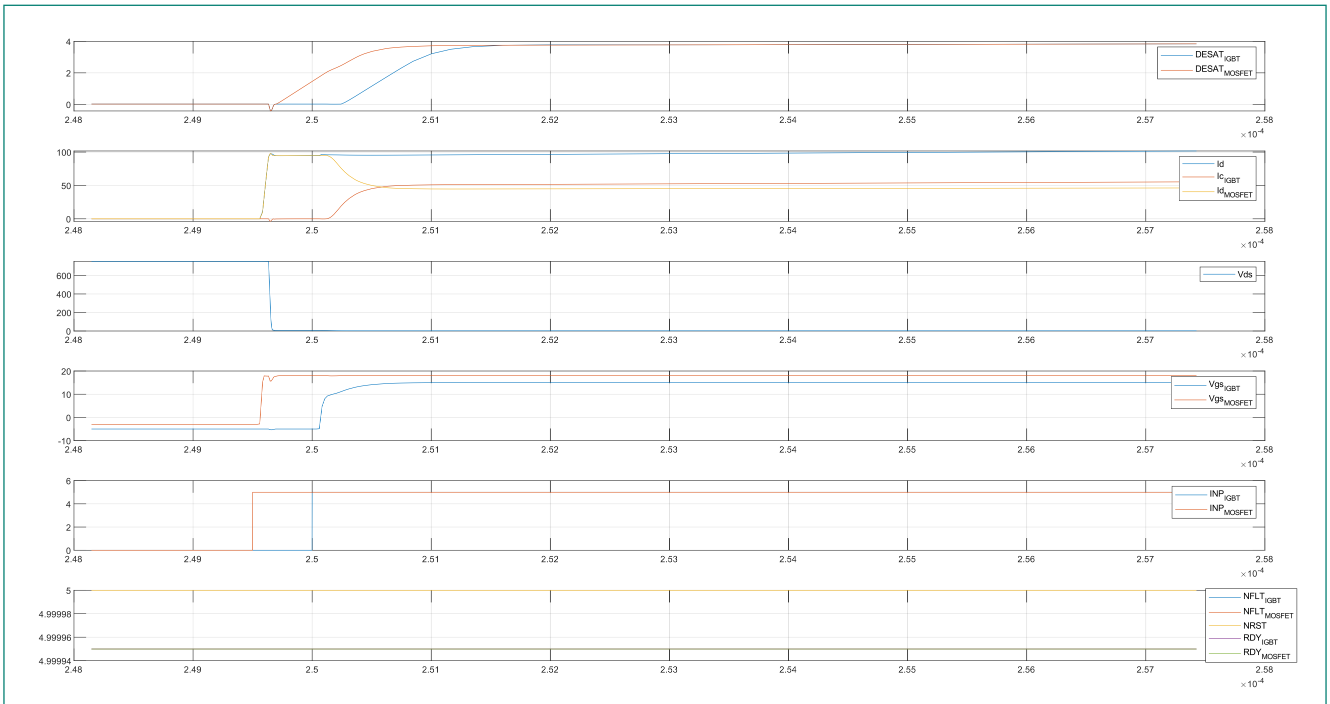


Figure 33 Turn-on behavior with EiceDRIVER™ 1EDI3025AS and EiceDRIVER™ 1EDI3035AS gate drivers in individual In2G mode

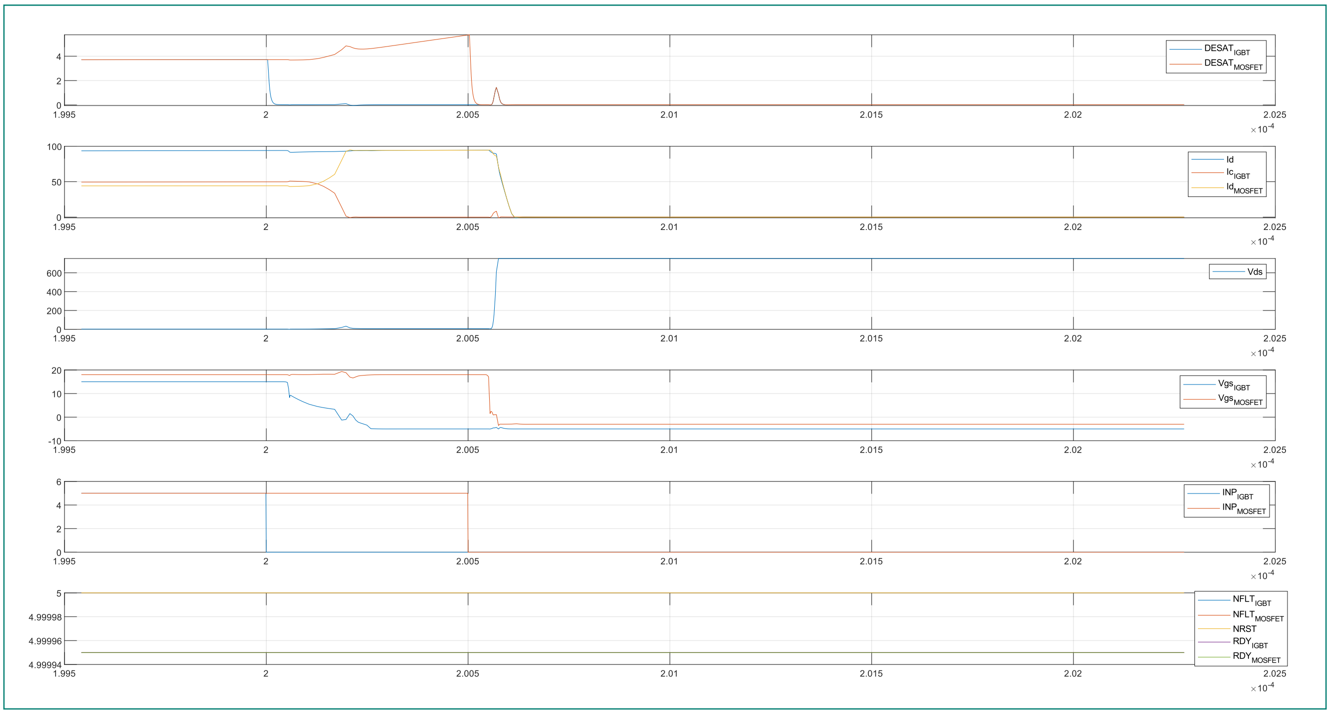


Figure 34 Turn-off behavior with EiceDRIVER™ 1EDI3025AS and EiceDRIVER™ 1EDI3035AS gate drivers in individual In2G mode

Bridge short circuit (type 1)

Two separate gate drivers mean that SiC and IGBT short circuits can be independently detected and actioned. Short-circuit behavior is simulated in Figure 35. SiC turns on first and then DESAT voltage starts to rise. As soon as the SiC DESAT threshold is crossed, a DESAT fault is triggered on the SiC gate driver and a SOFTOFF is initiated to safely reduce the current through the SiC. After the delay time, the IGBT turns on, detects the fault, and the IGBT DESAT voltage starts to rise. As soon as the IGBT DESAT threshold is crossed, the IGBT is safely turned off. With this scenario, we have two short-circuit events in the system – one for SiC and one for IGBT. It is important to note that each device is still protected by its own optimized DESAT sense and reaction circuitry but that the system overall is subjected to two short-circuit events.

Depending on the delay time chosen between SiC and IGBT, the system can be programmed either to recognize the SiC fault by the primary-side microcontroller and then to disable the IGBT before it turns on or to allow the IGBT to turn on in the presence of the fault, sense the fault, and then turn off (SOFTOFF). For the plot in Figure 35, the delay time between turning on SiC and IGBT is increased to 2 µs to demonstrate this behavior (5th diagram, red line @ t= 1.03 and blue line @ 1.05). In this case, by the time the SiC fault signal is available on the primary microprocessor (6th diagram, red line, t= 1.054), IGBT has already turned on. Hence a safe reaction would be to allow the IGBT to detect DESAT on its own and then do a SOFTOFF.

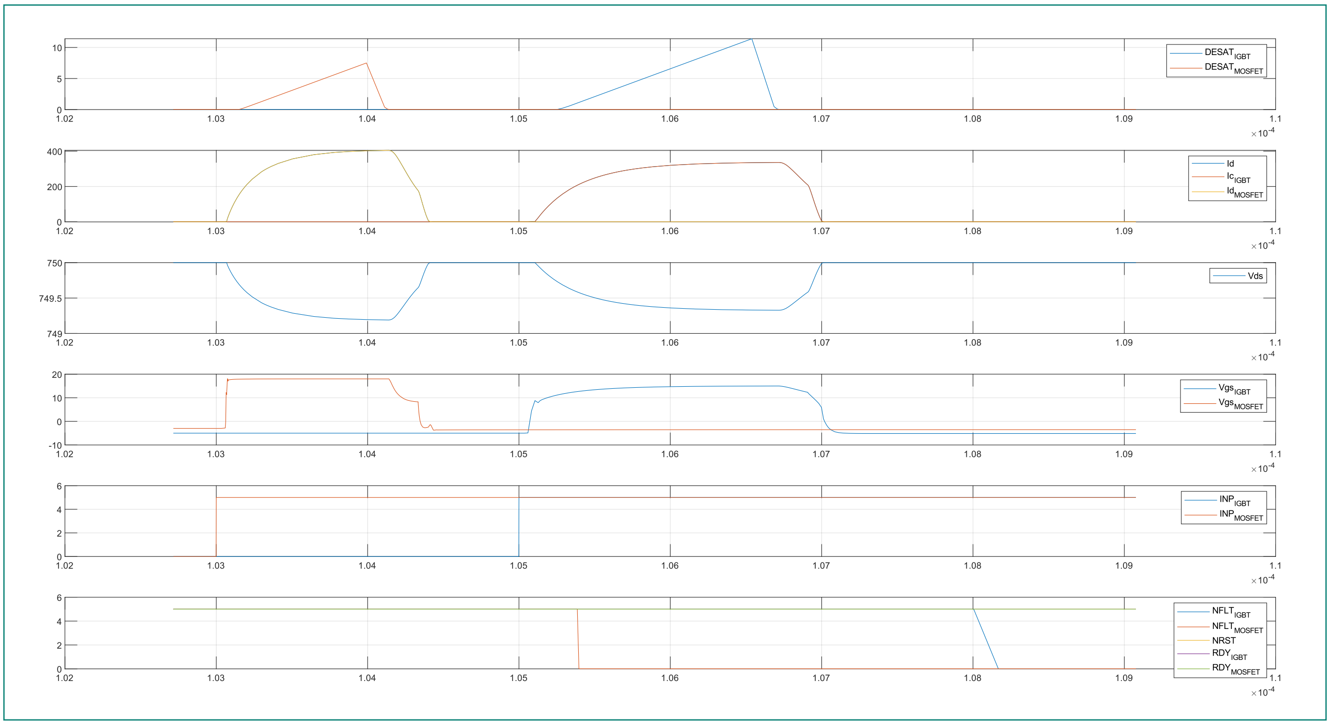


Figure 35 Short-circuit behavior with EiceDRIVER™ 1EDI3025AS and EiceDRIVER™ 1EDI3035AS gate drivers in individual In2G mode

6.5.1.5 Redundancy considerations in In2G_Red mode

For the different signal flow options, as shown in previous chapters, the solutions trade slight efficiency reductions for significant cost savings. Another aspect of the fusion concept is safety and availability. This brings us to In2G_Red mode. This mode is the same as In2G but includes a certain level of redundancy ("Red"). This extends from various redundant power semiconductors (Si and SiC) through redundant gate drivers (Si- and SiC- gate driver) for each switch to redundant calculation of the PWM pattern at different cores of an AURIX™ (see Figure 36). This takes the fusion concept to a new level, targeting future use cases. The basis of this is the redundant (two switches in parallel) and diverse (Si and SiC) power switches, as this is obviously the main concept of fusion inverters. Instead of doubling up the microcontroller, too, the multi-core architecture of the AURIX™ is used to create the redundancy inside just one microcontroller. By following this approach, a high degree of redundancy can be achieved, in addition to the benefits of the general fusion approach. The In2G_Red method could be applied in applications like robotaxies or other applications where a high level of availability and reliability is needed. Of course, this method implies some addition to the standard inverter BOM, but it has to be compared to systems which deliver an equal degree of redundancy, like a setup with two eAxles.

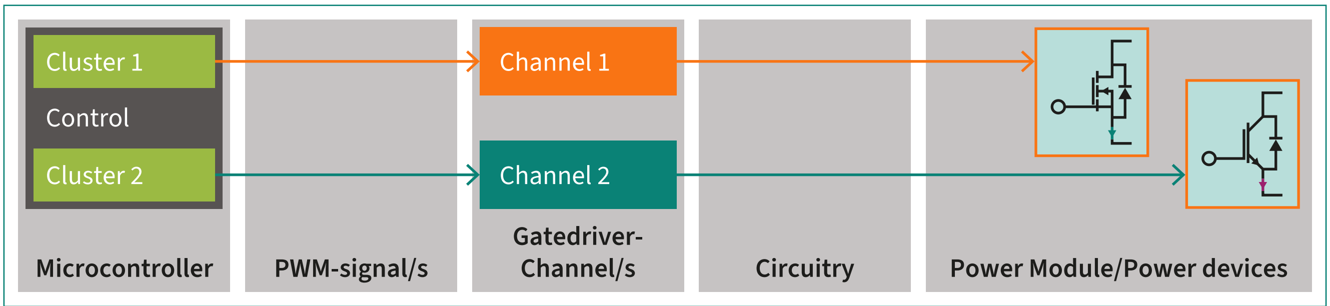


Figure 36 Individual switching with additional redundancy feature

7 Functional safety in fusion inverters

7.1 General safety considerations

The safety-related electrical and/or electronic (E/E) system in scope consists of the traction inverter including external sensors. The E/E system is supplied by a low-voltage battery (LVBAT) and a high-voltage battery (HV+_HV-). The traction inverter communicates with an external control unit to receive commands for control and configuration and to exchange information, for instance about the actual status of the E/E system.

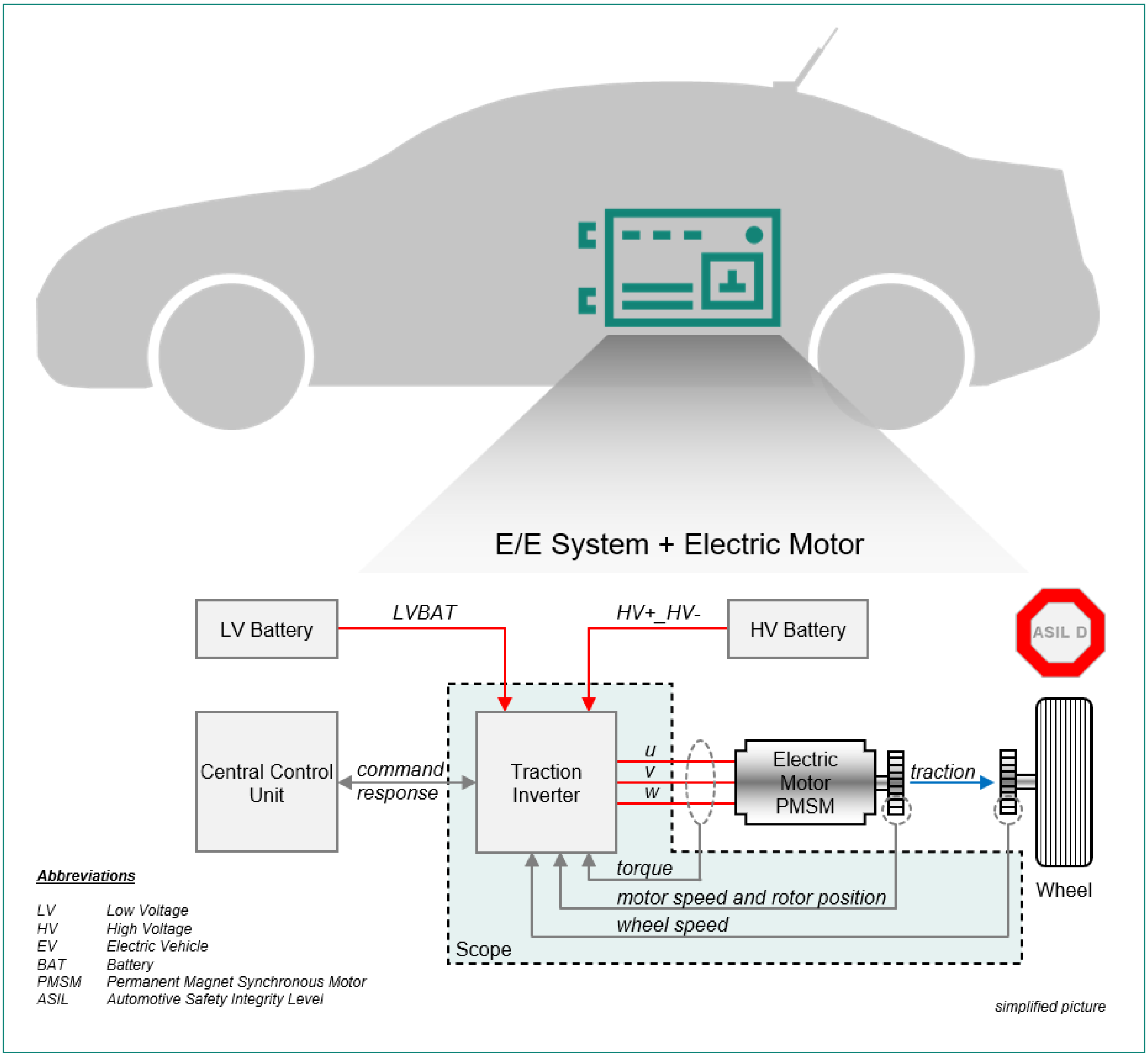


Figure 37 Traction inverter system with safety-related E/E system

Safety-related requirements at vehicle level (see Figure 37), such as safety goals (SGs), must be fulfilled to avoid or control hazardous events. Typical examples of this include unintended changes of vehicle speed due for instance to a blocked drive shaft – this could destabilize the vehicle. Similar to conventional powertrain applications, the highest expected Automotive Safety Integrity Level (ASIL) is ASIL D, depending on the dedicated safety goal.
In case of a hazardous event that could violate a safety goal, the E/E system transitions the vehicle into a safe state, e.g. to achieve a torque-free and unblocked drive shaft. It can do so by means of an active short circuit (ASC; figure 30 left) or freewheeling (FW; Figure 30 right) of the motor windings. Depending on the motor speed and other determining factors, different scenarios such as a dynamic change between ASC and FW are also conceivable.

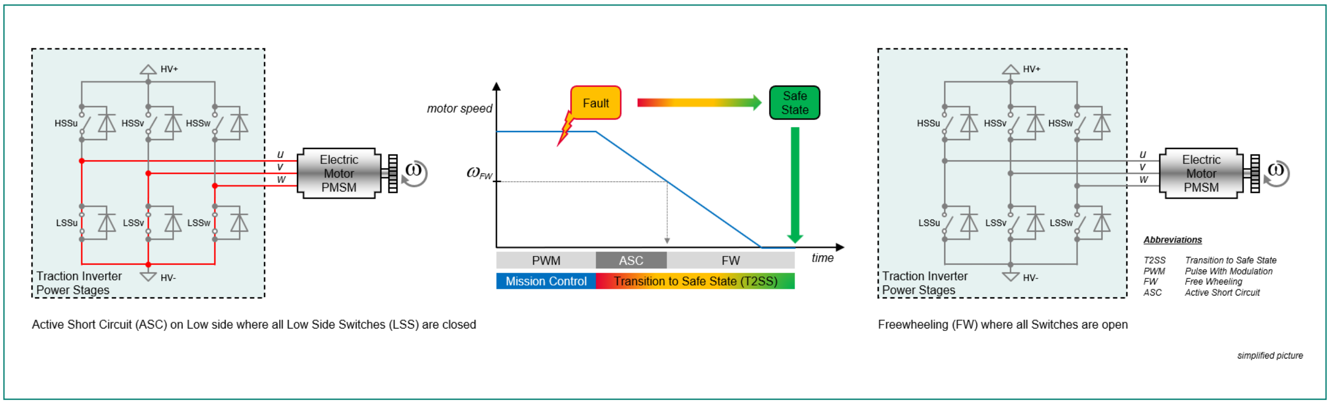


Figure 38 Safe state with active short circuit (ASC) and freewheeling (FW)

Generic Technical Safety Concept (TSC) for traction inverters

Several Technical Safety Concepts (TSCs) with different levels of HW/SW involvement are possible. Figure 39 below shows a generic TSC HW architecture where transition to safe state is controlled from the LV domain.

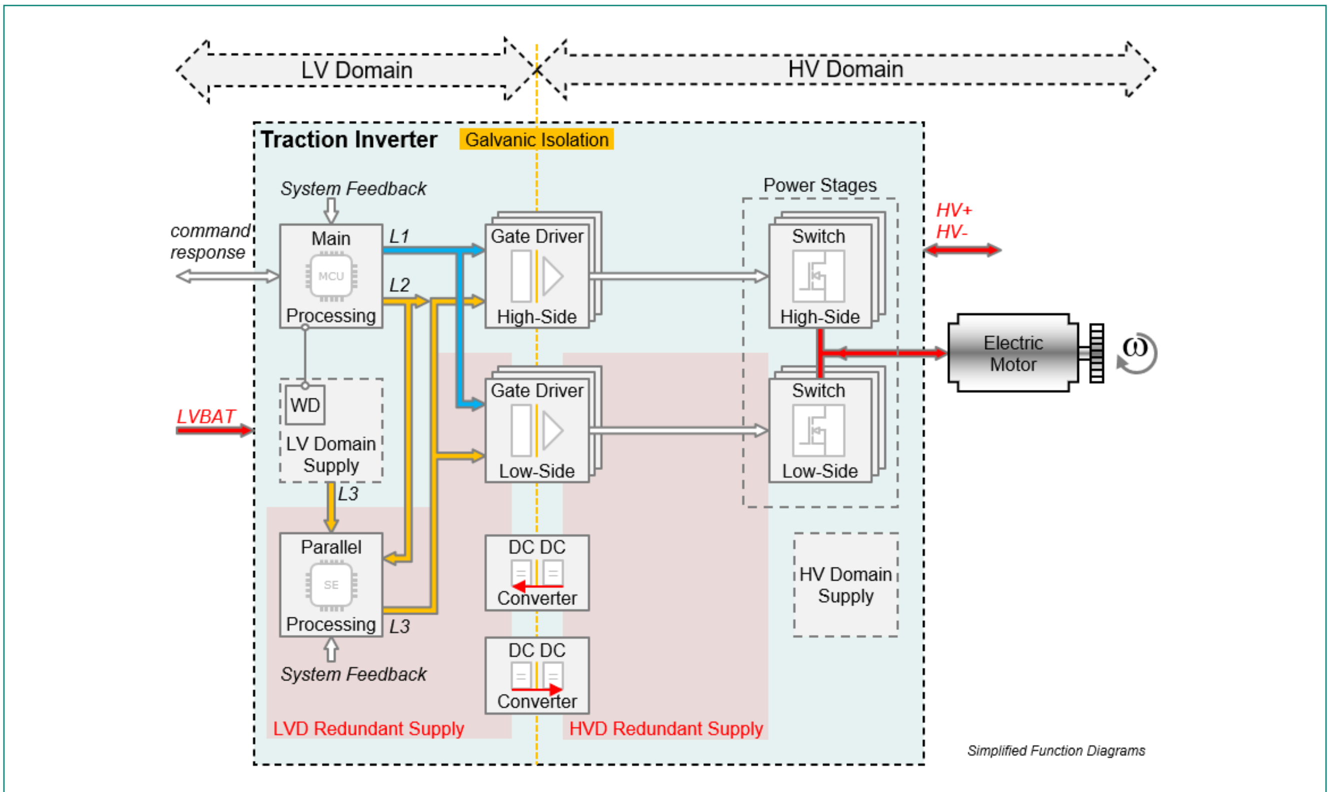


Figure 39 Generic Technical Safety Concept (TSC) for traction inverters

The TSC can be divided into three levels from L1 to L3 where:
- Level 1 represents mission control, e.g. to drive the motor via PWM signals
- Level 2 covers function monitoring, e.g. plausibility checks where the commanded request is compared with the system feedback
- Level 3 monitors safety-related HW, e.g. external watchdog monitors the microcontroller

Compared with a conventional powertrain TSC for an E/E architecture, two additional functions are needed to transition the vehicle to a safe state. One is the parallel processing unit that is responsible for transitioning the vehicle to safe state (e.g. via ASC and FW) based on system feedback, e.g. based on the actual speed of the electric motor. The second one is a redundant supply concept to make sure that safe mode is also available if one of the power supplies (LV domain supply or HV domain supply) is not available.
For safety partitioning, different ASILs can be assigned to the elements (e.g. via ASIL decomposition), whereby at the end the ultimately ASIL on at car level has to must be fulfilled.

7.2 Fusion-specific considerations

Designers can take the generic TSC shown in the previous chapter and adapt it to the different switching modes. The effort required for the adaptations will vary from one switching mode to another.

Safety considerations for exclusive switching modes: Ex2G & Ex2G_S

For the exclusive switching mode, an additional function – the Selector – is needed within the signal path. A safety integrity level (ASIL) is assigned to this additional function based on the assumption that a failure within this function could lead to a violation of a safety goal.
In addition, the Selector has to be considered within the TSC. For example, if the main control fails, a parallel processing unit has to take over control of the Selector.

Safety considerations for simultaneous switching modes: S2G, S2G_dir & S1G

For the simultaneous switching mode S2G_dir, a TSC as shown in the previous chapter can be applied because the architecture of the signal path is similar to that of a non-fusion signal path.
For the simultaneous switching mode S2G and S1G, the architectural conditions are similar to those of the exclusive switching modes, in that there is an additional function – the Adaptation – in the signal path. It can be assumed that the Adaptation function is assigned a safety integrity level (ASIL).

Safety considerations for individual switching modes: In2G & In2G_Red

The major difference between an individual switching mode signal path and a non-fusion signal path is the two-channel architecture. From a safety perspective, these two channels can be seen as one channel. This means that the established TSC (the generic safety concept illustrated above) can be used as the basis with small adaptations. In addition, the redundancy of the In2G_Red architecture presents an architectural advantage with the TSC, e.g. in that it lowers the safety integrity level (ASIL) by decomposition.

Conclusion

It can be assumed that the effort to fulfill safety-related requirements is much higher for the exclusive switching modes Ex2G & Ex2G_S and for the simultaneous switching modes S2G & S1G than that required for other switching modes.
For switching modes In2G, In2G_Red, and S2G_dir, the signal path can be described as similar to that of a non-fusion architecture. That means that a non-fusion-based TSC can be used as a basis with small adaptations.

8 Cost and size comparison of different inverter implementation modes

Besides the technical possibilities of the fusion approach, the cost structure of a fusion inverter must be investigated to judge the advantage on system level. To simplify the comparison between the seven different fusion implementation methods, a grouping with the amount of gate driver channels (see Figure 14) is done, as this is the main differentiator at BOM level:
- 1 channel: S1G, S2G and S2G_dir
- 2 channels: In2G, In2G_Red
- (Exclusive switching (Ex2G and Ex2G_S) is excluded as it would need an additional Si area for full power operation and is therefore not as attractive as the other solutions (see "Summary" for more information))

1-channel design

With this concept, designers can expect a slight increase in the gate driver (GB) PCB BOM because of the "adaptation" circuitry (see Figure 40: right side, blue marking). As this circuit part would just need some passive components, the BOM impact is quite small (see Figure 41, <0.7% BOM increase). The variant "S2G_dir" does not even need these modifications, as the two gates can be directly hard-connected. The one-channel design offers the following impact:
- Additional PCB space is minor, as just the adaption circuitry must be added
- No changes on the control PCB needed
- No additional modifications to the size and layer stack of the gate driver PCB needed
- The main components (galvanic isolation transformers, gate drivers, current sensors) remain the same (Figure 40, marked in orange)

Consequently, the 1-channel fusion approach does not generate relevant additional BOM costs but leverages the full potential of saving of the SiC replacement. Figure 41 shows the relative costs of the 1-channel design compared with a full SiC inverter and a 2-channel fusion approach. As an assumption for the SiC content of the power switches, the SiC area was reduced to 17% AA, which is equal to 1/3 of the output current.

2-channel design

Given their function and purpose, the fusion variants In2G and In2G_Red require two gate driver channels. This influences the GB PCB BOM. Figure 40 shows an exemplary gate driver design: The blue-marked area B represents the gate driver IC itself and the supply structure; the yellow-marked areas A represent clamping structures (DESAT) and gate resistors. As the 2-channel design requires a redundant setup, both areas (A and B) need to be doubles to support the In2G or In2G_Red method. The number of PCB components and required footprint increase to accommodate the duplication of the gate driver core. This results in:
- Individual supply voltages for the Si gate and the SiC gate ensure precise turn-on and turn-off definition
- Individual gate resistors ensure the optimal switching speed for each technology (depending on the actual variant implemented)
- As the current sensing needs to be done for Si and SiC independently, the AC current sensors need to be doubled as well. Coreless AC current sensors are suitable for this purpose, as the impact of the BOM cost can be reduced compared to the example calculated below.

Overall, the doubling of the gate circuit results in an increase of about 4% in the inverter BOM and the doubling of the current sensors results in another 2%, which could be drastically reduced by using coreless current sensing techniques.

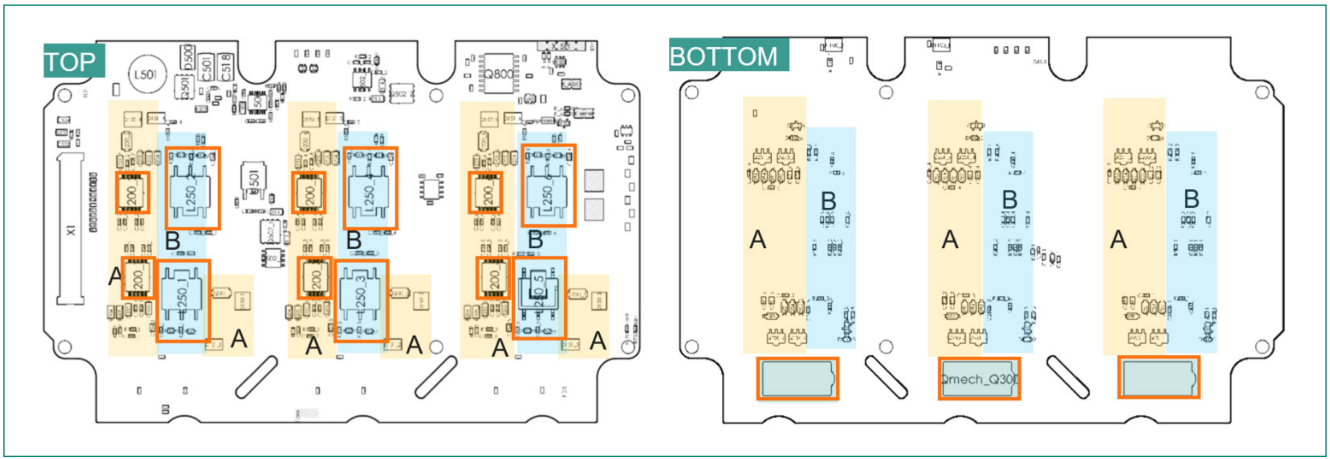


Figure 40 Exemplary gate driver board, illustrating the areas which have to be duplicated for 2-channel fusion applications

Taking the above points into consideration, the following BOM comparison can be drawn:

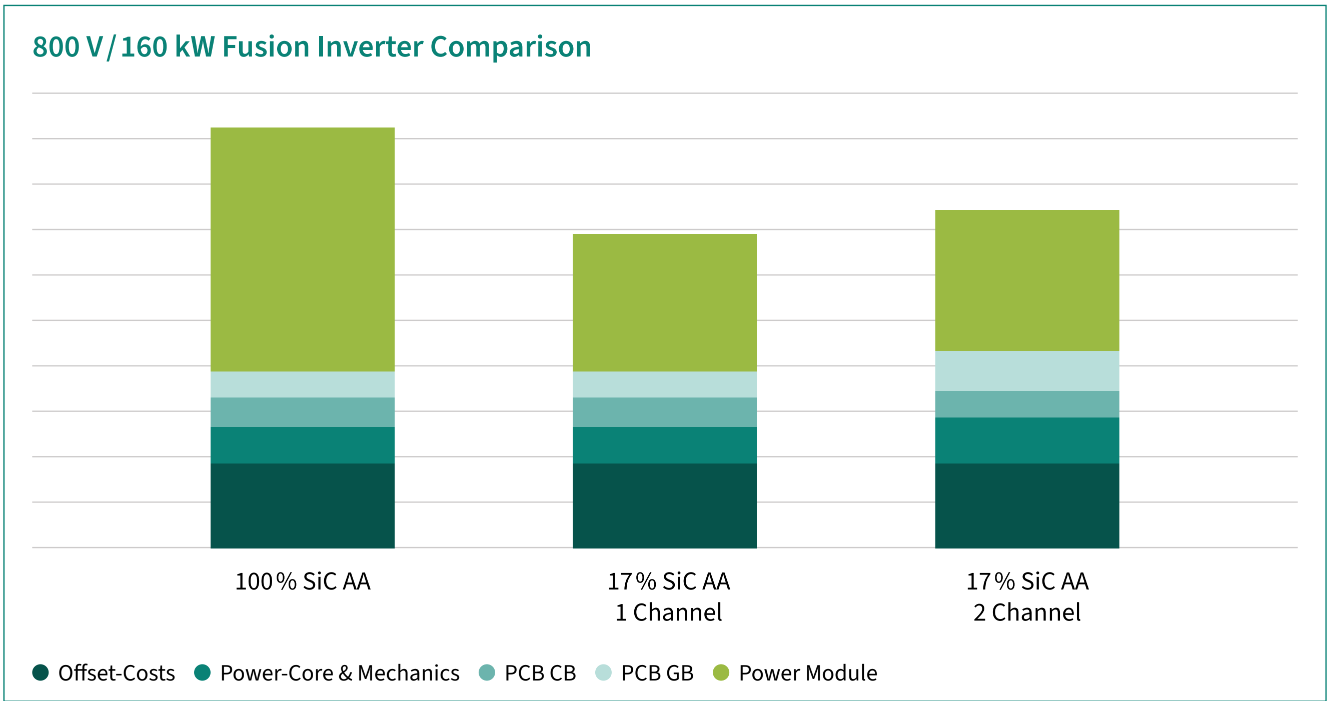


Figure 41 Comparison of inverter BOM costs for 1-channel fusion (S1G, S2G, and S2G_dir), 2-channel fusion (In2G and In2G_Red), compared to a full SiC inverter (left)

9 Efficiency comparison of different implementation modes

Based on a reference SUV with a 400 V battery, we have compared the inverter efficiency levels of the different implementation methods and the same boundary conditions. In Figure 42, the full silicon variant can be found on the far left and the full SiC variant can be seen on the far right. The different fusion implementation modes are positioned between these two extremes.

It can be observed that there is a big efficiency increase between full Si and the various fusion variants. The efficiency increases between the full SiC variant and the various fusion variants are only slight.

This graph demonstrates that inverter efficiency can be increased regardless of the fusion variant chosen. The step from 17% SiC AA (in any fusion configuration) to full SiC is not that significant considering the additional cost for the additional SiC AA (17% AA SiC represents 1/3 of the power of the complete inverter).

S1G and S2G (see "S" in Figure 42) are the variants with the lowest impact on existing non-fusion inverter designs promising the most accessible benefits (79% efficiency gain moving from Si to SiC). The most complex variant (Ex2G, Ex2G_S. In2G, and In2G_Red, see "Ex" and "In" in Figure 42) promises a slightly higher gain (88% efficiency gain moving from Si to SiC), but comes with additional BOM and development costs.

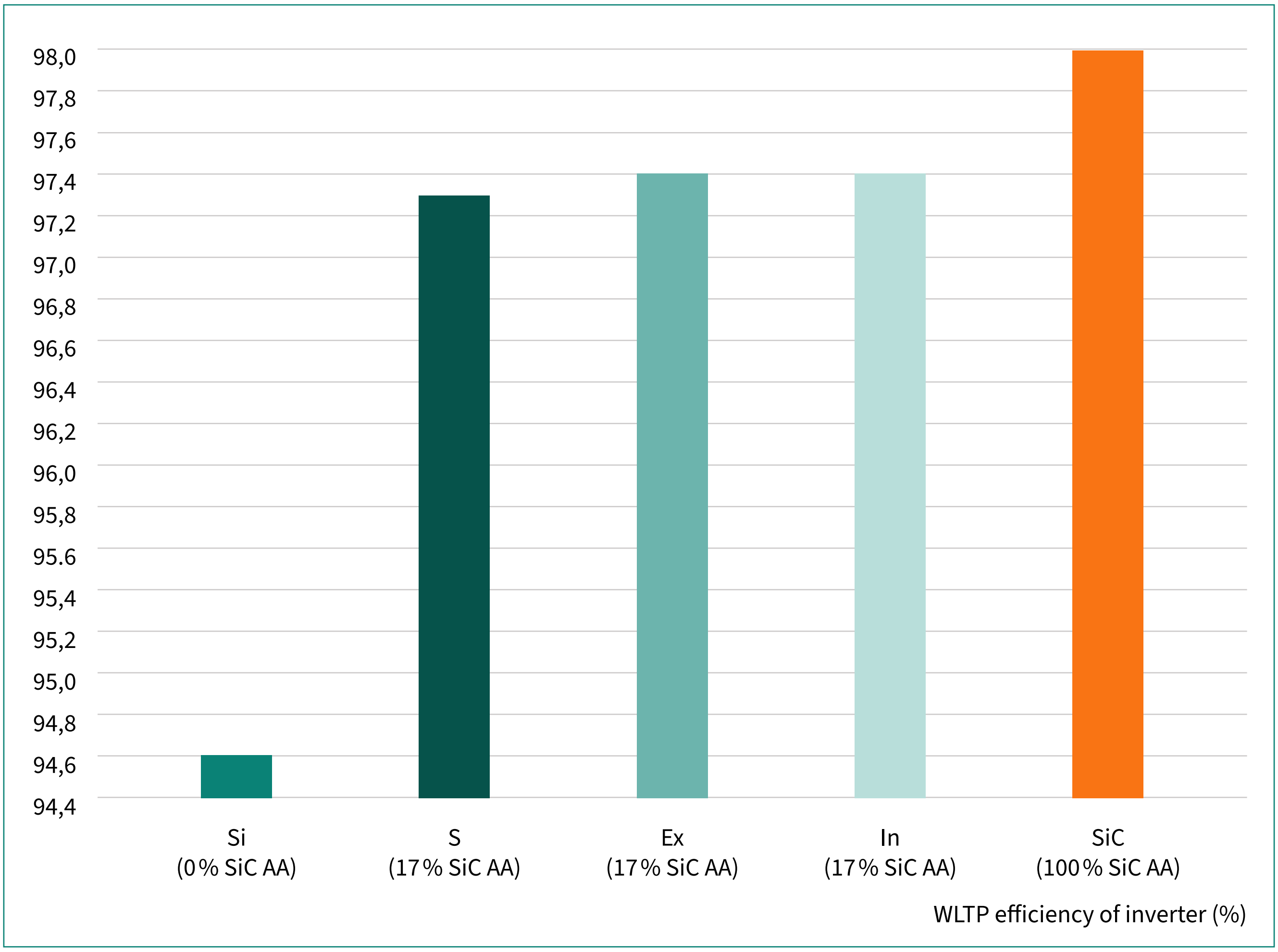


Figure 42 Inverter efficiency according to WLTP

10 Conclusion

After having evaluated the seven different types of fusion inverter, one thing is becoming clear: No matter how it is implemented, each option brings different benefits to the application. However, some implementation methods are more promising than others.

The reduced switching losses of SiC due to the commutation through the parallel silicon diode, which comes with the Si IGBT, are especially beneficial.

At first, the exclusive switching must be de-nominated, as, given by the principle of exclusive switching, just one technology is working at a time. Hence, the silicon area must be dimensioned for full system performance, which reduces the benefit of the fusion approach. In all other fusion variants, the SiC and the Si content together build the current capabilities for full system performance.

Simultaneous switching (S1G, S2G, S2G_dir)

With simultaneous switching, the benefit lies in the simplicity of the circuit. There is just one gate driver channel, as is usual with a two-level inverter, and the adaption circuit could be quite simple in design with just a few resistors. The optimal variant of simultaneous switching is S2G_dir, as there are no additional components and the two gates could just be hardwired together. The enabler for this variant is a matching front-end technology, which enables proper operation of silicon and silicon carbide in parallel. Infineon's technology enables this outperforming variant. In summary, with S2G_dir, the cost benefit of the fusion approach can be leveraged the most, as there is no relevant additional BOM in this variant.

Individual switching (In2G and In2G_Red)

Individual switching is the most versatile variant, as the designer has the freedom to decide online which fusion mode to use. In normal operation, Si and SiC are operated simultaneously (see S2G). However, in case of a failure, the inverter could still operate on just one technology (In2G_Red). This means that this fusion method not only leverages the BOM benefit with low impact on efficiency, but it uses the two different technologies ("redundant and diverse") to increase the availability and redundancy of the system. Implementing In2G_Red is the way towards achieving a fail operational inverter.

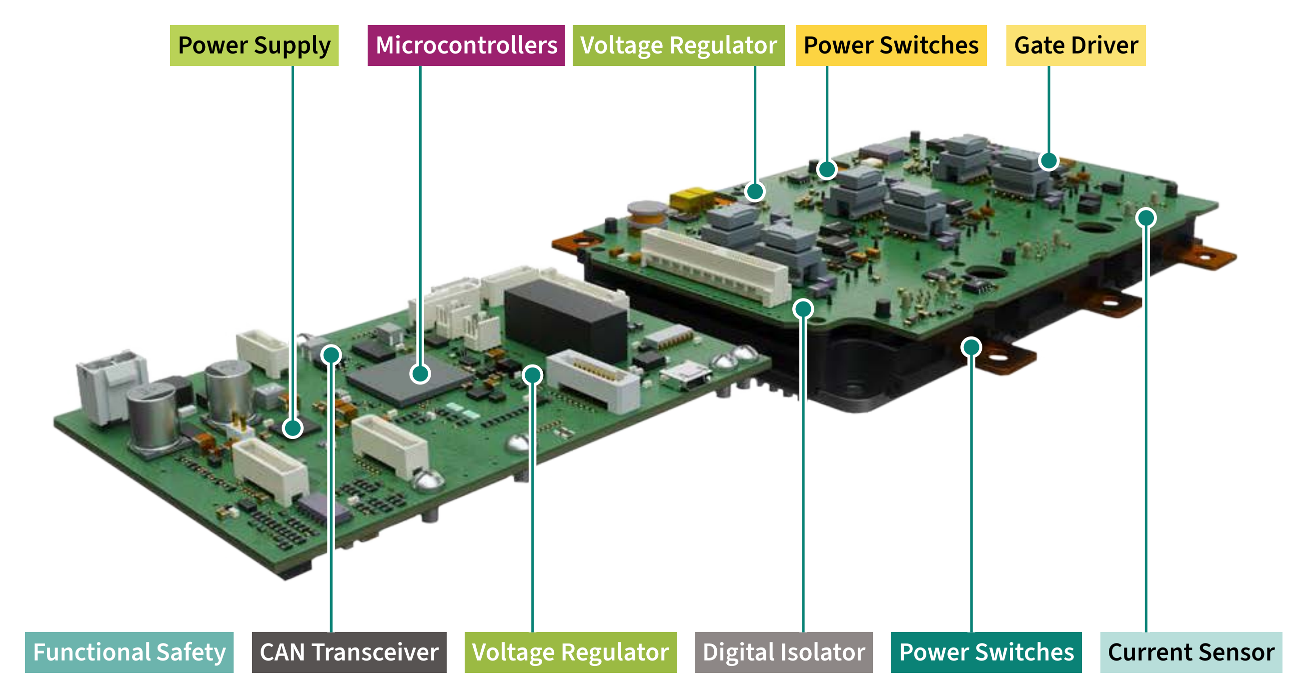
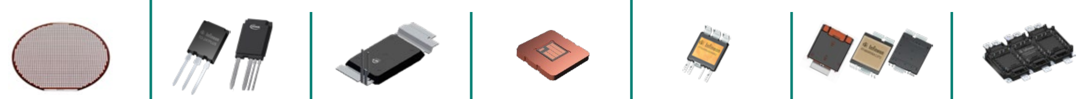


Figure 43 Complete and complementary product portfolio for traction inverter designs

Infineon is currently expanding its portfolio to leverage the benefits of fusion technology inverters. In particular, it is expanding its HybridPACK™ Drive portfolio to support different Si and SiC fusion operating modes (Figure 43).

Infineon spans the full spectrum from bare dies available in Si and SiC through discretes all the way to modules supporting both technologies (Figure 44). Building on this broad and growing portfolio, Infineon's development team is exploring all avenues to give customers the greatest possible choice, and is currently evaluating both technologies in one package. Figure 44 shows the different products and their current availability.



	Bare-Die	Discretes			HybridPACK™ Modules		
		TO247plus	TPAK/IDPAK	EMBEDDING	B2 DSC	B2 SSC	B6 SSC
Si	✓	✓	Development	–	✓	Development	✓
SiC	✓	Planned	Development	Development	✓	Development	✓

Figure 44 Availability of different package variants and technologies

Building on Infineon's experience with different packages, this portfolio also reflects the company's broad expertise in current handling and integration of bare dies. This bundled know-how allows Infineon to create the right fusion technology traction inverter products.

Figure 45 demonstrates this bundled know-how in action, showing different HybridPACK™ Drive B6 bridges with different voltage classes and semiconductor technologies offering different current capabilities. As the fusion approach is also possible with the use of discrete packages, such as IDPAK™, Figure 46 shows this strong portfolio as well.

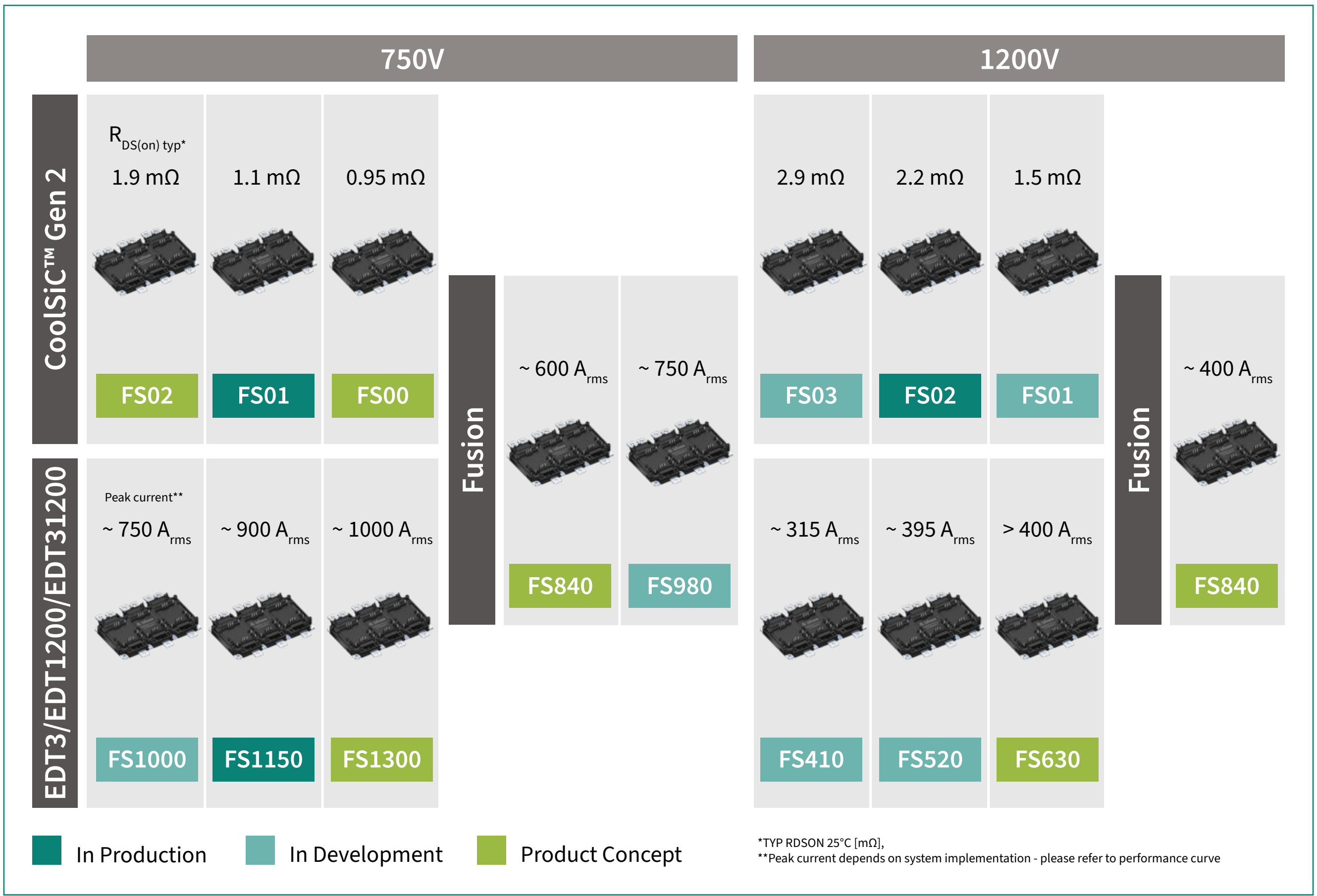


Figure 45 HybridPACK™ Drive portfolio and roadmap

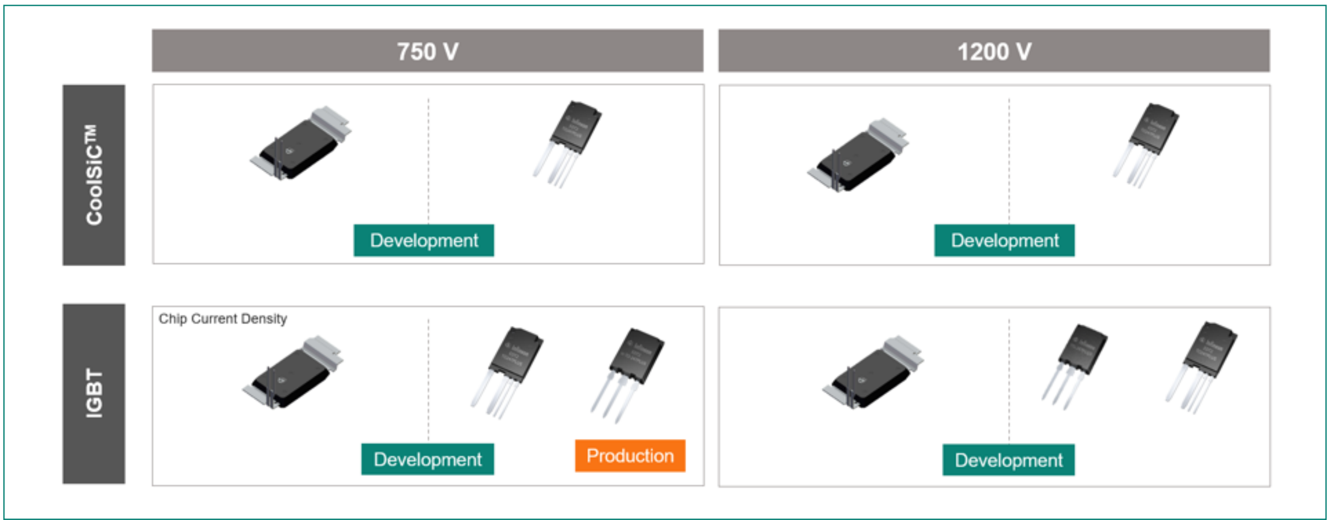


Figure 46 IDPAK™ portfolio and roadmap

12 Outlook

In addition to optimizing performance and efficiency in traction inverters based on SiC, fusion technology solutions can be a very effective way to target market segments that demand a good compromise between efficiency, cost, and availability. In addition, as technology evolves, the energy efficiency and sustainability of modern EV architectures is improving further – making them an even more attractive option (Figure 47).

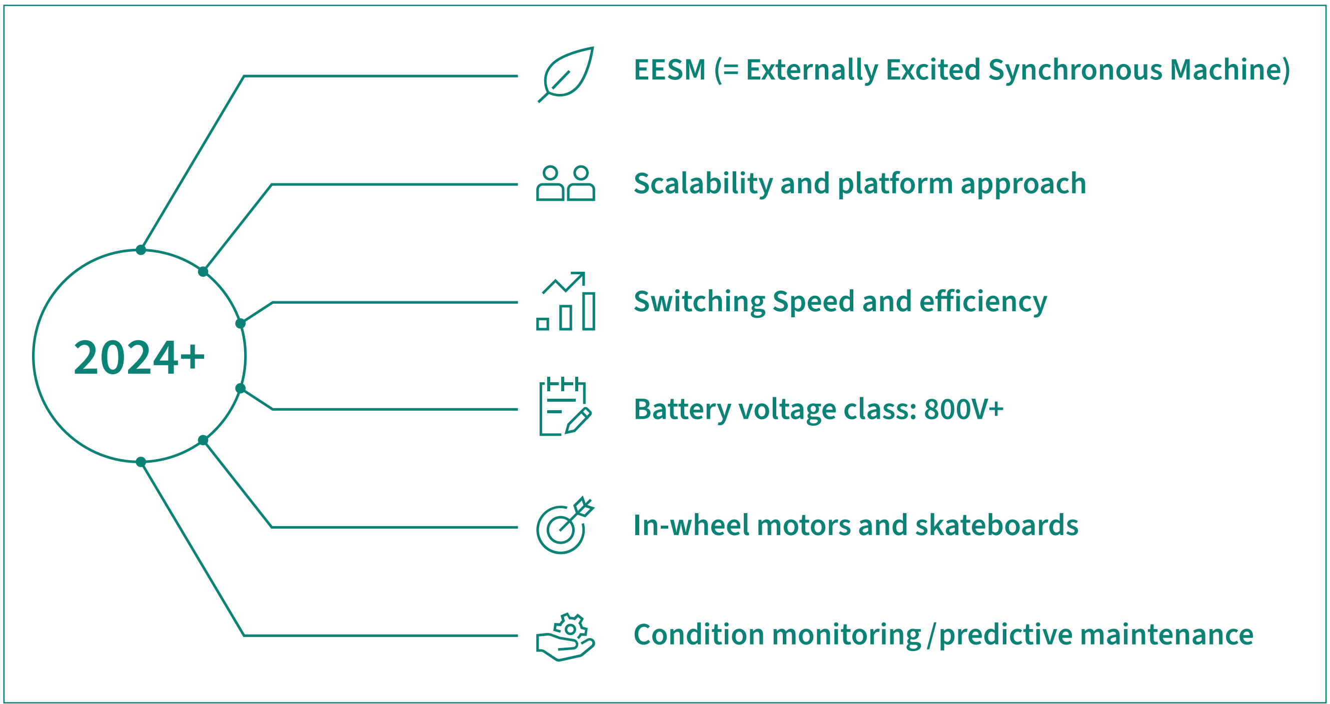


Figure 47 Current traction inverter trends enabling efficient EV designs

As the industry strives to shape a greener future, the importance of a circular economy is moving center-stage. Optimizing energy efficiency, minimizing material usage, and embracing sustainable practices are key elements of a holistic circular economy. Local sourcing, simplified supply chains, and repurposing materials like EV batteries can contribute to the overall sustainability of the electric vehicle ecosystem.

Enabling application solutions that take advantage of the different semiconductor power technologies requires a competent partner with system competency and a semiconductor supplier with a broad product portfolio. EV designs must address efficiency requirements, cost considerations, and sustainability.

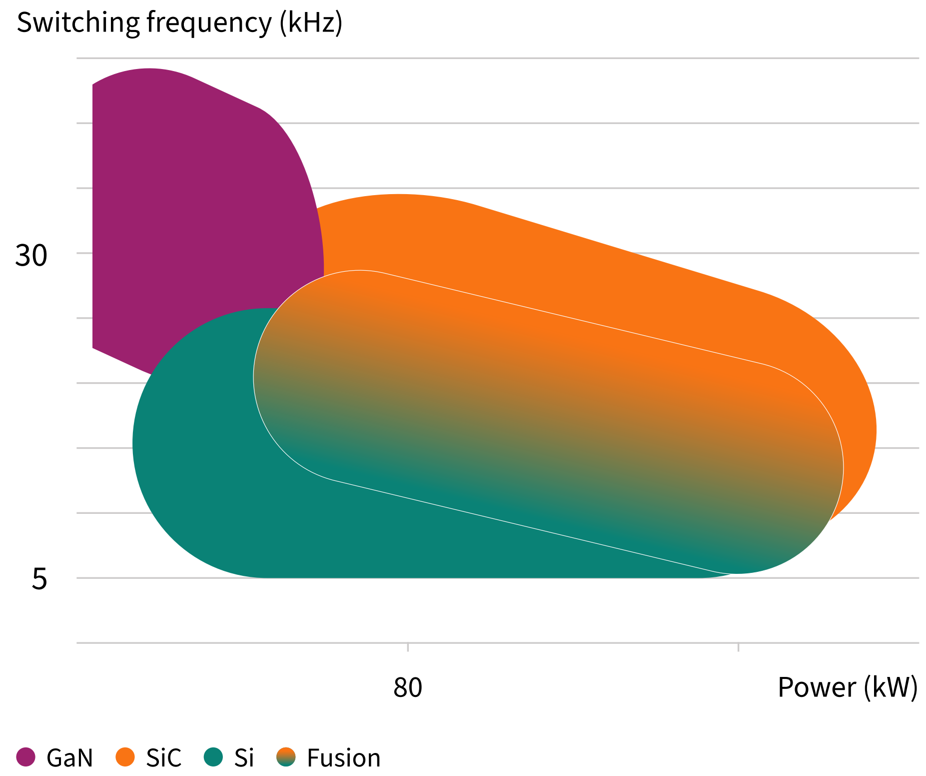


Figure 48 Semiconductor fit for an assumed use case of a 2-level traction inverter (400 V) for an OEM SOP in 2030

While gallium nitride (GaN) may not initially match the power capabilities of SiC, specific solutions can be developed to leverage its benefits as a promising solution for future traction inverters. At present, GaN is used in DC/DC converters and on-board chargers, where higher switching frequency (and higher du/dt values) provides the most benefits.

SiC emerges as the technology of choice for traction inverters, offering benchmark performance and efficiency. Optimizing costs and efficiency involves determining the appropriate SiC content for a vehicle, based on its target use case. Fusion technology traction inverters, delivered through comprehensive product portfolios for the best application match, pave the way for efficient, cost-effective, and sustainable electric drivetrains that can help shape a greener and more sustainable future for transportation.

Figure 48 illustrates the different possibilities to set up the power stage of a two-level traction inverter. It illustrates quite well that all variants have their sweet spots. Where this sweet spot is and when a transition to another variant is needed changes by use case and will evolve over time, as development continues.

Fusion technology traction inverters from Infineon are paving the way for the next generation of efficient, cost-effective, and sustainable electric mobility solutions. By combining the strengths of silicon and silicon carbide, these innovative designs unlock performance while optimizing material usage and overcoming supply constraints. As the industry's technology leader, Infineon is uniquely positioned to support manufacturers on their electrification journey. With a comprehensive portfolio of complementary components and deep system expertise, Infineon empowers its customers to deliver the mobility solutions of tomorrow – today.

One inverter – One Infineon

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