650 V CoolMOS™ CFD7A for on-board chargers and DC-DC converters

High performance superjunction MOSFETs for HEV and EVs

About this document

Scope and purpose

This document is intended as a guide to using Infineon's automotive power devices for high-voltage (HV) on-board chargers and on-board DC-DC systems. The document emphasizes the use of CoolMOS™ CFD7A – the latest superjunction (SJ) power MOSFET series – in power factor correction (PFC) and DC-DC stages in electric vehicles, such as plug-in hybrid, hybrid, fuel-cell and battery-electric vehicles.

Additionally, the document gives an overview of CoolMOS™ CFD7A technology and highlights the advantages in typical applications over the next best competitor.

Intended audience

Design engineers who are responsible for selecting the best-fitting HV power devices for on-board-power electronics. Engineers who are currently working in the concept phase or in the design phase of on-board chargers and on-board HV-LV DC-DC converters, or active discharge applications.

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1 Introduction

The world of mobility is about to change. Combustion engines have been the state-of-the-art solution for more than a century, but now electro-mobility (eMobility) is revolutionizing the way how we will travel in the future.

Although some big players in the automotive industry are skeptical about eMobility, the majority believe it to be necessary to achieve the CO_2 targets set by various governmental organizations.

One key benefit of electric cars is their simplicity in the drive-train concept. Instead of having numerous mechanical parts in the power-train, the electric drive-train could consist of merely an electrical engine (which acts as motor or generator), an inverter (which is a power electronic system) and an energy source (commonly a traction battery, a fuel-cell stack or a combustion engine in hybrid power-trains).

Semiconductors play an important role in the management of the power flow in electric cars. Power-semiconductors are used throughout the electric car: in the traction inverter system, which controls the engine; in the on-board charger, which provides the right amount of energy needed to refill the battery; and in the on-board DC-DC converters, which maintain the power flow between HV and LV domains in the car.

Infineon Technologies provides the most advanced semiconductors for a holistic solution. CoolMOS™ CFD7A, the new automotive 650 V SJ MOSFET technology, enables the next level of quality, reliability and performance in on-board chargers and on-board DC-DC systems.

Figure 1 gives an overview of the “electric car” system and the use of Infineon’s power-semiconductor technologies.

Note: *For more design-in support material, please refer to application note “General design considerations for using high-speed superjunction MOSFET devices from Infineon” and “650 V CoolMOS™ CFD7A for on-board chargers and DC-DC converters ” and also consider contacting our experts via our Technical Assistance Center at [https://www.infineon.com/cms/en/about infineon/company/contacts /product-support-form/](https://www.infineon.com/cms/en/about-infineon/company/contacts/product-support-form/).*

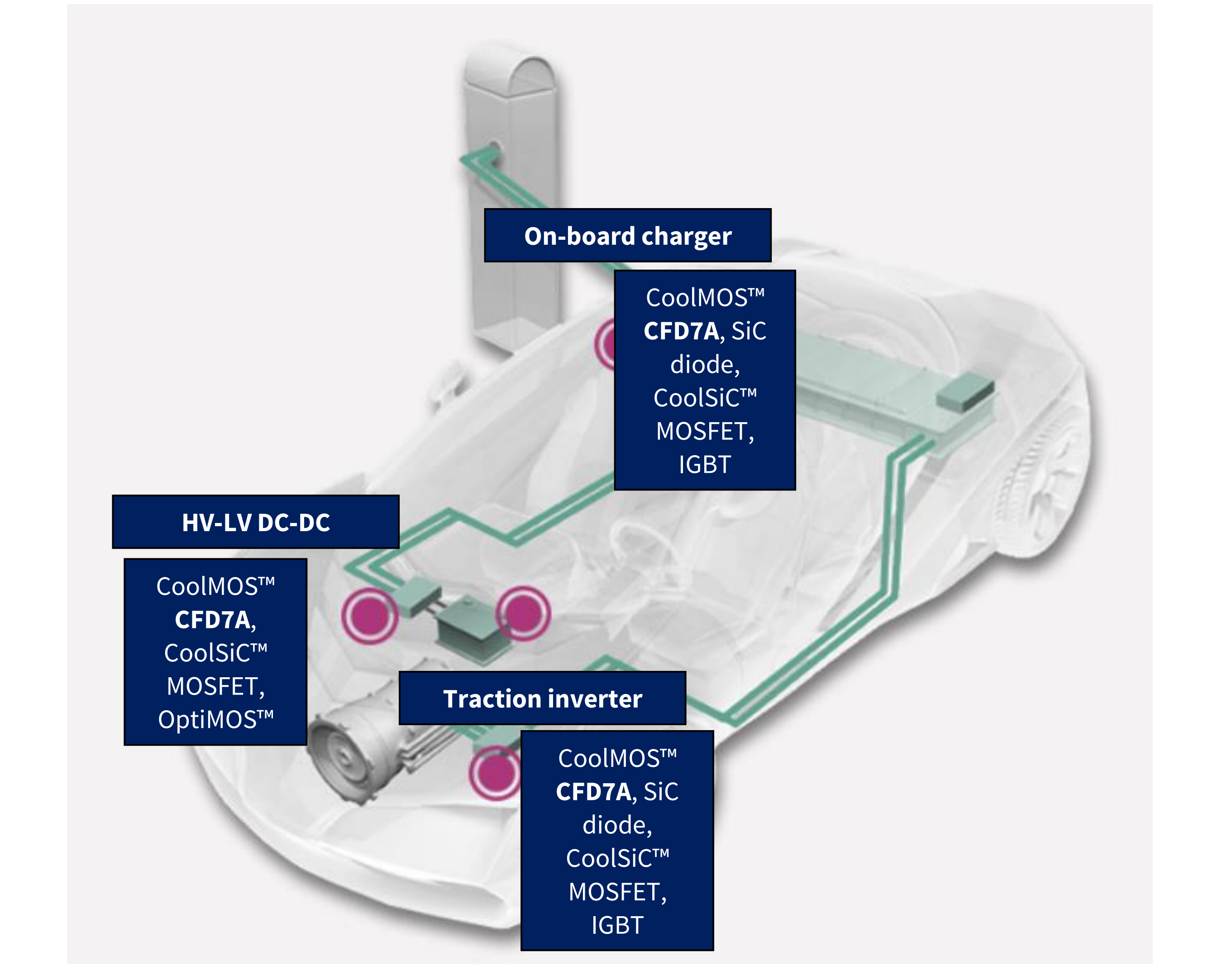


Figure 1 **The battery electric vehicle (BEV) with the different subsystems showing Infineon's discrete power solutions**

Figure 2 introduces a basic block diagram with the most important HV subsystems in an electric car.

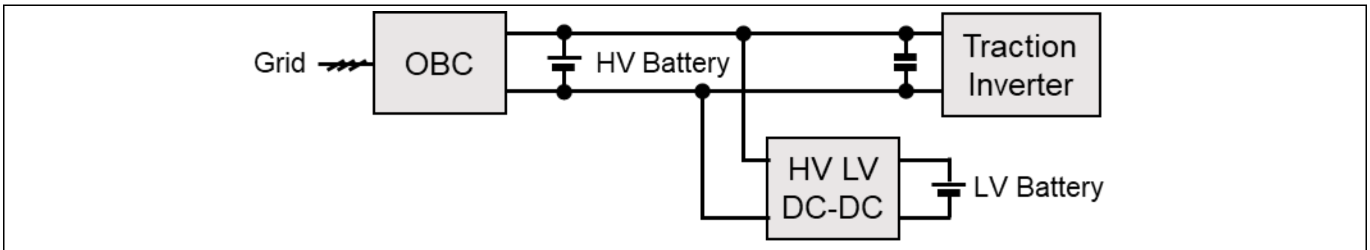


Figure 2 **Block diagram with the most important subsystems in an electric vehicle**

Attention: ***Typically, voltages in the HV domain go up to ~500 V, whereas the voltages in the LV domain are typically 12 V nominal.***

This document focuses further on on-board chargers (OBCs) and on-board DC-DC converters for plug-in hybrid vehicles and BEVs:

Table 1 gives a quick overview of the usage of the right semiconductors in different topologies. Chapter 1 goes into detail about the different applications and the device usage.

Chapter 2 gives an overview of the properties and advantages of the CoolMOS™ CFD7A technology and gives hints for correct usage.

Information about the right Infineon solution for other subsystems (such as traction inverters, aux supplies, ProFETs and other automotive solutions) is available at https://www.infineon.com/automotive/.

1.1 Quick overview of topologies and power semiconductor suggestions

Table 1 Topology overview

System	Topology PFC stage	Topology DC-DC stage
Single-phase OBCs (unidirectional) up to 500 V system voltage	Classic boost with 650 V TRENCHSTOP™ H5 IGBT, 650 V CoolMOS™ CFD7A with CoolSiC™ Schottky diode 650 V Gen5 Dual-boost PFC with 650 V TRENCHSTOP™ H5, 650 V CoolMOS™ CFD7A with CoolSiC™ Schottky diode 650 V Gen5 Totem-pole PFC with 650 V TRENCHSTOP™ H5 IGBT	Phase-shifted full-bridge (PSFB) with 650 V CoolMOS™ CFD7A on primary side, HV diodes or 650 V CoolMOS™ CFD7A on secondary side LLC with 650 V CoolMOS™ CFD7A on primary side, HV diodes or 650 V CoolMOS™ CFD7A on secondary side
Single-phase OBCs (bidirectional) up to 500 V system voltage	Totem-pole PFC with 650 V TRENCHSTOP™ H5 IGBT	PSFB with 650 V CoolMOS™ CFD7A on primary and on secondary side CLLC with 650 V CoolMOS™ CFD7A on primary and on secondary side
Three-phase OBCs (unidirectional) up to 500 V battery voltage with single-phase support via neutral line	Stacked approach: Classic boost with 650 V TRENCHSTOP™ H5 IGBT,650 V CoolMOS™ CFD7A with CoolSiC™ Schottky diode 650 V Gen5 Dual-boost PFC with 650 V TRENCHSTOP™ H5, 650 V CoolMOS™ CFD7A with CoolSiC™ Schottky diode 650 V Gen5 Totem-pole PFC with 650 V TRENCHSTOP™ H5 IGBT	Stacked approach: PSFB with 650 V CoolMOS™ CFD7A on primary side, HV diodes or 650 V CoolMOS™ CFD7A on secondary side LLC with 650 V CoolMOS™ CFD7A on primary side, HV diodes or 650 V CoolMOS™ CFD7A on secondary side Dedicated approach: PSFB with CoolSiC™ MOSFETs 1200 V on primary side, HV diodes or 650 V CoolMOS™ CFD7A on secondary side

System	Topology PFC stage	Topology DC-DC stage
	Dedicated approach: Four-leg bridge with CoolSiC™ MOSFETs 1200 V	LLC with CoolSiC™ MOSFETs 1200 V on primary side, HV diodes or 650 V CoolMOS™ CFD7A on secondary side
Three-phase OBCs (bidirectional) up to 500 V battery voltage with single-phase support via neutral line	Stacked approach: Totem-pole PFC with 650 V TRENCHSTOP™ H5 IGBT and CoolMOS™ CFD7A in slow-switching leg Dedicated approach: Four-leg bridge with CoolSiC™ MOSFETs 1200 V	Stacked approach: PSFB with 650 V CoolMOS™ CFD7A on primary and on secondary side CLLC with 650 V CoolMOS™ CFD7A on primary and on secondary side Dedicated approach: PSFB with CoolSiC™ MOSFETs 1200 V on primary side, 650 V CoolMOS™ CFD7A on secondary side CLLC with CoolSiC™ MOSFETs 1200 V on primary side, 650 V CoolMOS™ CFD7A on secondary side
Batteries with voltages less than 500 V	See above	See above, with following modification: 1200 V diodes or CoolSiC™ MOSFETs 1200 V on secondary side

Note: *The topology figures in this document focus on better readability. That means that the figures showing topologies omit components that are required by the real world system, such as inrush current management, or the input and output filters required to fulfill the stringent EMI requirements. This is done intentionally for better readability of the core concepts of the individual power conversion topologies.*

2 The on-board charger system

The on-board charger system is a vital subsystem in all plug-in hybrid vehicles and BEVs. As the name indicates, it has the task of charging the high-voltage traction battery with energy supplied by the AC grid.

Figure 3 shows an on-board charger topology, which is basically an AC-DC converter. It comprises of a PFC stage, the DC link and a DC-DC block.

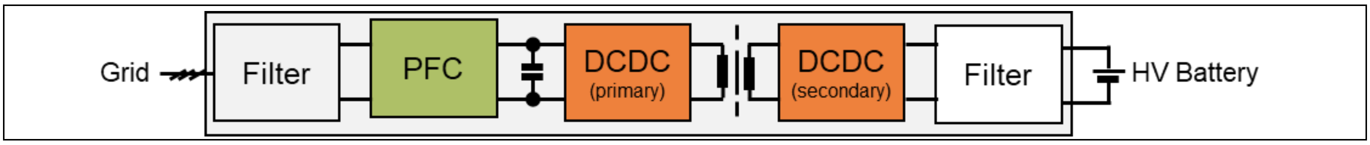


Figure 3 Typical on-board charger system comprising a PFC and a DC-DC stage

The majority of today's on-board chargers are galvanically isolated AC-DC converters, which offer modularity on the power classes and interoperability with the different AC grids throughout the world. As a consequence, various topologies and concepts are visible on the market.

An important requirement for the on-board charger system is to achieve high efficiency in the conversion by minimizing power losses. The advantages are two-fold: firstly, higher efficiency will deliver more energy to the battery and thus the charging process is faster than for low-efficiency charger systems. Secondly, higher efficiency also means lower power losses. This is beneficial for the end customer, but also for on-board charger manufacturers, since their systems could be built to be more compact and thus, the power density could be improved.

The conversion efficiency becomes particularly important for bidirectional on-board charger systems. In this scenario the charger is also used to supply electrical energy to external loads or to the AC grid besides charging the traction battery. As a consequence, the energy will flow between the battery and the AC grid multiple times, raising the need for a higher conversion efficiency in both directions.

Another key requirement is high power density. The on-board charger shall be small and compact but able to handle high power. Latest industry trends show that the chargers become smaller for a given power level – or that the power level increases for chargers exhibiting the same mechanical dimensions.

High conversion performance and high power density can be achieved using Infineon's latest-generation CoolMOS™ CFD7A. The CoolMOS™ CFD7A series is a flexible technology tailored to the needs of the automotive industry, which can be used in the PFC stage and the DC-DC stage of on-board charger systems and DC-DC converters.

CoolMOS™ CFD7A is fully compatible with system voltages up to 470 V DC (according to voltage class "HV_2b" of "LV123: Electrical characteristics and electrical safety of high-voltage components in road vehicles").

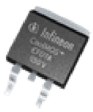
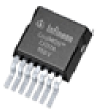
$R_{DS(on),max}$ in mΩ	TO-263 D²PAK 3-pin 	TO-263-7 D²PAK 7 pin 	TO-220 	TO-247 	TO-247 short leads 
230	IPB65R230CFD7A	IPBE65R230CFD7A			
190	IPB65R190CFD7A	IPBE65R190CFD7A	IPP65R190CFD7A	IPW65R190CFD7A	
145		IPBE65R145CFD7A		IPW65R145CFD7A	
115	IPB65R115CFD7A	IPBE65R115CFD7A	IPP65R115CFD7A	IPW65R115CFD7A	
99	IPB65R099CFD7A	IPBE65R099CFD7A	IPP65R099CFD7A	IPW65R099CFD7A	
75		IPBE65R075CFD7A		IPW65R075CFD7A	IPWS65R075CFD7A
50	IPB65R050CFD7A	IPBE65R050CFD7A	IPP65R050CFD7A	IPW65R050CFD7A	IPWS65R050CFD7A
35				IPW65R035CFD7A	IPWS65R035CFD7A
22				IPW65R022CFD7A	IPWS65R022CFD7A

Figure 4 Automotive CoolMOS™ CFD7A $R_{DS(on)}$ and package portfolio

2.1 Power factor correction (PFC) stage

Due to the various interoperability requirements, many different PFC topologies are in use within the industry.

The vast majority of PFC stages in OBCs are being operated in continuous current mode (CCM). This leads to the requirement for semiconductors, which are robust against hard commutation on their body diode. Superjunction devices, like the CoolMOS™ CFD7A series, can be used perfectly in CCM PFC stages with a silicon-carbide diode as commutation partner (see **Figure 6c**). An alternative is to use either TRENCHSTOP™ AUTO F5 or CoolSiC™ wide-bandgap MOSFETs in a CCM PFC since these technologies are inherently robust against hard commutation.In this case, two switches can be used in a half-bridge configuration, whereas the superjunction MOSFET will only work in combination with a SiC diode.

This document gives an overview of the most common PFC topologies, their key performance parameters and the optimal technology selection for high-voltage power switches in discrete packages for on-board charger systems.

2.1.1 Classic boost PFC

The simplest topology to achieve power-factor-correction functionality is to use a boost converter topology as shown in **Figure 5**. This topology is also known as “classic PFC” or “classic boost PFC”.

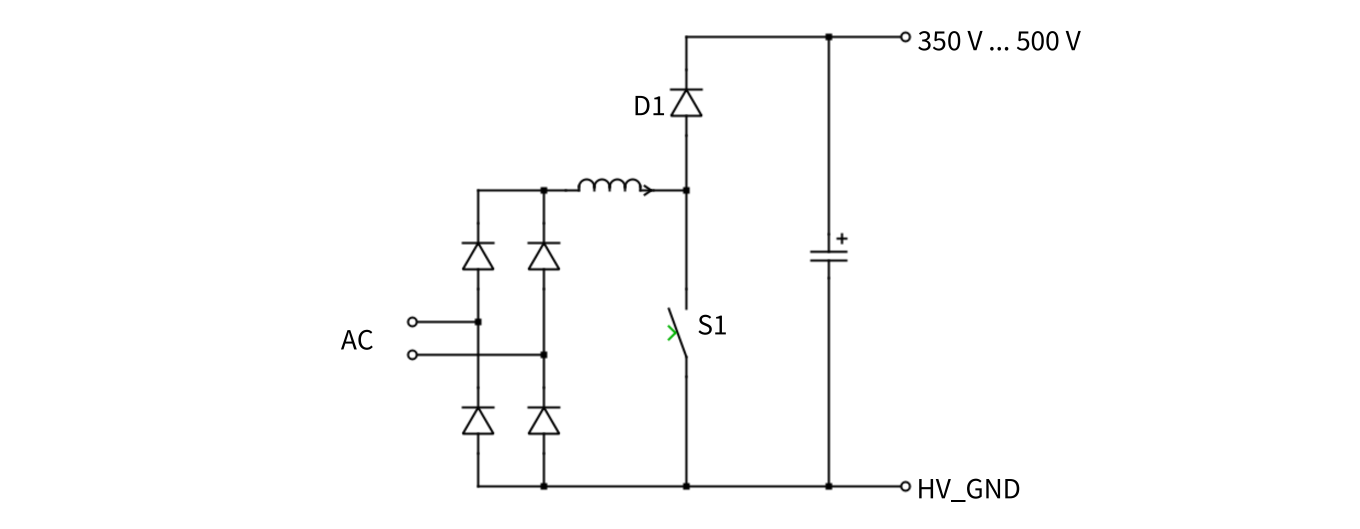


Figure 5 **Operating principle of a boost PFC (a diode across S1 is implied but omitted for better understanding)**

This simple circuit comprises a half-bridge configuration realized by a switch and a diode, an inductor and a diode bridge rectifier on the AC input side. On the DC output side, buffer caps are commonly used to stabilize the output voltage. The most common mode of operation to achieve a high power factor is continuous conduction mode (CCM). This is achieved by hard commutation of the current between the switch and the diode.

This topology offers a unidirectional power flow from the AC input to the DC output. For details of how to design a boost PFC stage, please refer to [1].

As mentioned above, a hard commutation occurs within the half-bridge. Therefore, one requirement is that the semiconductors which are used, can be able to withstand continuous commutation.

A reasonable choice, therefore, is to use the automotive-qualified CoolSiC™ Schottky diode 650 V Gen5 device for position "D1". Various semiconductor switches can be used as a power switch in the PFC stage.

Figure 6 gives an overview of the different solutions. Infineon's automotive-qualified TRENCHSTOP™ AUTO 5 IGBT offers high-speed switching capabilities with a 650 V breakdown voltage. An overview of IGBTs with AEC Q101 qualification is available at [3]. IGBTs are available as single IGBTs or IGBTs with an integrated Si or SiC diode. If single IGBTs are used, we recommend using a small anti-parallel PN diode between the collector and emitter nodes to avoid negative voltage spikes on the IGBT.

To achieve the highest efficiency in a simple PFC topology, we recommend using a MOSFET instead of an IGBT. The latest automotive CoolMOS™ generation (CoolMOS™ CFD7A) from Infineon is perfectly suited to this topology if a SiC diode is being used as a counterpart. The MOSFET has the advantage of resistive behavior in the channel, does not suffer from a tail current and offers lower switching losses overtemperature in relation to an IGBT. All these advantages translate into lower power losses and therefore a higher conversion efficiency.

Note: *The boost diode "D1" must not be replaced with a second SJ MOSFET in hard-switching (CCM) PFCs.*

Another possibility is to use a wide-bandgap MOSFET in the classic boost PFC. Nonetheless, the efficiency would not increase, since wide-bandgap MOSFETs cannot fully exploit the advantages of their wide-bandgap material in this topology. An overview of the automotive wide-bandgap devices from Infineon is available at [4].

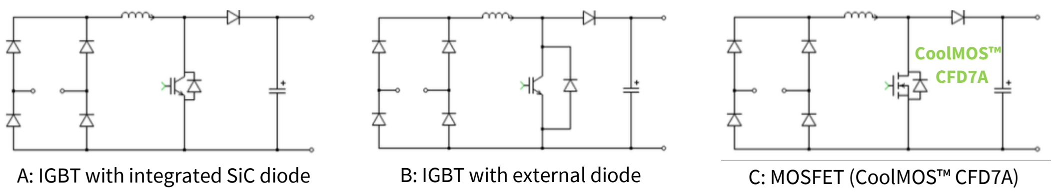


Figure 6 **Example PFC stage for single-phase on-board charger: a) IGBT with integrated SiC diode; b) single IGBT with external protection diode c) MOSFET CFD7A (with intrinsic body diode)**

2.1.2 Dual-boost PFC

An attractive way to leverage the performance is to utilize the so called "bridgeless" PFC topologies. As the name indicates, these topologies do not use a diode bridge on the AC input side, but utilize semiconductor switches to increase the efficiency. **Figure 6** shows the "dual-boost PFC" topology, which is a prominent example of a bridgeless PFC rectifier.

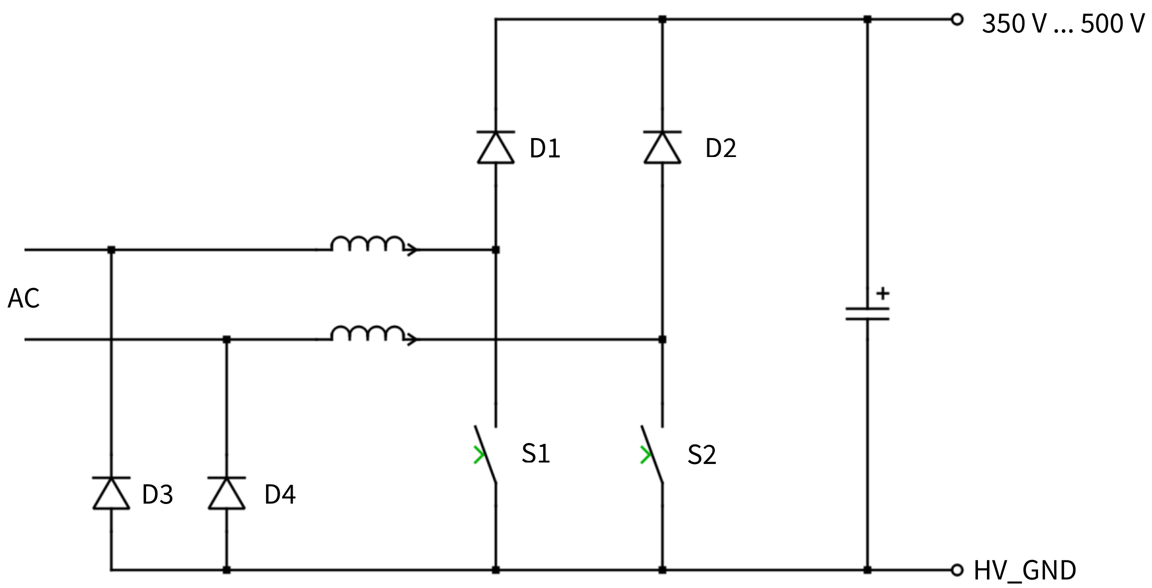


Figure 7 **Dual-boost topology as a representative of a "bridgeless" PFC topology**

The working principle of the dual-boost topology is very similar to the classic boost PFC. Therefore the selection of semiconductor components is also similar to a classic boost PFC. The obvious difference on the topology level is that each AC semi-cycle will be handled by one dedicated half-bridge instead of rectifying the AC before. This raises the number of active switches, but also increases conversion efficiency due to the absence of the diode rectifier on the input.

Infineon's high-speed TRENCHSTOP™ 5 IGBT or CoolMOS™ CFD7A will be an optimal choice for "S1" and "S2". The suggestion for "D1" and "D2" is to use CoolSiC™ Schottky diode Gen5, whereas D3 and D4 could be PN rectification diodes. An additional way to increase the efficiency is to use active switches in parallel to D3 and D4 for phase rectification. Further information about this concept is available at [5].

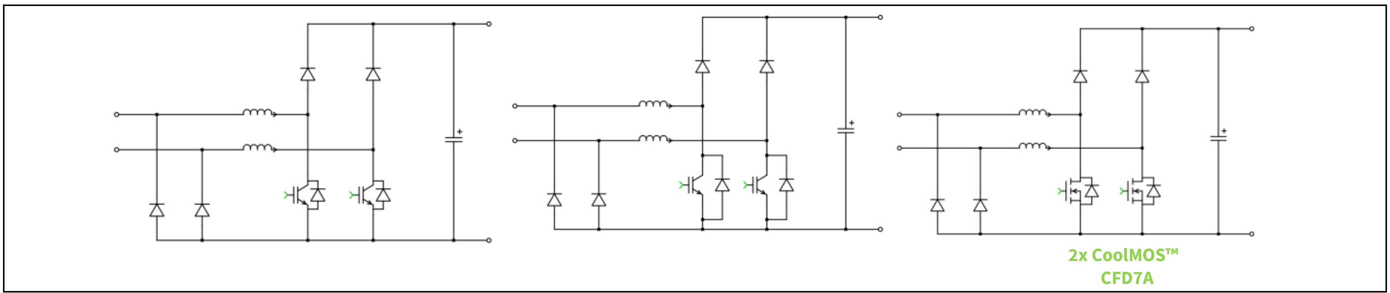


Figure 8 **Dual-boost topology with a) IGBT with integrated SiC D b) TRENCHSTOP™ IGBT H5 with external PN diode and c) CoolMOS™ CFD7A**

2.1.3 Totem-pole PFC

A common topology for bidirectional on-board chargers is the so-called "totem-pole" PFC topology. The concept of this topology is to replace all diodes with active power switches to enable a bidirectional power flow capability. **Figure 9** shows the concept of this topology.

Another advantage of using active switches instead of diodes is that the efficiency will become higher as well. Nonetheless, this modification also increases the complexity, because more power semiconductors must be controlled within the circuitry.

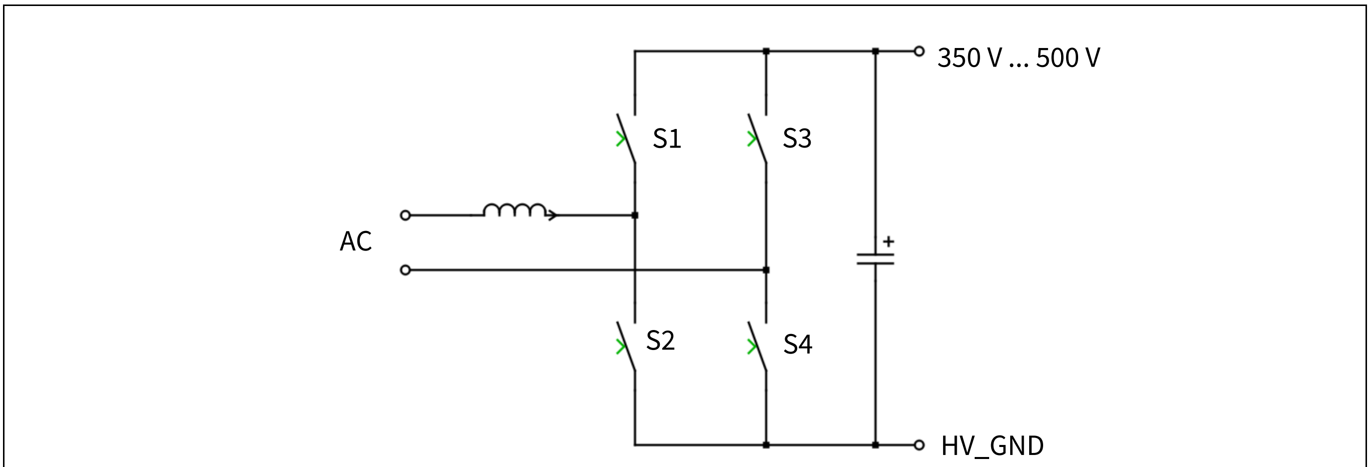


Figure 9 **Totem-pole PFC topology**

Note: *The totem-pole PFC is also known as full-bridge PFC.*

The totem-pole PFC consists of a fast-switching leg ("S1" and "S2") and a slow-switching leg ("S3" and "S4"). "S1" and "S2" require semiconductors that are able to withstand hard commutation of the load current in between two active switches at high-frequency. Therefore the best choices for "S1" and "S2" is to use TRENCHSTOP™ 5 IGBTs or the CoolSiC™ MOSFETs.

Note: *SJ MOSFETs are not suitable for the fast-switching leg ("S1" and "S2") in a totem-pole PFC due to the relative large Q_{rr} of the inherent body diode, but they are perfectly suited to the slow-switching leg ("S3" and "S4").*

The switches in the slow-switching leg (“S3” and “S4”) are fulfilling a phase rectification functionality. Thus, they are turned on and off with the AC frequency during zero-crossing of the AC input (zero voltage switching, ZVS).

One common way to realize a totem-pole PFC is to use IGBT switches for positions “S1”, “S2”, “S3” and “S4”. Infineon’s high-speed TRENCHSTOP™ 5 IGBT is the best IGBT choice for on-board charger systems.

It is recommended to use the CoolMOS™ CFD7A for the slow-switching half-bridge (“S3” and “S4”) to leverage the efficiency further. This use of superjunction MOSFETs is possible due to the soft-switching nature at AC frequency.

Infineon’s SiC MOSFETs are wide-bandgap devices with ultralow reverse recovery charge. Therefore these devices can be used to realize a hard-switching totem-pole PFC comprising four SiC MOSFETs. Another advantage of Infineon’s SiC MOSFETs is that they are offered with 1200 V breakdown voltage. This enables support for higher DC link voltages (above 650 V).

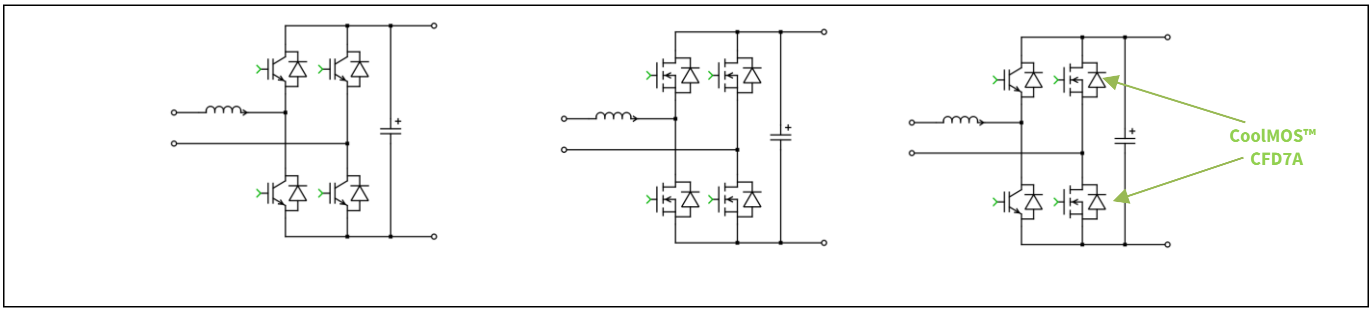


Figure 10 **Totem-pole PFC a) with IGBTs b) SiC MOSFETs c) with IGBTs and CoolMOS™ CFD7A (as phase rectifier)**

An improvement of the conversion efficiency can be achieved if the soft-switching technique is exploited. Soft-switching will also enable the use of CoolMOS™ power semiconductors in full-bridge topologies (as shown in **Figure 10b**). These PFC stages are commonly known as “triangular current mode” PFCs. The disadvantage of this approach is that a variable frequency is required to control the stages, and that the power factor will decrease in comparison to a CCM PFC. This could be compensated by interleaving of several soft-switching PFC stages. More information about soft-switching PFC stages is available in literature, such as [6].

2.2 DC-DC converter stage

As shown in **Figure 2**, a typical on-board charger system comprises an isolated DC-DC block to meet the requirements in terms of isolation and safety. Furthermore, this stage also has the role of regulating the actual charging voltage on its output depending on the state of the HV traction battery.

Most common topologies are soft-switching PSFB converters and LLC converters. Due to the superior switching speed, MOSFETs play a dominant role in modern DC-DC converters. Infineon’s latest CoolMOS™ automotive generation – the CoolMOS™ CFD7A series – is fully optimized to be used in soft-switching DC-DC converter stages.

2.2.1 Phase-shifted full-bridge (PSFB)

A common DC-DC topology seen on the market is the so called "phase-shifted full-bridge" topology, shown in **Figure 11**. It consists of a full-bridge on the primary side of the DC-DC converter, a resonant inductor, an isolated transformer and a rectification on the secondary side.

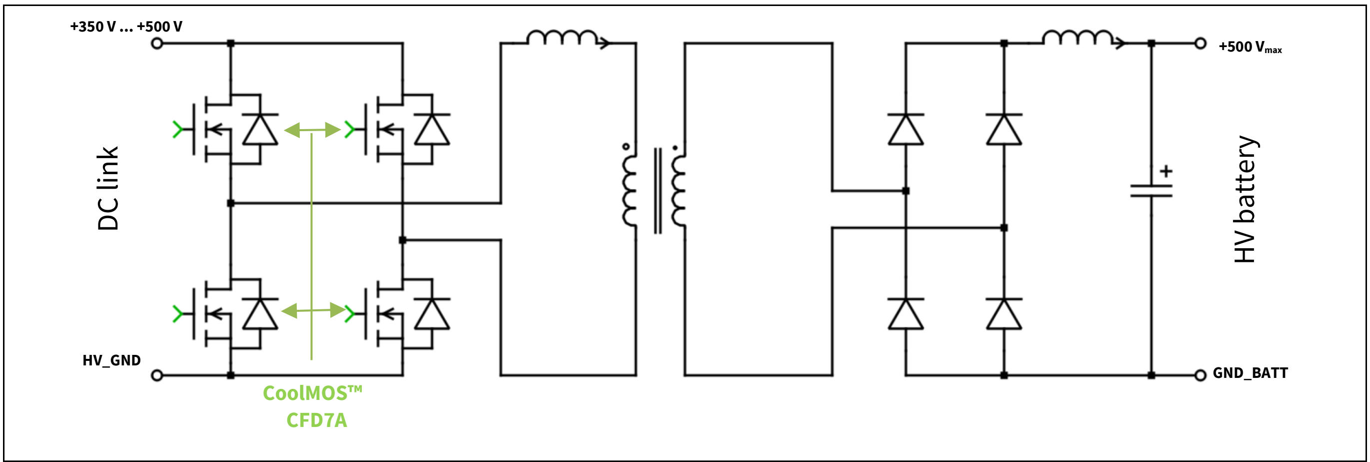


Figure 11 PSFB topology comprising diodes on the secondary side

A big advantage of this topology is that it is highly efficient, since it can be operated in soft-switching mode over a wide load range. That means that energy stored in the parasitic capacitances of the MOSFETs can be recycled, which reduces the power losses, reduces the heat dissipation and elevates the conversion efficiency. An additional inductor on the primary side (Lr) ensures soft-switching of the MOSFETs in conjunction with the controller. Nonetheless, due to the intrinsic nature of this topology, full ZVS cannot be achieved for all MOSFETs over the full output range. Typically hard-switching of the different MOSFETs occurs at light load conditions (when the resonant energy is not high enough to sustain ZVS). This hard-switching phenomenon is also the reason why Infineon recommends silicon MOSFETs with fast-diode properties, such as CoolMOS™ CFD7A, to ensure reliable long-term operation, or wide-bandgap MOSFETs like Infineon's CoolSiC™ series for automotive applications.

Another advantage of this topology is that the controlling effort compared to LLC converters is relatively low. The regulation of the power flow is achieved by controlling the phase shift in between the two half-bridge legs without the need to modify the frequency or the duty cycle. Moreover, the PSFB topology can achieve a wider conversion ratio than the LLC converter.

The secondary side has the task of performing a rectification of the transmitted energy from the primary side. There are several ways to achieve this. One way would be to use full-bridge rectification (as shown in **Figure 11**) or a center-tapped transformer. For both variants, either diodes or active MOSFET switches are commonly used.

More information about the design of a PSFB DC-DC converter is available at [7].

State-of-the-art on-board chargers utilize MOSFETs based on silicon or silicon carbide. IGBTs are commonly not used due to the high switching frequency requirements for compact DC-DC converters.

Infineon offers the CoolMOS™ CFD7A with fast body diode combined with outstanding performance for this topology. If wide-bandgap devices are preferred, the MOSFETs of Infineon's CoolSiC™ family are the number-one choice.

The PSFB topology can also be used for bidirectional on-board chargers if the secondary side of the DC-DC is utilizing active switching and a proper control strategy is applied. **Figure 12** shows the concept of a bidirectional PSFB. As the figure shows, no further modification of the hardware components is required to support a bidirectional power flow.

A fully operational evaluation board utilizing CoolMOS™ in a bidirectional PSFB is available at [8].

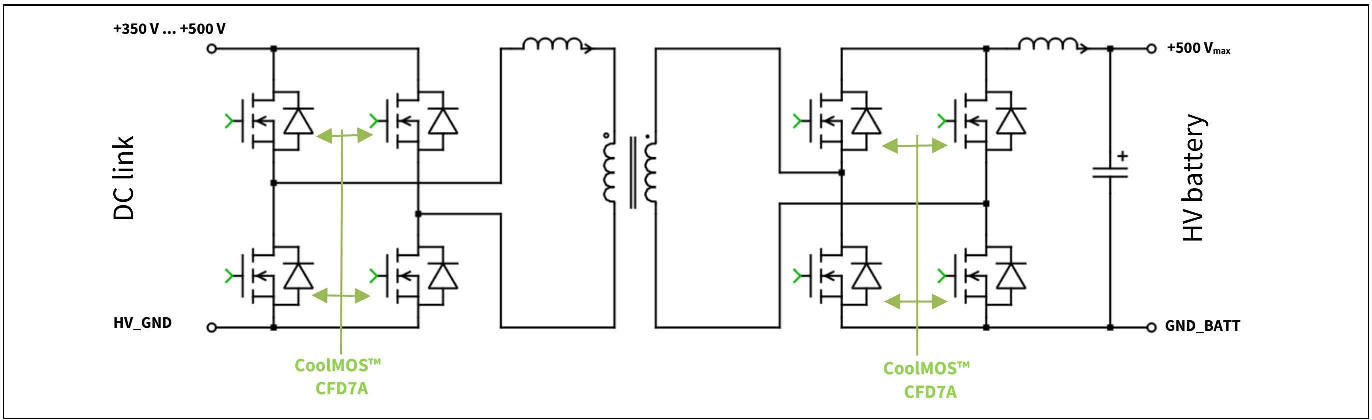


Figure 12 PSFB topology for bidirectional usage

2.2.2 LLC topology

The LLC topology is an ideal topology for highest efficiency. Compared to the PSFB, this topology can achieve an even higher efficiency resulting in lower losses during operation. Thus, even higher power density converters can be achieved.

Most LLC converters used in on-board chargers are full-bridge LLC converters. A full-bridge configuration on the primary side helps to reduce the current through the power switches, since the primary side winding of the transformer will see a higher voltage (by a factor of two) compared to a half-bridge LLC converter. Due to the doubled voltage it is possible to transfer double the amount of power for a given transformer size. This principle is valid for all half-/full-bridge converters and is not a unique feature of the LLC converters. Nonetheless, it is more common to use half-bridge LLC converters for lower-power applications.

Another advantage of well-designed LLC topology is that ZVS can be achieved over the full load range. Nevertheless, hard-switching of the MOSFETs is prone to occur at startup and some critical conditions only (e.g., "capacitive mode" operation). Therefore we recommend using MOSFETs with a fast body diode to ensure long-term reliability. Infineon's automotive CoolMOS™ CFD7A is the perfect choice for this topology, since the technology offers outstanding commutation robustness.

One drawback of the LLC topology is that the power flow is controlled via variable frequency rather than variable duty cycle. Due to the required frequency range, the design for EMI filters might become more challenging. Furthermore, synchronization of parallel stages of LLC converters becomes more complex because it is difficult to dictate current sharing. Also, the LLC topology suffers from a rather limited conversion rate.

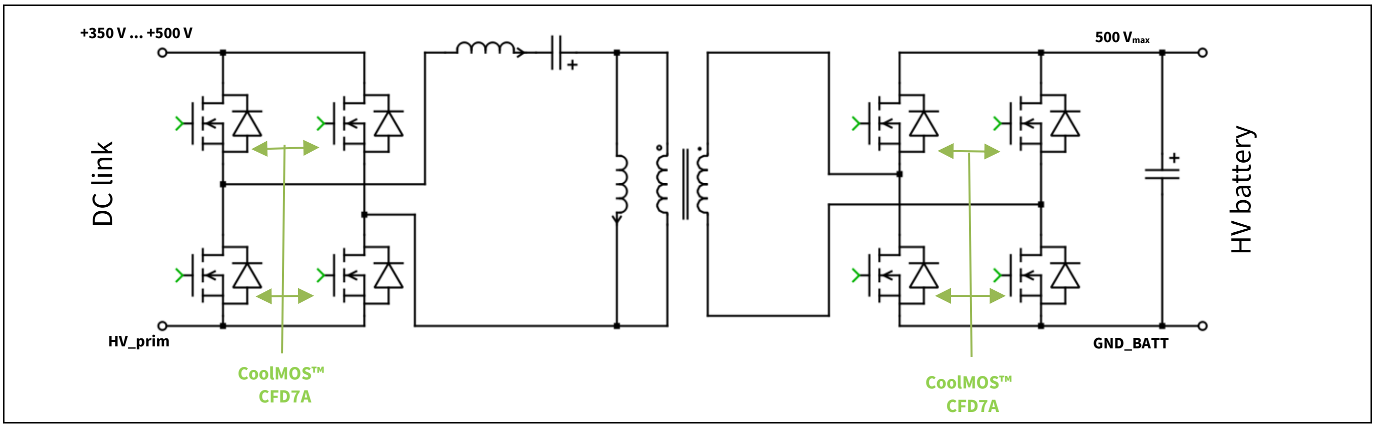


Figure 13 **Full-bridge LLC converter for unidirectional operation (with active synchronous rectification on the secondary side)**

Figure 13 shows a typical full-bridge LLC converter used in on-board chargers. The secondary side of the converter is also designed as full-bridge. To achieve the best performance, CoolMOS™ CFD7A MOSFETs should be placed on the secondary side instead of diodes.

2.2.3 CLLC topology

If the on-board charger is required to support bidirectional power flow, a small modification of the resonant tank is required: an additional capacitor on the secondary side leads to a symmetrification of the resonant tank.

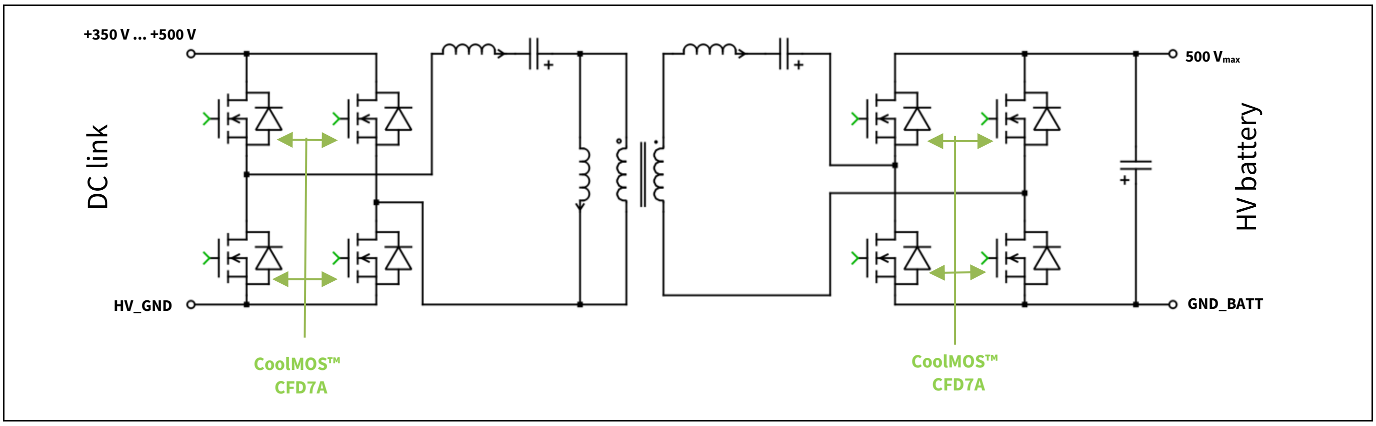


Figure 14 **Full-bridge CLLC converter for bidirectional operation**

2.3 On-board chargers with three-phase AC input

As mentioned previously, the different AC infrastructure all over the world required the OBC to be flexible to deal with the various AC voltages and the available number of phases. In principle all the above-mentioned topologies could be used for single- as well as three-phase AC inputs, as long as the potentially higher system voltages are taken into consideration for the selection of the proper semiconductors.

2.3.1 Three-phase PFC

Three-phase PFC systems are used for on-board chargers with higher power classes. There are several ways to implement PFC for three-phase AC inputs. The next chapters give an overview of the most common techniques.

2.3.1.1 Stacking of single-stage modules

A common way to achieve three-phase support is to "stack" individual single-phase modules. This is achieved by referring the AC phases to the neutral line on the input side.

Figure 15 gives an example of this stacking. It shows three single-phase classic boost PFC stages forming a scalable three-phase PFC. However, this concept also applies to other single-phase PFC topologies such as dual-boost PFC or totem-pole PFC, as shown in **Figure 16**.

The big advantage of this concept is that it can support single- and three-phase operation: a phase-switch on the AC input selects operating the modules in parallel for single-phase or in three-phase configuration, as shown below. Also, the DC link voltage will remain in the range of 400 V, which enables the use of a subsequent single-stage DC-DC utilizing 650 V devices.

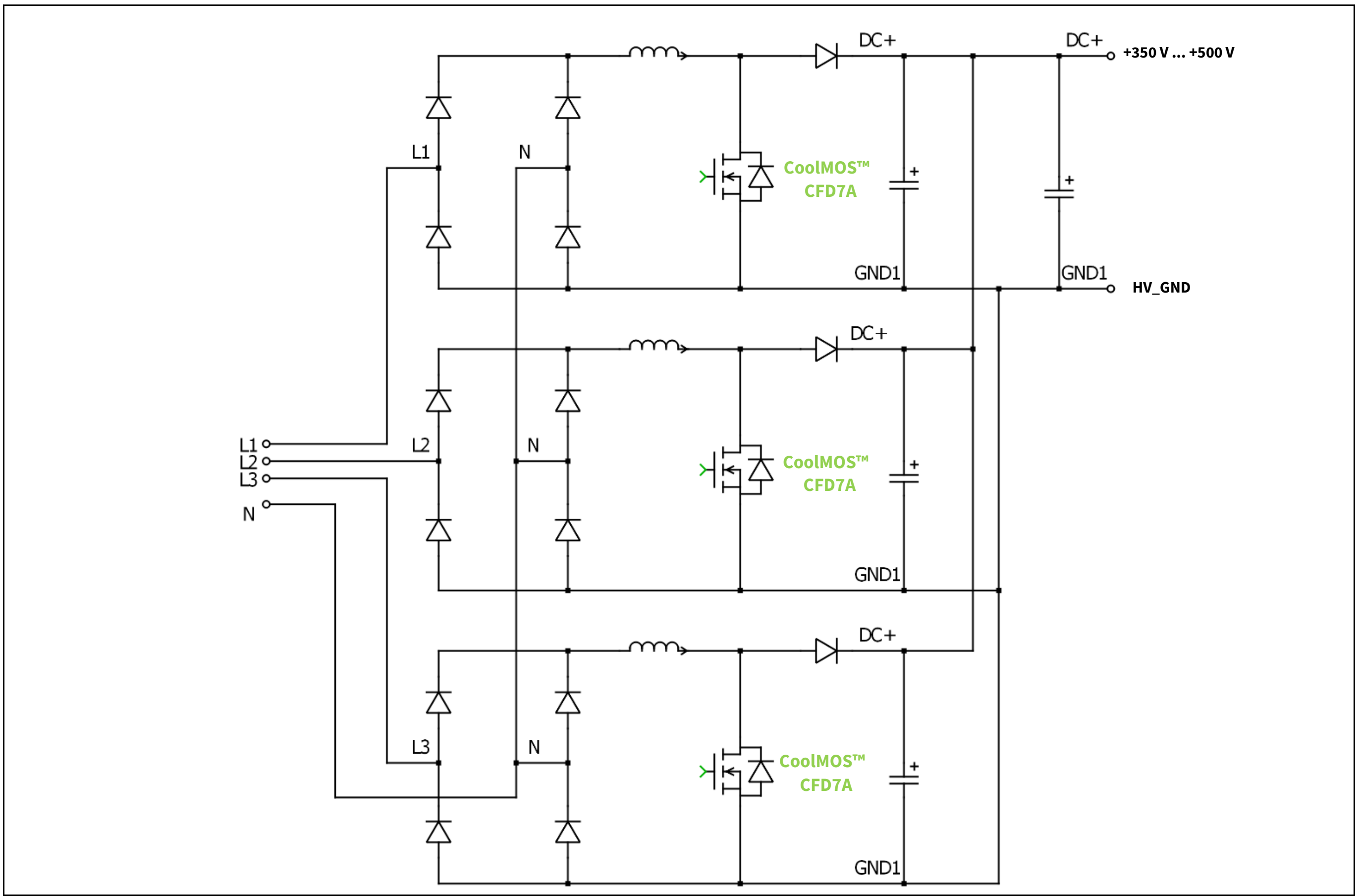


Figure 15 A three-phase PFC stage realized by stacking three individual single-phase PFC stages. The single stages are classic boost PFCs comprising CoolMOS™ CFD7As

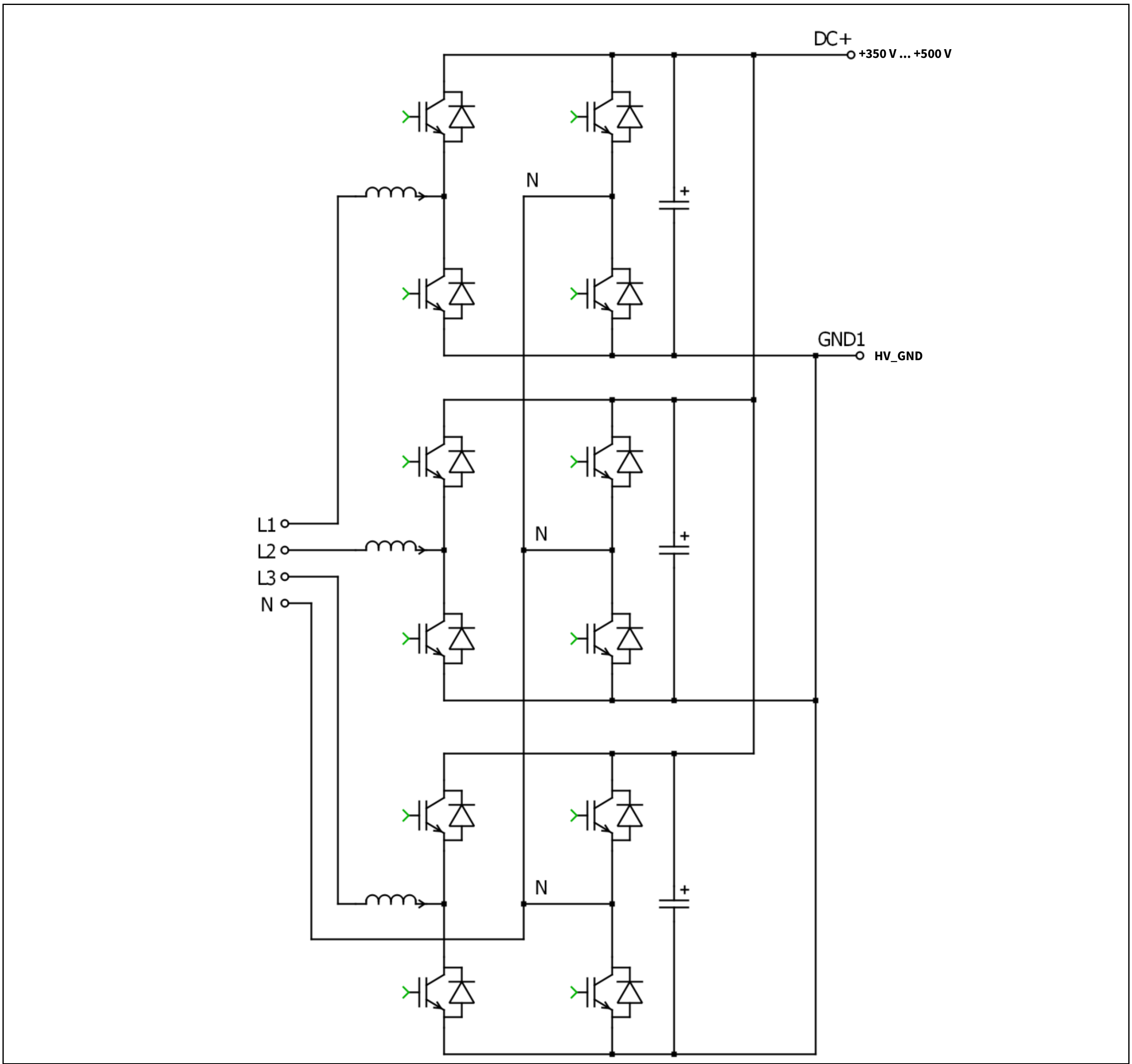


Figure 16 A three-phase PFC realized by stacking three individual totem-pole stages

2.3.1.2 Three-phase full-bridge PFC

An obvious topology for a three-phase AC grid is the three-phase full-bridge PFC. This topology is also known as B6 or as "three-leg bridge". **Figure 17** shows this topology for an operation exclusively with three-phase AC input. If an additional single-phase operation is required, the topology could be extended easily to incorporate the neutral line. **Figure 18** shows this extension.

Commonly the operation mode is continuous current mode – therefore semiconductors such as SiC MOSFETs are required to withstand the continuous hard commutation.

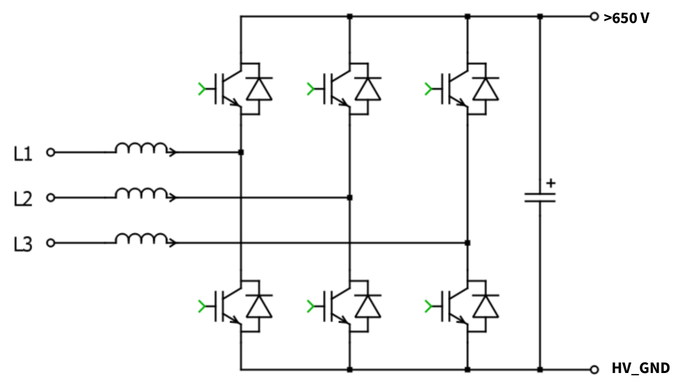


Figure 17 B6 topology: a "true" three-phase PFC topology (without using the neutral line)

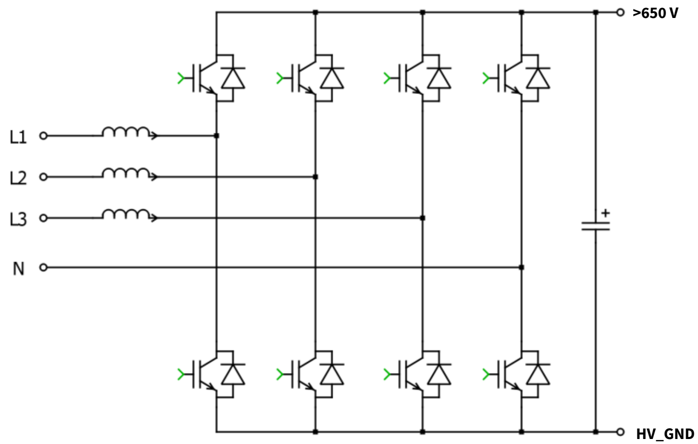


Figure 18 Four-leg bridge: a three-phase PFC topology with support for single-phase operation comprising the neutral line.

The most significant difference compared to the stacked topologies is that the DC-link voltage of these topologies must be higher. This is caused due to the higher input voltage between the AC phases. Typical DC-link voltages are around 650 V, which raises the voltage requirements for the semiconductors. Infineon recommends the CoolSiC™ 1200 V family for these PFC stages.

2.3.1.3 Vienna rectifier

Dedicated topologies for three-phase AC systems can also be used beside these topologies. The Vienna rectifier topology is a well-known example of the "true three-phase" topology.

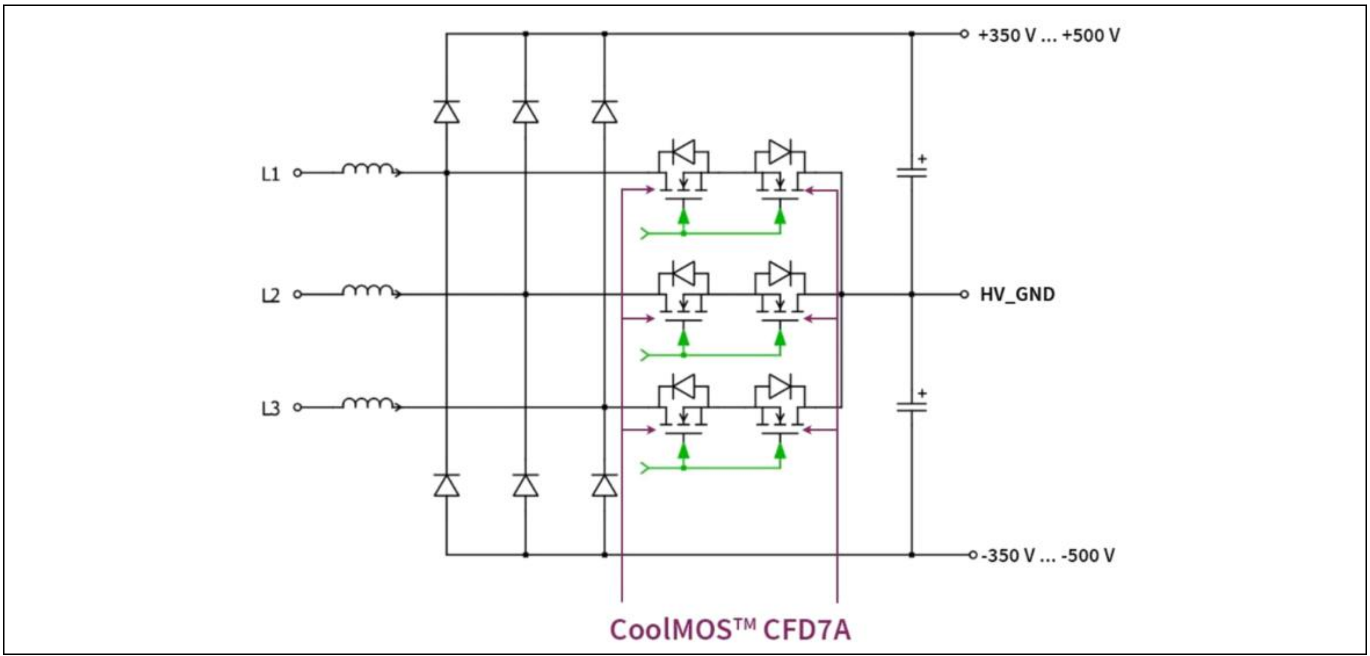


Figure 19 Vienna rectifier topology, representive of a "true three-phase" PFC topology

Nowadays Vienna rectifier topologies are being used as PFCs for EV charging stations due to the comprehensive availability of three-phase AC infrastructure at the location of the charging stations, but it can also be used for on-board chargers.

The topology utilizes 650 V semiconductor switches in a back-to-back configuration, and SiC diodes with more than 650 V blocking capabilities. Infineon's recommendation is to use either TRENCHSTOP™ AUTO F5 topology or automotive CoolMOS™ CFD7A as power switches, and CoolSiC™ Schottky diodes 1200 V Gen5 family to achieve the best performance at low semiconductor costs.

Another advantage of the Vienna rectifier is that it provides an additional terminal, splitting the DC link voltage in half on the DC side. As a result of this center connection, the DC-DC stage can also utilize 650 V CoolMOS™ CFD7A devices. **Figure 20** shows this arrangement.

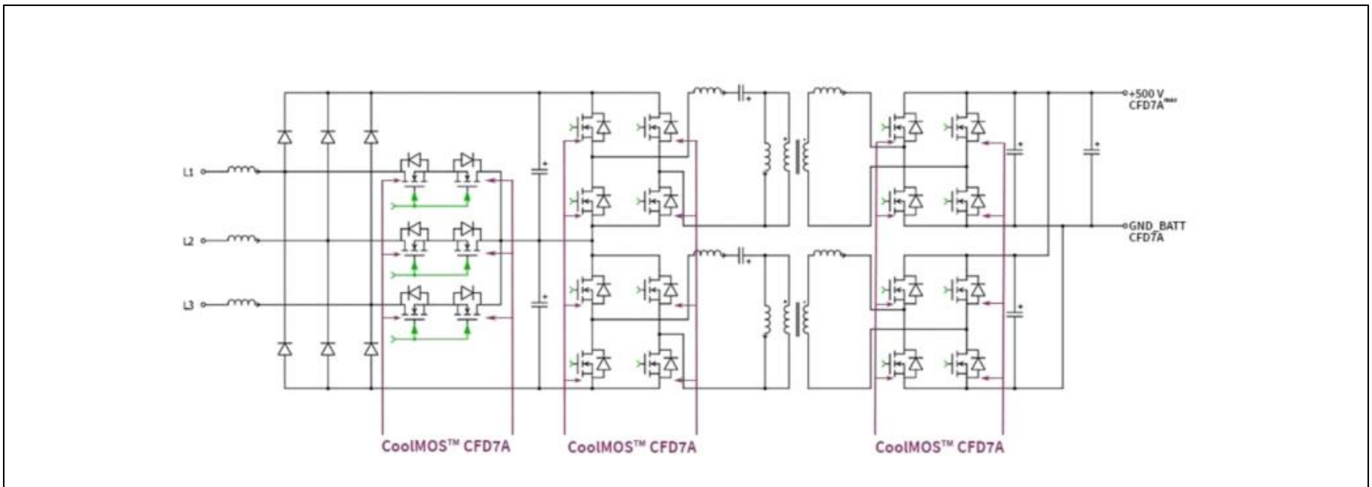


Figure 20 Three-phase on-board charger: Vienna rectifier PFC with subsequent LLC stages

3 HV-LV DC-DC converter

Even pure battery electric vehicles (BEVs) with a HV traction battery make use of a conventional lead-acid battery. A vast number of components are available in the automotive industry for this voltage class. Also, due to additional safety requirements a second independent source of energy (such as the LV battery) could be beneficial. The nominal voltage of this battery is usually 12 V.

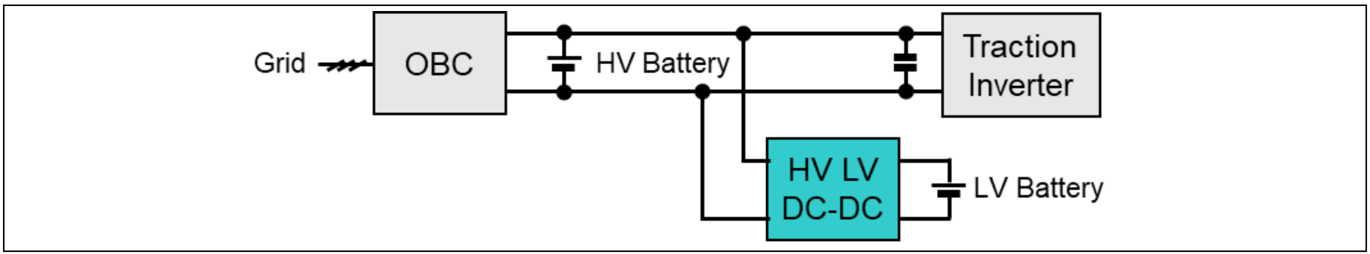


Figure 21 The HV-LV DC-DC converter couples the HV battery to the LV battery

High-voltage to low-voltage DC-DC converters are used to couple the HV with the LV domain in a modern electric vehicle. As the name indicates, a HV (on the primary side) is being converted into the LV (on the secondary side). Therefore the requirements are quite similar to the DC-DC stage of the on-board charger. As a consequence, similar topologies are established across the industry.

Therefore also the requirements for the primary side MOSFETs are very similar. As in OBC, the state-of-the-art HV-LV DC-DC converters utilize the soft-switching technique to minimize losses and increase performance. The CoolMOS™ CFD7A is the number-one choice for the primary side for battery voltages up to ~500 V. The CoolSiC™ series can be used on the primary side for higher battery voltages.

On the secondary side LV MOSFETs are required to perform a synchronous rectification. Due to the high output current, the use of diodes for rectification is discouraged. The recommendation is to use Infineon's OptiMOS™ 5 automotive series as active rectifiers.

Modern HV-LV DC-DC converters are realized as uni- or bidirectional converters.

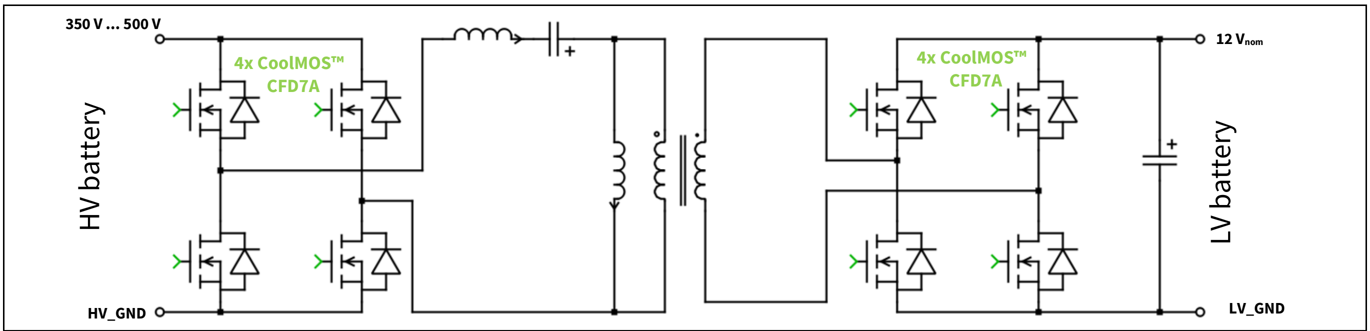


Figure 22 Exemplary on-board HV-LV DC-DC converter with CoolMOS™ CFD7A in a LLC topology

Note: *The synchronous rectification stage (on the secondary side) can also be realized differently (e.g., center-tapped transformer, e.g., using diodes for unidirectional solutions).*

HV-LV DC-DC converter

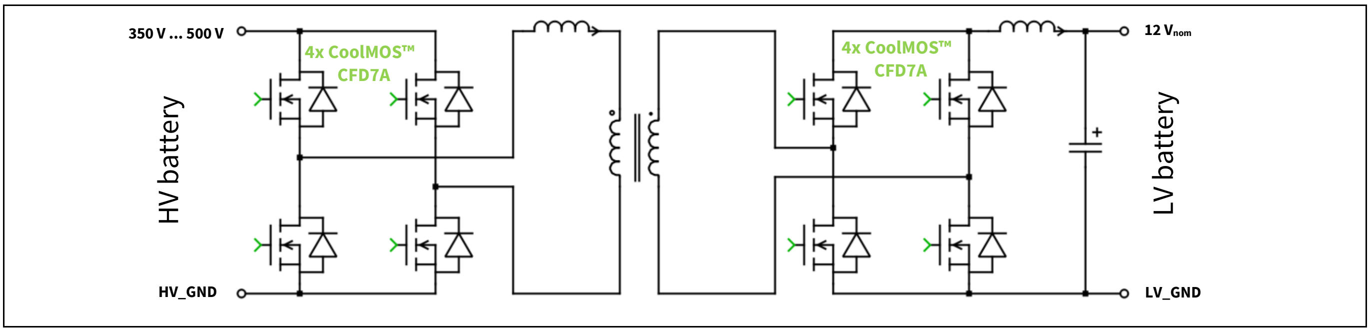


Figure 23 PSFB topology for uni- or bidirectional HV-LV DC-DC converter

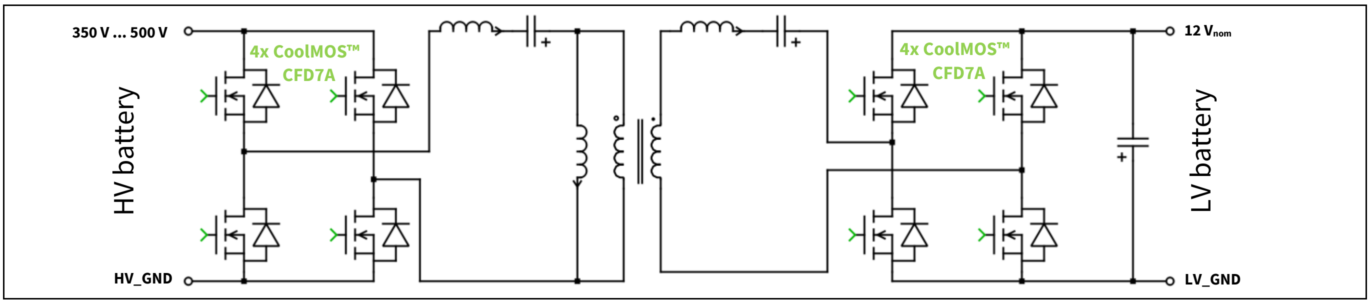


Figure 24 Full-bridge CLLC converter for bidirectional HV-LV DC-DC converters

4 CoolMOS™ CFD7A product performance

The CoolMOS™ CFD7A technology is a silicon-based superjunction MOSFET technology tailored to meet the needs of a highly efficient HV automotive on-board electronic power system.

There are two key principles being exploited by the CoolMOS™ CFD7A: being a SJ transistor, the main current path is more heavily doped than that of a conventional MOSFET. This enables a better conductance within the channel and therefore lower on-state resistance.

Nevertheless, this modification alone will not allow blocking capabilities against high electrical fields. Therefore a second principle is used: so-called “p-columns” create a vertical compensation structure for the electric field. This results in a heavily doped current path with outstanding transconductance and HV blocking capabilities for which the CoolMOS™ CFD7A series is famous. More details about the SJ MOSFET principle are available at [9].

In addition to the outstanding performance, the automotive CoolMOS™ CFD7A series offers a high level of robustness with the cost advantage of a silicon semiconductor technology.

The comparisons of the product parameters are based on the latest datasheets of the following AECQ101 devices. Parameters that are not shown in the datasheets were obtained via standard characterization measurements within Infineon Technologies.

1. *IPB65R115CFD7A: Infineon Technologies’ latest 650 V SJ MOSFET technology with integrated fast body diode [10]*
2. *IPB65R110CFDA: 650 V MOSFET from Infineon Technologies’ previous SJ MOSFET technology [11]*
3. *STB37N60DM2AG: 600 V MOSFET from STMicroelectronics [12]*
4. *NVHL110N65S3F: 650 V MOSFET from ON Semiconductor [13]*
5. *FCH104N60F_F085: 600 V MOSFET from ON Semiconductor [14]*

Figure 25 shows the most important figure-of-merit (FoM) parameters of comparable HV SJ MOSFETs with AEC Q101 qualification. Generally, the lower the value, the better the device performance. The basis for these comparisons are the parameters specified in the individual datasheets.

The “gate charge figure-of-merit” is shown in **Figure 25a** and is defined as:

$$FoM_{Qg} = Q_{g,typ} \frac{R_{DS(on),max}}{V_{(BR)dss}}$$

… whereas $Q_{g,typ}$ is the typical value for parameter gate charge total, $R_{DS[(on)(max)]}$ is the maximal on-channel resistance at 25°C and $V_{(BR)dss}$ is the breakdown voltage as defined in the individual datasheets. The unit of FoM_{Qg} is nC*mΩ/V.

Figure 25b shows the “output energy figure-of-merit”. It is defined as:

$$FoM_{Eoss} = E_{oss@400V} \frac{R_{DS(on),max}}{V_{(BR)dss}}$$

E_{oss} is the energy in microjoules, which is stored in the parasitic output capacitance at a drain-source voltage of 400 V. This E_{oss} value is a typical value specified in the respective datasheets. It is calculated based on the C_{oss} curve of the individual MOSFETs.

The unit of FoM_{Eoss} is uJ*mΩ/V.

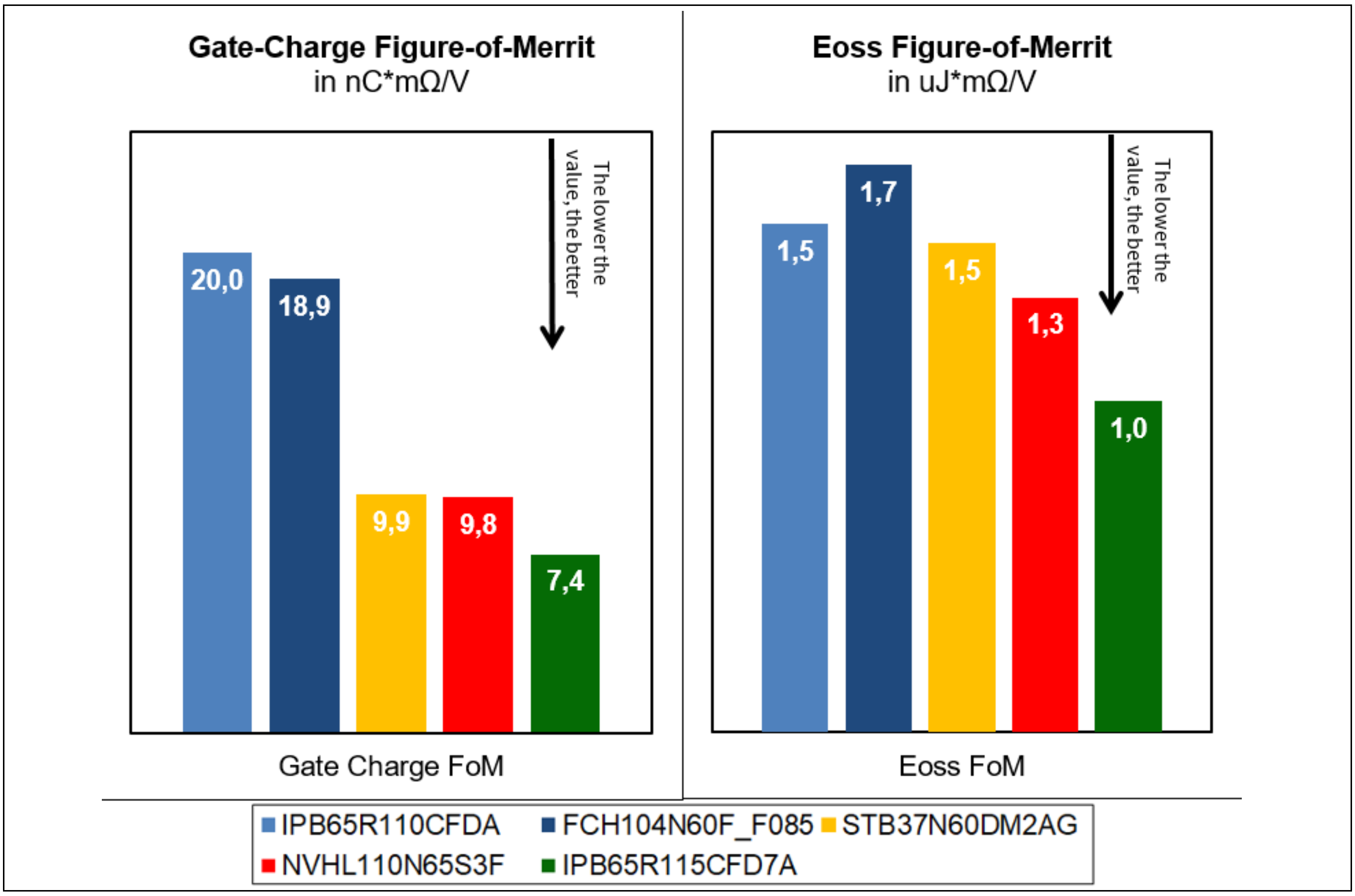


Figure 25 **Overview of the most important electrical parameters of CoolMOS™ CFD7A 115 mΩ against next-best competitors with automotive qualification grade and fast-body diode properties**

4.1 Reduction of C_{oss} and E_{oss}

The dominant parasitic capacitance in a HV MOSFET is the output capacitance (C_{oss}). C_{oss} is a non-linear capacitance. The C_{oss} values contribute significantly to losses in hard-switching applications like the CCM PFC topologies (as shown in **Figure 6**).

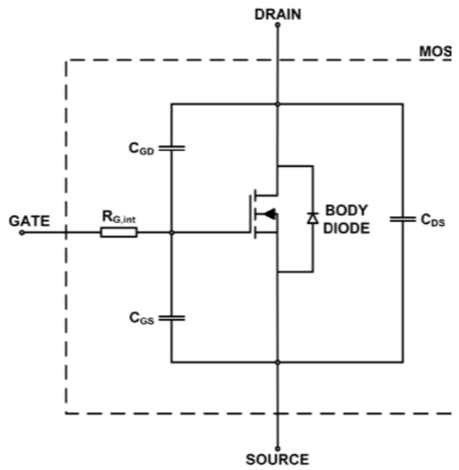


Figure 26 Equivalent circuitry of the power MOSFET showing the most important parasitic elements

Half of the integral of the MOSFET's C_{oss} value over the V_{ds} voltage squared defines the energy (E_{oss}), which is stored in the MOSFET during the off-stage:

$$E_{oss}(V_{ds}) = \int_0^{V_{ds}} C_{oss}(v) \times v \times dV$$

The lower the E_{oss}, the less energy is dissipated into heat within the channel during hard turn-on of the MOSFET.

As shown in **Figure 27** and **Figure 28**, the CoolMOS™ CFD7A technology offers the best-in-class E_{oss} parameter within the automotive industry. As a consequence, the efficiency of hard-switching PFC stages in on-board chargers can be improved. **Figure 33** highlights this benefit of the CoolMOS™ CFD7A in a hard-switching PFC stage.

The advantage of the CoolMOS™ CFD7A becomes particularly important with higher switching frequencies, since the swiching losses in the AC-DC converter increase with the frequency.

CoolMOS™ CFD7A product performance

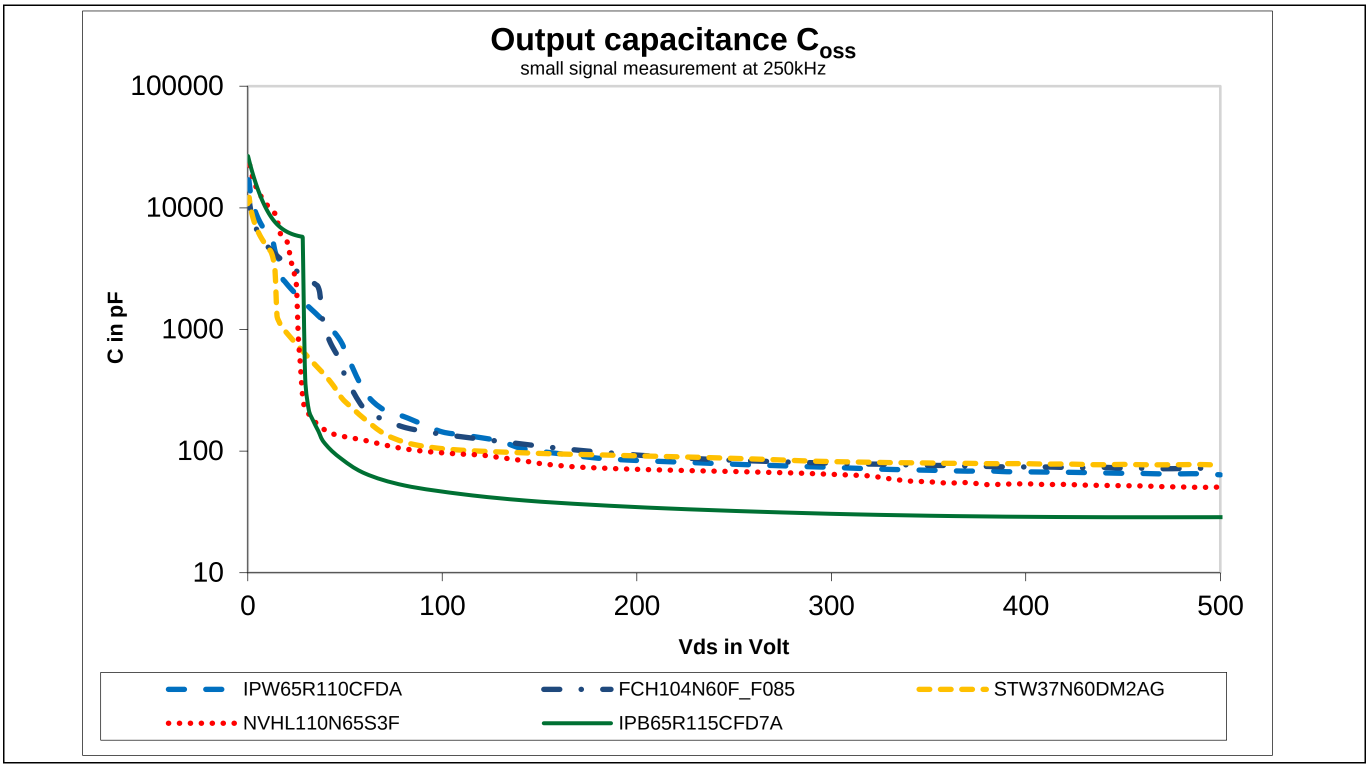


Figure 27 C_{oss} characteristics of CoolMOS™ CFD7A (green curve) compared to competitor MOSFETs

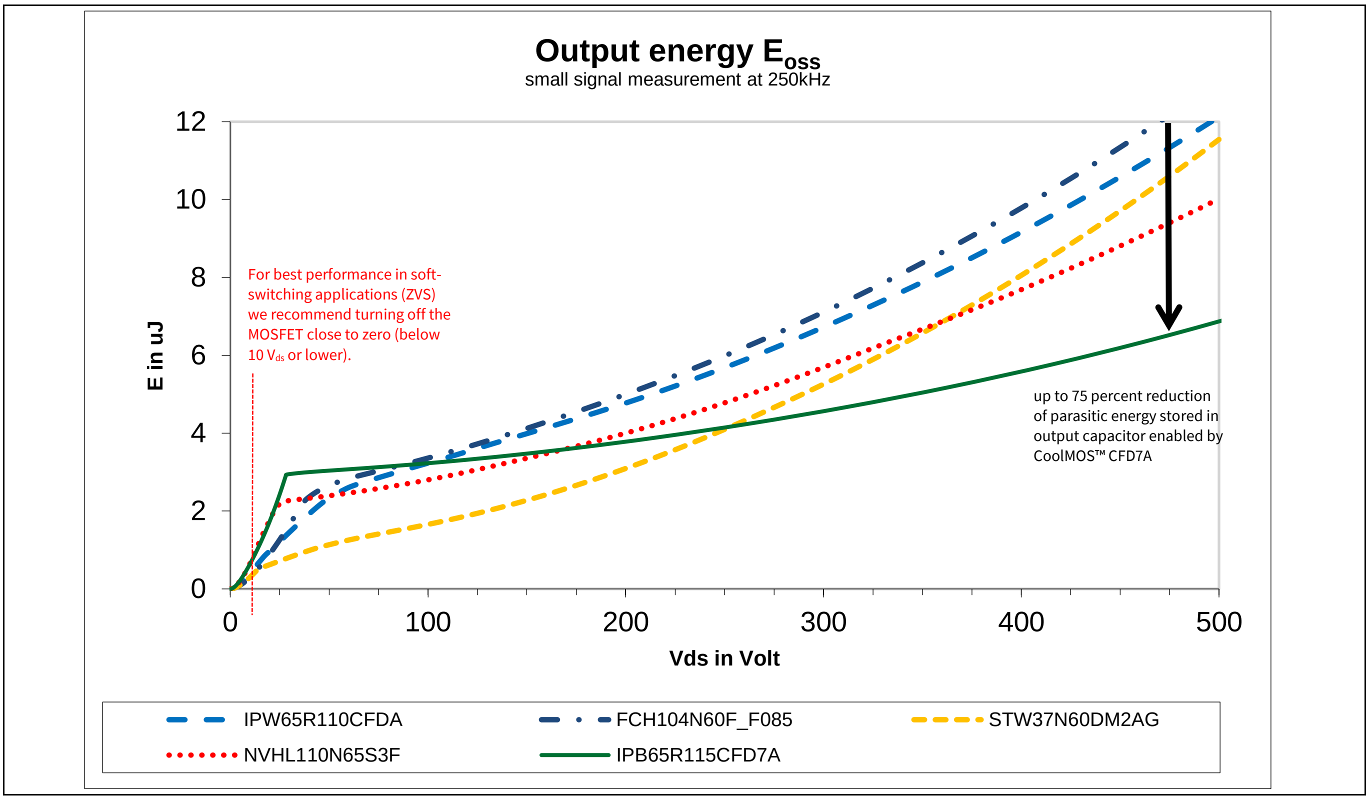


Figure 28 The parasitic energy stored in the CoolMOS™ CFD7A (green curve) is significantly lower at high DC-link voltages than other devices

4.2 Reduction of gate charge

Another outstanding feature of the new CoolMOS™ CFD7A technology is the tremendous reduction of the total gate charge (Q_g) compared to CoolMOS™ CFDA.

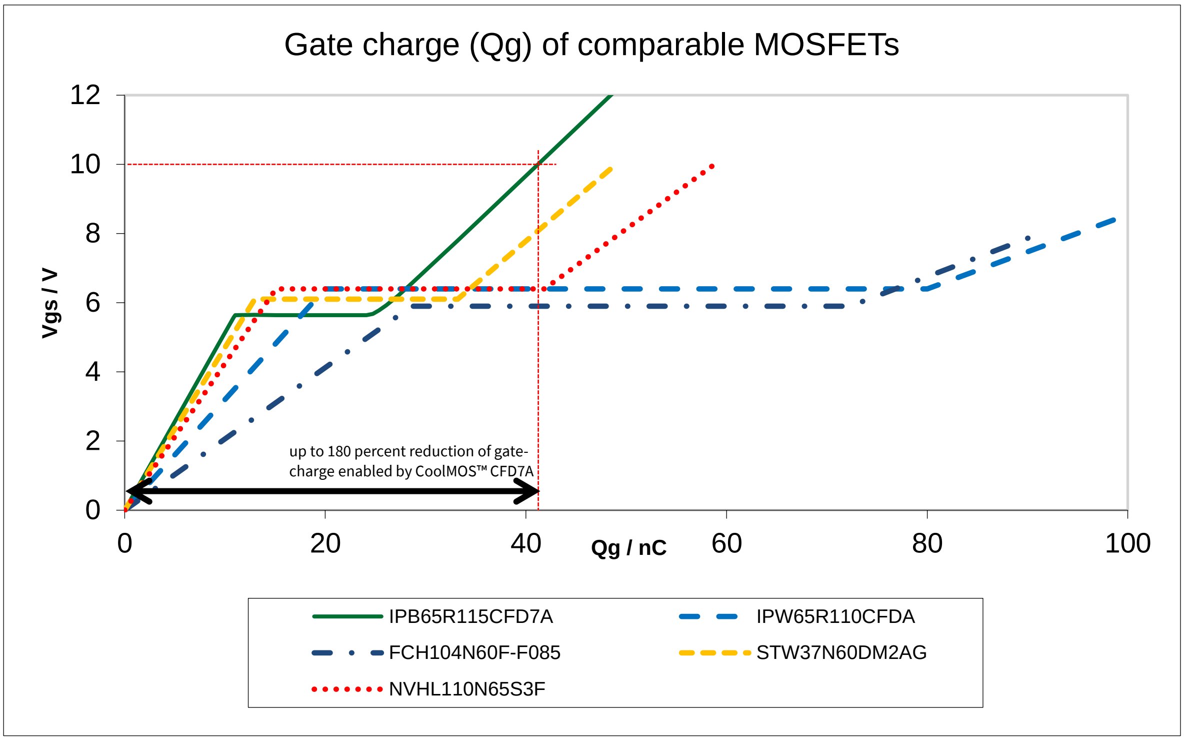


Figure 29 CoolMOS™ CFD7A offers the lowest gate charge among all comparable devices

This reduction of gate charge offers multiple advantages:
First, it allows faster switching of the devices, since with the same gate driver the charge to the gate can be provided more quickly for turn-on, or removed for turn-off, respectively. Conversely, the use of gate drivers with lower current capability becomes possible while keeping the switching times at the same level. This dependency is depicted in the next formula:

$$I_{GDRV} = \frac{Q_G}{t_{g,sw}}$$

Second, the total power dissipation needed to drive the gate is also reduced by a reduction of Q_g:

$$P_{GDRV} = Q_G \times V_G \times f_{sw}$$

Due to the low Q_g, the CoolMOS™ CFD7A is the number-one choice to enable higher efficiencies in fast-switching on-board charger systems.

4.3 Fast body diode feature of CoolMOS™ CFD7A

Although SJ power MOSFETs offer outstanding features compared to standard MOSFETs, the SJ principle suffers from one shortcoming: the charge that is required to block a forward-biased body diode (Q_{rr}) is rather high. Due to this fact, a continuous commutation on the body diode of SJ MOSFETs at high-speed for high currents is not recommended, since it will increase the stress conditions across the power MOSFETs significantly. The parameter describing this quantity is called reverse recovery charge, Q_{rr}.

The new automotive CoolMOS™ CFD7A technology offers a fast body diode. This means the Q_{rr} is much smaller compared to conventional SJ MOSFETs, and the MOSFET is robust against spurious hard commutations on the body diode.

Nonetheless, we recommend using an automotive CoolSiC™ Schottky diode Gen5 as the commutation partner for the CoolMOS™ CFD7A for applications where continuous hard commutation occurs each switching cycle, as well as high currents (such as CCM PFCs).

Alternatively, we recommend using automotive high-speed TRENCHSTOP™ 5 IGBT or CoolSiC™ MOSFETs for hard-commutation applications such as totem-pole PFC and inverter applications.

If soft-switching is applied, the Q_{rr} of the body diode can be neglected, because the MOSFETs are being turned on in zero-voltage conditions. Therefore SJ MOSFETs can be perfectly used in half- and full-bridge configurations with soft-switching. Soft-switching became a standard method for modern DC-DC converters because it enables increasing the switching frequency by reducing the losses at the same time.

Nevertheless, we recommend using CoolMOS™ with fast-diode properties (CoolMOS™ CFD7A) for improved robustness in case of spurious hard commutations in DC-DC converters. CoolMOS™ CFD7A offers considerably lower Q_{rr} values compared to previous generations. As consequence the reverse recovery time (t_{rr}) is shortened and the reverse recovery current (I_{rrm}) is also reduced, which brings a higher margin in hard commutation of the body diode. Consequently, the reliability of the system can be improved as well. The principle of the fast-body-diode advantage is shown in **Figure 30**. The behavior of the CoolMOS™ family with the fast body diode is represented by the red curve: the Q_{rr}, t_{rr} and I_{rrm} are significantly lower than for conventional SJ MOSFETs (blue curve).

For more information about the advantages of the fast body diode of a CoolMOS™ SJ MOSFET, please refer to [15].

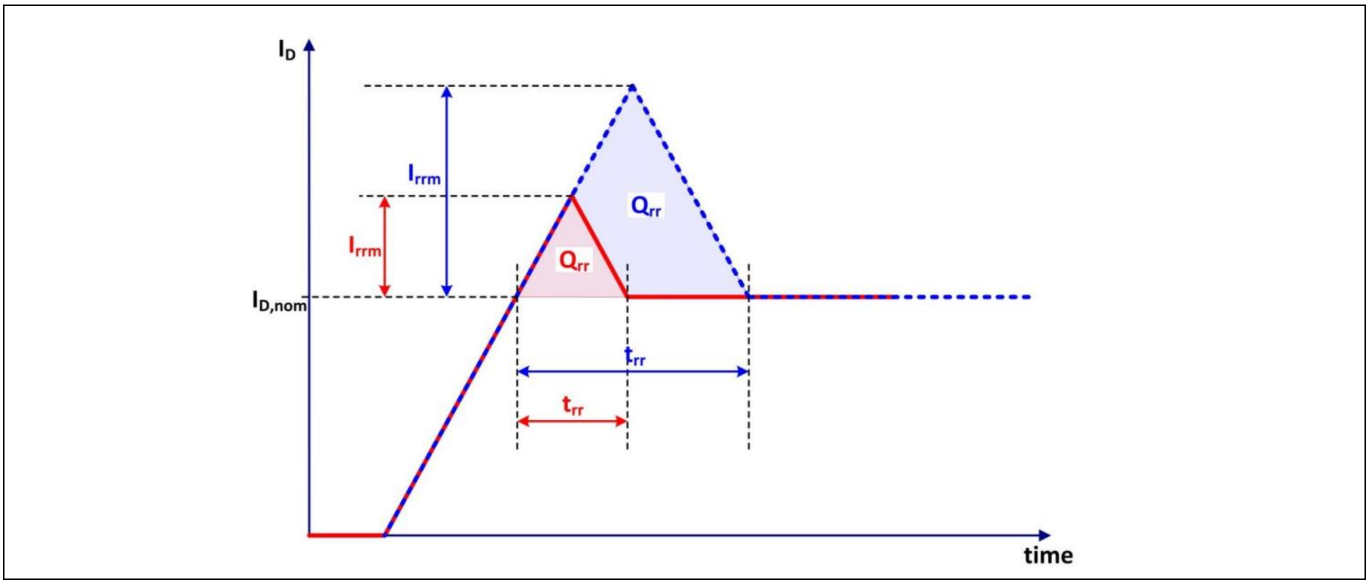


Figure 30 The advantage of a CoolMOS™ with fast body diode (CFD7A; red curve) vs. a conventional SJ technology without fast diode (blue curve)

4.4 SMD package with wide-creepage distance

The CoolMOS™ CFD7A is offered in a wide variety of standard packages and $R_{DS(on)}$ classes. Additionally, Infineon offers a new wide-creepage distance SMT package: the D2PAK seven-pin (TO263-7-11) for advanced reliability at higher system voltages – a novelty within the automotive industry.

Figure 31 shows this D2PAK seven-pin package. Apart from the 4.3 mm creepage distance, the package also offers additional pins for advanced driving of the power MOSFETs. This is enabled by offering an additional driver-reference pin, the so called "sense-source" contact. The switching times could be reduced significantly if the sense-source pin is used as MOSFET driver reference. Infineon recommends utilizing the sense-source contact wherever possible.

The principle is shown in **Figure 32**. More details are available in [16].

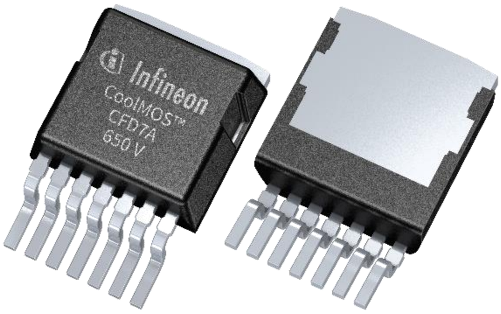


Figure 31 CoolMOS™ CFD7A in TO263-7-11 package for higher system voltages and advanced gate driving

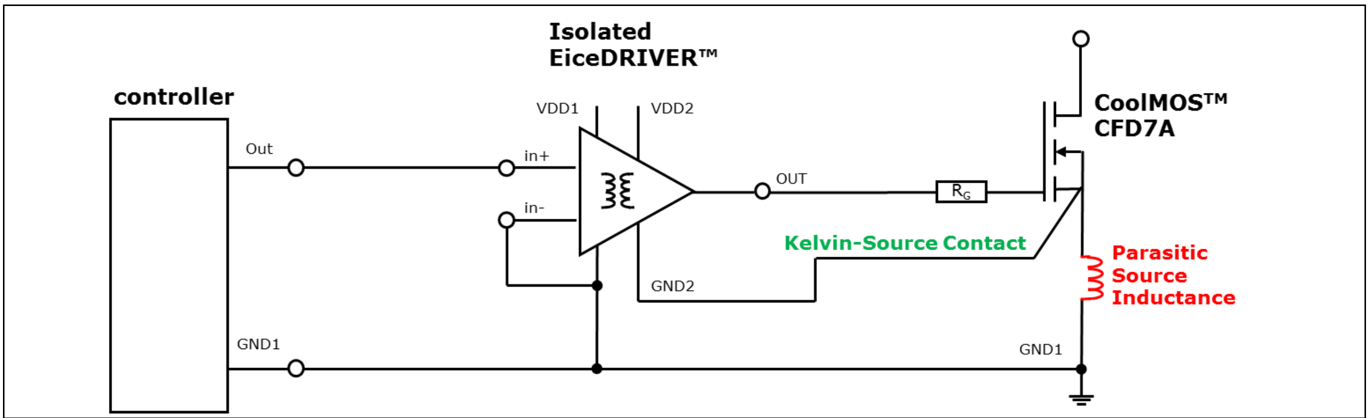


Figure 32 Advanced gate driving with CoolMOS™ CFD7A and Kelvin-source contact offered by TO263-7-11 package

4.5 ESD robustness

All CFD7A devices are able to withstand ±2000 V ESD pulse on the gate (in accordance with Class 2 HBM of the IEC 61000-4-2 standard). This is achieved by integrated ESD protection and inherent immunity by chip design.

This has the advantage of making CoolMOS™ CFD7A devices more robust during handling in manufacturing.

4.6 Efficiency performance in PFC and DC-DC stages

As noted above, the CoolMOS™ CFD7A devices can be used in PFC and DC-DC stages. This chapter shows some experimental results obtained by lab measurements.

4.6.1 Efficiency results in a CCM PFC

Figure 33 shows the performance of the CoolMOS™ CFD7A in a hard-switching PFC stage. The efficiency results were obtained via lab measurements on an Infineon demo board. The demo board is shown in **Figure 33**. The SJ MOSFETs were used in combination with a CoolSiC™ Schottky diode Gen5 from Infineon, forming a classical boost PFC topology operated in CCM. This topology is shown in **Figure 6c**. More details about the PFC demo board are available at [17]. The demo board is available to order via www.infineon.com [18].

The board is operated at an input voltage of 230 V_{rms}. The switching frequency is set to 100 kHz. The efficiency is the total AC-DC efficiency obtained by high-precision power analyzers. The gate resistors (which determine the switching speed of the devices) are chosen in full compliance with the datasheet of the individual devices to obtain a fair comparison on the application level. Additionally, only devices in TO263 (D2PAK) have been selected to eliminate influences from different package attributes. These devices were soldered onto a daughter PCB to fit the TO247 footprint of the PCB.

Figure 33 Photograph of a PFC evaluation board, which was used to determine the efficiency measurements shown. This demo board is available to order under "EVAL_2k5W_CCM_4P_V3" via www.infineon.com [18]

Figure 34 shows the measured efficiency results. The CoolMOS™ CFD7A device offers best performance over the entire load range. The efficiency was obtained via high-precision power analyzers in a standardized setup to enable reproducibility. The estimated measurement error on the efficiency result is below 0.1 percent (worst case).

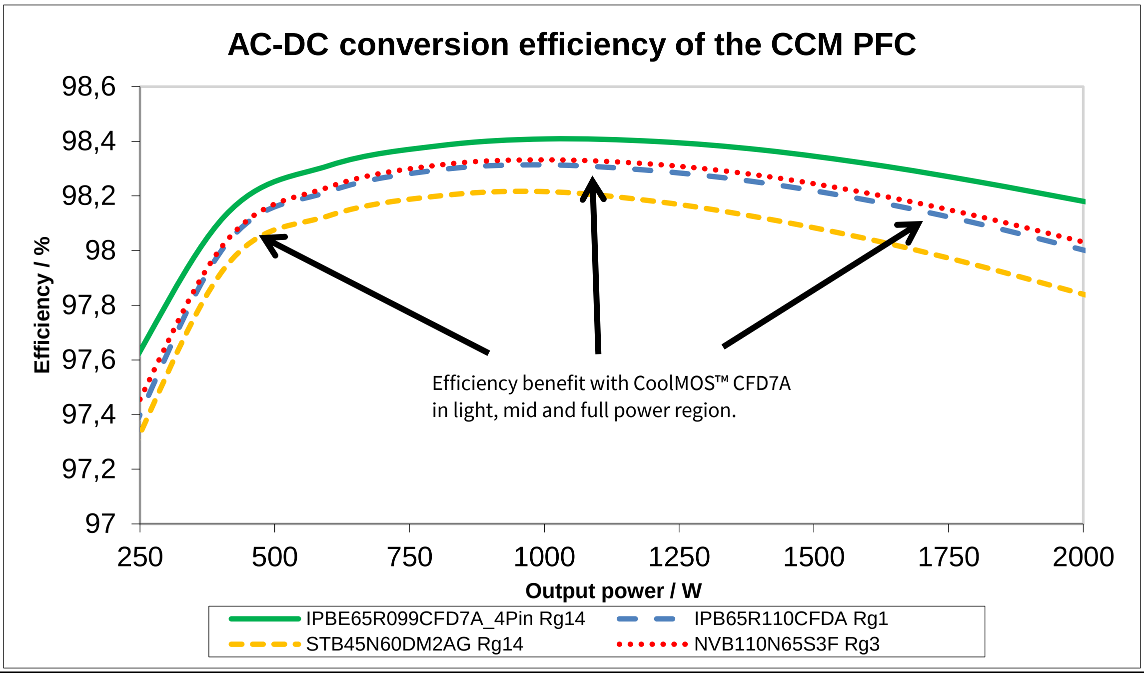


Figure 34 **Total efficiency of the classic PFC stage at 230 V AC, f_{pwm} = 100 kHz: CoolMOS™ CFD7A reaches the highest conversion efficiency across the entire load range**

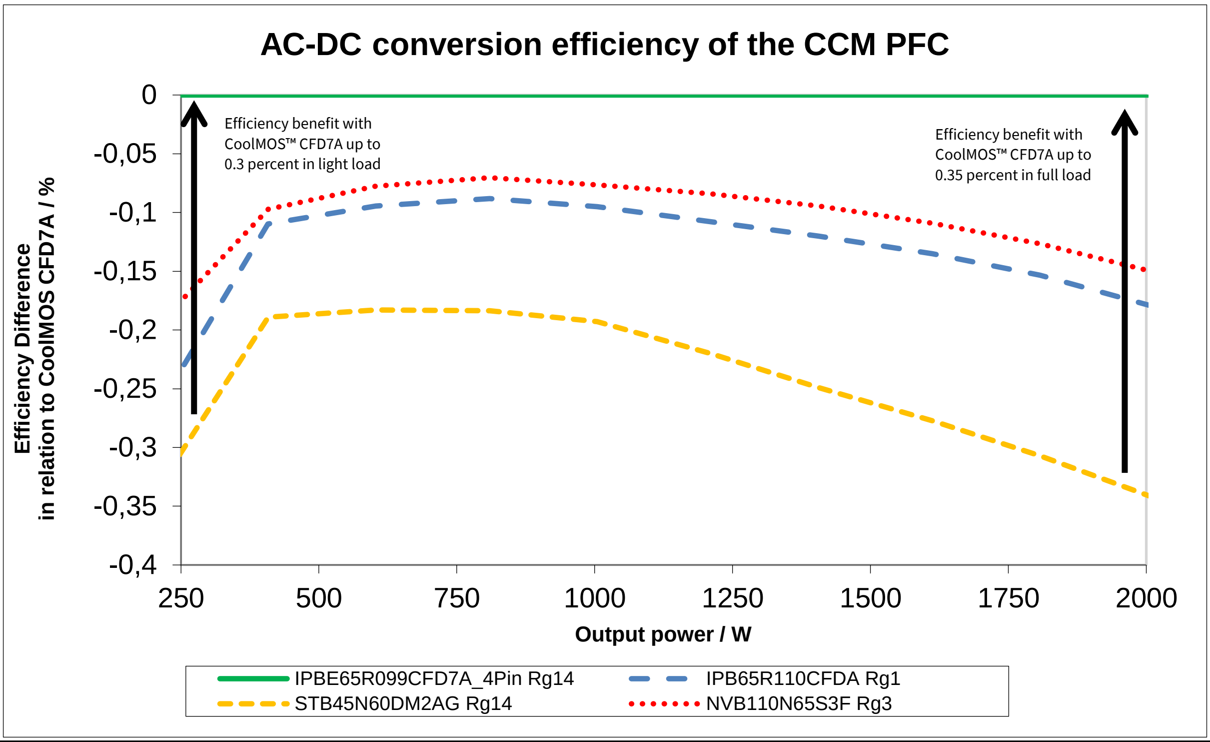


Figure 35 **Relative efficiency of the PFC stage (compared to CoolMOS™ CFD7A with the same test conditions as in Figure 34)**

Figure 36 shows the power losses that occur in the PFC stage. Power losses are caused by the parasitic elements of the components. The lower the power losses, the less effort is required to cool the electronic power system. CoolMOS™ CFD7A devices exhibit the lowest power loss over the entire load range.

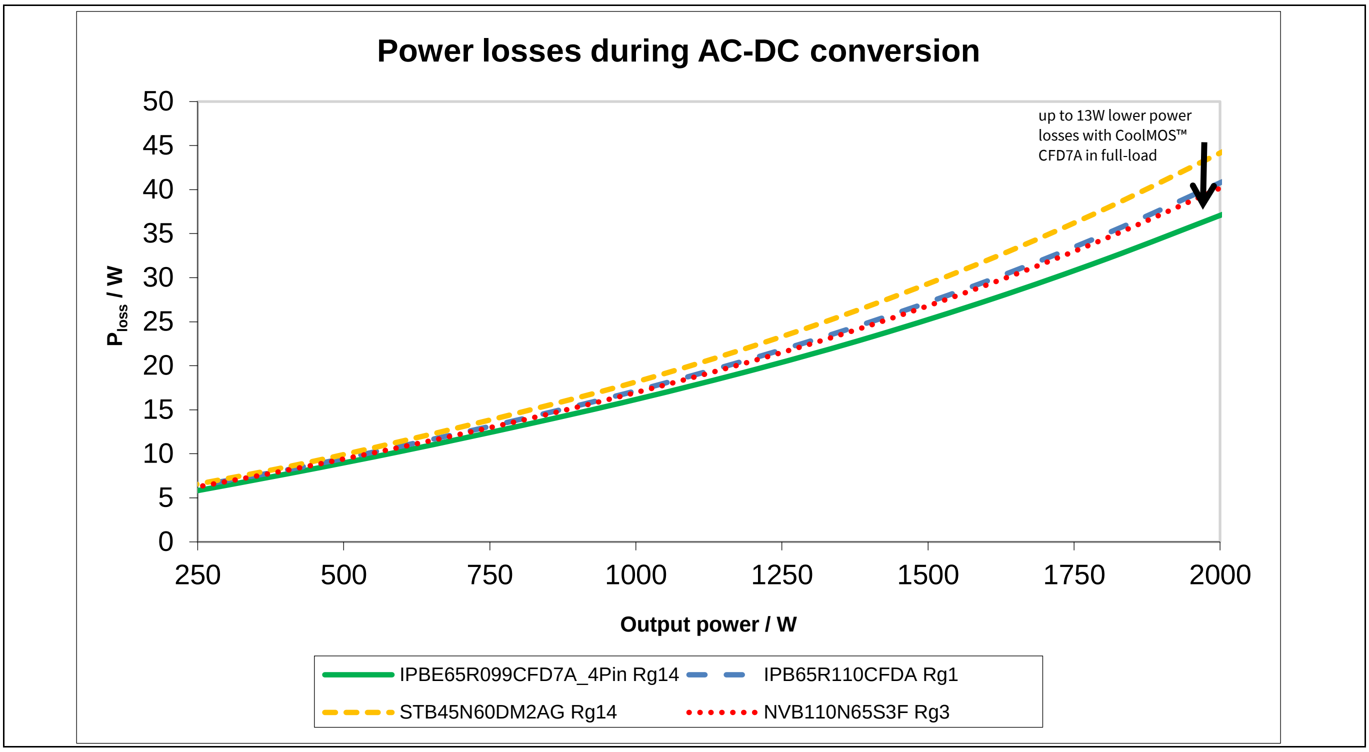


Figure 36 Power losses during the conversion; CoolMOS™ CFD7A has the lowest losses across the entire load range

Figure 37 shows the temperature of the MOSFETs in the PFC stage. The CoolMOS™ CFD7A device reaches a maximum temperature of about 71°C at full load, which represents the lowest device temperature among all selected power MOSFETs. The hottest device is STB45N60DM2AG, which reaches a maximum temperature of about 79°C – this is about 10 percent hotter than the CoolMOS™ CFD7A device.

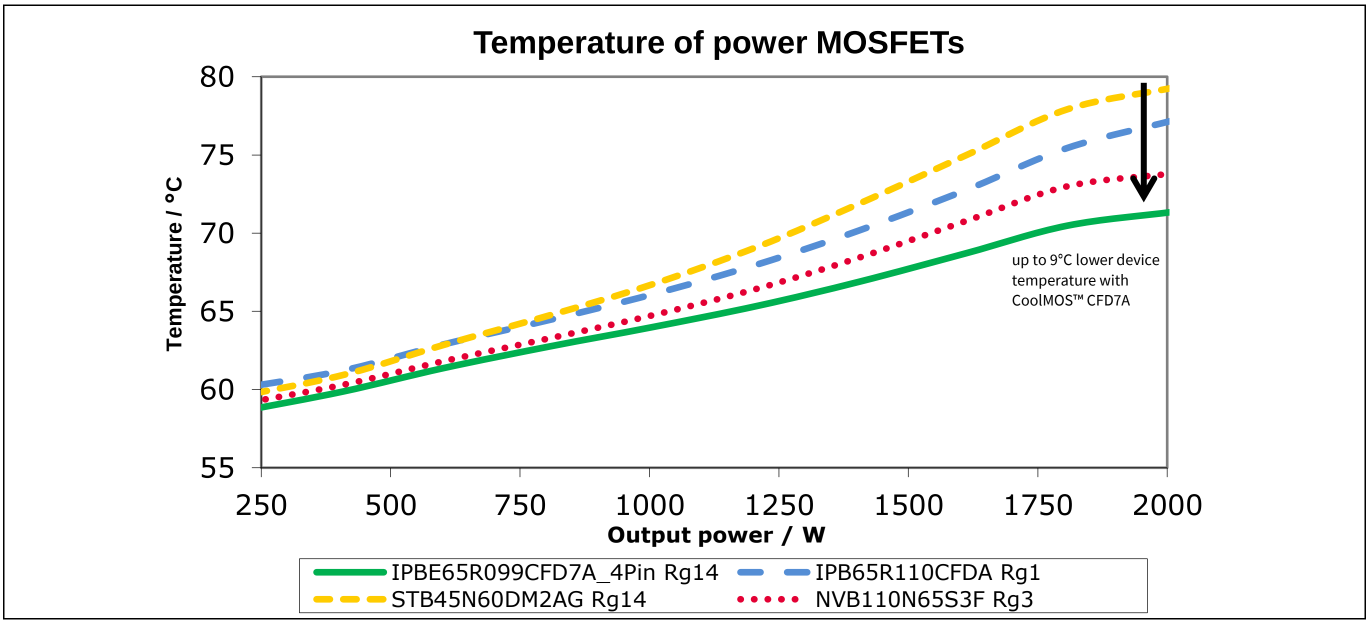


Figure 37 Power device temperatures during PFC operation: CoolMOS™ CFD7A is the coolest device

4.6.2 Efficiency results in a soft-switching LLC

Similar to the measurements in Chapter 4.6.1, a performance in a LLC has been taken as representative for soft-switching DC-DC converter topologies.

Figure 37 shows the results of this measurement. The baseline for comparison is the efficiency achieved with the NVHK110N65S3F device from ON Semiconductor. All other devices reach a better efficiency – their efficiency curve lies above this reference line. The CoolMOS™ CFD7A out-performs all other devices across the complete load range with advantages at light load and full load. The dead-time settings were adapted accordingly to achieve ZVS for each individual device (no visible Miller plateau). The gate drive resistors were set up in such a way that the voltage peaks at start-up do not exceed the datasheet of the individual devices. The rest of the hardware (resonant tank, magnetics, etc.) were not modified during this comparison.

This demo board is a dual-phase LLC converter with a resonant frequency of 130 kHz. It is shown in **Figure 38**. The board is available to order under "EVAL_3KW_2LLC_CFD7" via www.infineon.com [19].

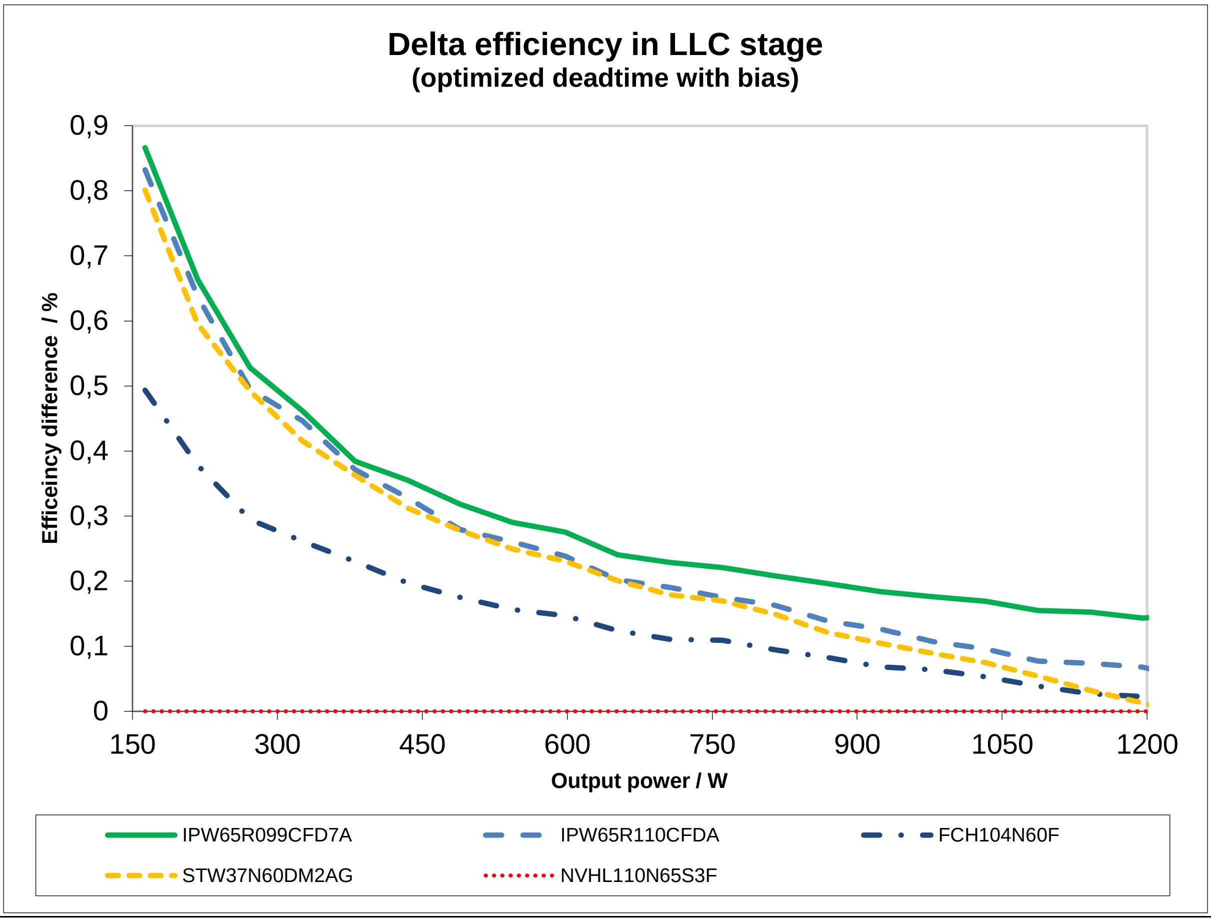


Figure 38 Efficiency of comparable power MOSFET devices in a soft-switching LLC converter

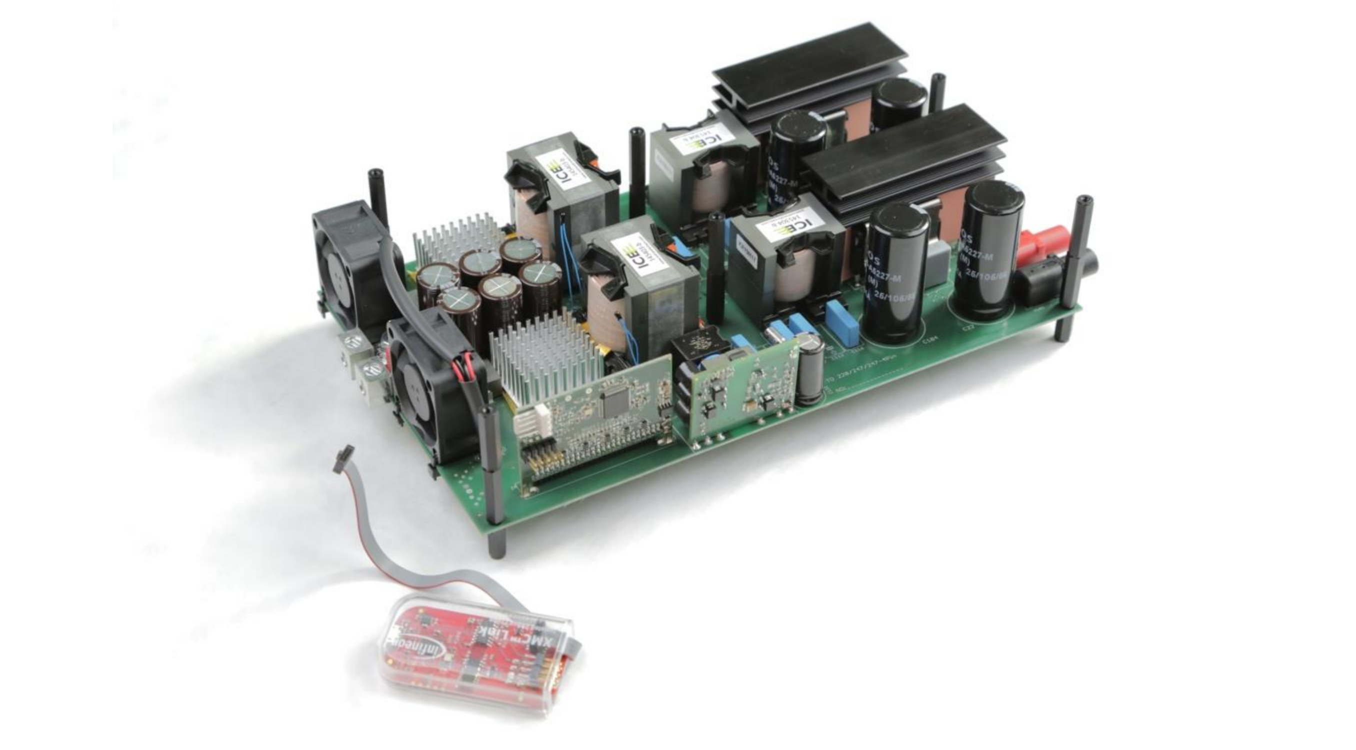


Figure 39 3 kW dual-phase LLC converter demo board used to gather the efficiency graphs in Figure 38

4.7 General design and layout recommendations

The CoolMOS™ CFD7A is a very fast-switching device enabling the highest performance in on-board chargers. Infineon recommends that you consider the general design and layout recommendations, especially for CoolMOS™ CFD7A.

Infineon application notes provide useful information on how to use CoolMOS™ most efficiently in terms of gate drive, PCB layout and paralleling of MOSFETs. Application notes "General design considerations for using high-speed superjunction MOSFET devices from Infineon" and "650 V CoolMOS™ CFD7A for on-board chargers and DC-DC converters" in particular give hints on how to use CoolMOS™ optimally.

Additionally [9] and [20] give hints that apply generally for high-speed MOSFETs and therefore are directly transferable to the CoolMOS™ CFD7A family.

Note: Generally, we recommend to avoid avalanche as operating mode. In avalanche osicllations at high frequencies might occur.

Note: Infineon offers technical assistance for your application. Please get in contact with us via our Technical Assistance Center at https://www.infineon.com/cms/en/about-infineon/company/contacts/product-support-form/.

5 References

[1] Infineon application note “PFC boost converter design guide”: https://www.infineon.com/dgdl/Infineon-ApplicationNote_PFCCCMBoostConverterDesignGuide-AN-v02_00-EN.pdf?fileId=5546d4624a56eed8014a62c75a923b05

[2] Infineon “CoolSiC™ Schottky Diode” landing page: https://www.infineon.com/cms/en/product/power/wide-band-gap-semiconductors-sic-gan/silicon-carbide-sic/coolsic-schottky-diode/

[3] Infineon “Automotive qualified IGBTs” landing page: https://www.infineon.com/cms/en/product/power/igbt/automotive-qualified-igbts/

[4] Infineon “Silicon Carbide MOSFET Discretes” landing page: https://www.infineon.com/cms/en/product/power/mosfet/silicon-carbide/discretes/

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