White Paper
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Topologies in on-board charging

Semiconductor recommendations for reliable charging solutions

Abstract

Together with the growing popularity of electric vehicles, the demand for highly reliable and long-lasting battery performance has also been growing. On-board chargers (OBCs) are an essential system for plug-in hybrid and battery electric vehicles. In this paper, we discuss the system architecture and the possible topologies for on-board charging and recommend the right choice of power semiconductors for OBCs.

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1 Introduction

Battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs) are expected to shape everyday street life much more sustainably in the next few years than they do today. Since these vehicles have no (or very low local CO_2 emissions) according to Worldwide Harmonized Light Vehicles Test Procedure (WLTP), manufacturers are increasingly relying on the emerging of these vehicles in order to achieve their fleet's CO_2 emission targets which were governed by the EU.

Both types of vehicles (PHEV and EV) commonly use lithium-ion battery packs with high voltages (typically in the range of 350 V – 475 V). State-of-the-art battery-electric vehicles deploy battery capacities up to approximately 100 kWh, which allows WLTP ranges over 400 km. Furthermore, electric cars with even higher battery capacities have been in development to accelerate the maximum achievable range possible with a single charging.

In comparison to battery electric vehicles, plug-in hybrid vehicles integrate smaller battery packs that are around 15 kWh since the electrical drive train is used for short-range driving only. Therefore the pure electrical range usually does not exceed 50 km. For BEVs, the charging of this battery by an external source is a basic need-to-have; for PHEVs, the charging by an external source is an addition to the charging by energy generation of the internal combustion engine.

The attractiveness of electro-mobility stands and falls by the batteries. Advancements in semiconductor technologies are required to achieve higher efficiencies and top performance, making electric vehicles a convenient and eco-friendly alternative for traditional means of transportation.

Battery performance and durability are also highly dependent on charging technologies and methods. In the next chapters, we take a more in-depth look into on-board charging, discuss the system architecture, and elaborate on the possible topologies for the PFC and the DC-DC stages.

2 On-board charging overview

As electro-mobility increasingly becomes part of daily life, there is a growing need for more efficient charging solutions. Fast electric vehicle (EV) charging stations equipped with powerful DC chargers are currently the answer. DC EV chargers are an attractive choice because they allow much faster charging than the standard AC-charging that many EV owners have available at home. Today, a DC charger with 150 kW can put a 200 km charge on an EV in around just 15 minutes. As fast charging and battery technologies continue to evolve and improve in the near future, experts anticipate the charging time to drop even further, mostly enabled by advance in battery chemistry and advanced thermal management concepts.

On-board charging (OBC) is the application that re-charges the high-voltage battery of a plug-in or battery-powered electric car from the grid while the car is parked and connected to an AC outlet. As this application is built into the car, it is called on-board charger.
Today's OBC typically offer a unidirectional power flow from the grid to the battery. However, there are also application scenarios (vehicle-to-load, vehicle-to-home, or even vehicle-to-grid) that require a bidirectional operation of the OBC.

The battery in an electric vehicle is useless without a battery charger. Furthermore, all electronic systems depend on the battery for power. In battery electric vehicles and plug-in hybrid electric vehicles, the battery can be charged from a standard power outlet. Charging via the main grid calls for design flexibility due to the different voltage and current levels in different countries. And needless to say, the charging time is also an essential factor for car drivers. System designers face the challenge of supporting the varied voltage- and current- levels while increasing the power density. When it comes to on-board charging, the key success factors involve efficiency and a high power density for a small form factor. The long-term trend is moving towards bidirectional charging, where the charger also feeds power from the car into the smart grid.

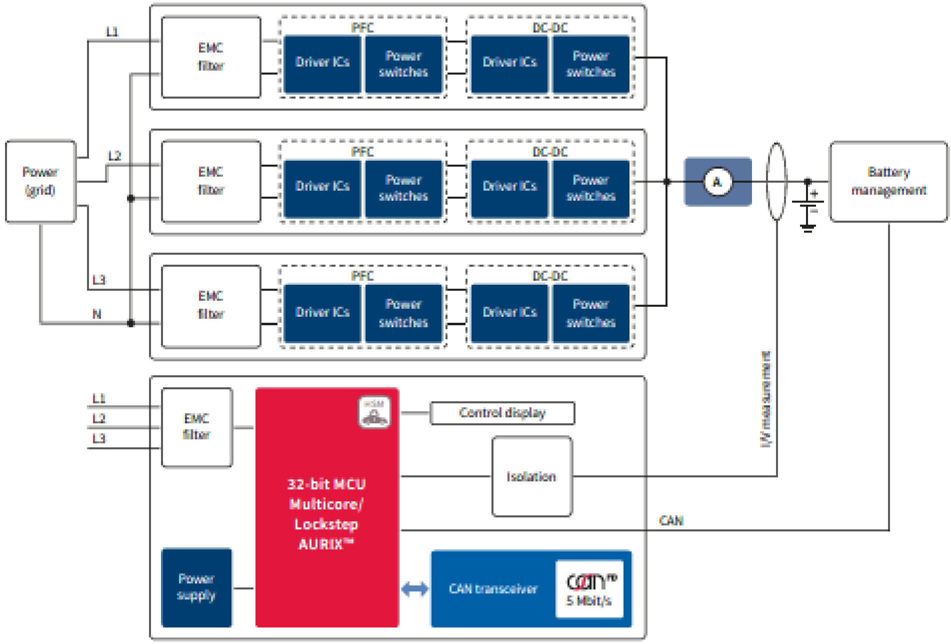

Figure 1 System block diagram for OBC

3 The on-board charger system

The on-board charger system is a vital subsystem in all plugin-hybrid and battery electric vehicles. As the name indicates, it has the task of charging the high-voltage traction battery with energy supplied by the AC grid. In the case of AC charging, an on-board charger is handling the conversion of the AC power into the DC power required by the battery. Obviously, the power losses during the conversion subtract from the power available to charge the battery. Thus one favorable attribute of an on-board charger is to have a high conversion efficiency. Today's OBCs are targeting typically 95 percent of total AC-DC efficiency or above. High conversion efficiency brings several advantages: the more efficient the conversion works, the less heat is generated in the system, and the less effort has to be spent on thermal management. Eventually, a reduced effort on thermal handling could also help to shrink the volume/weight of the whole on-board charger system enabling better power density.

Another requirement for OBC systems is to be scalable hence able to deal with different power classes and different AC inputs all over the world. As OBCs are part of the automotive environment, high reliability, and extended product lifetimes under harsh conditions are essential.

Figure 2 shows an on-board charger topology, which is basically an AC-to-DC converter. It comprises of a PFC stage, the DC link, and a DC-DC block.

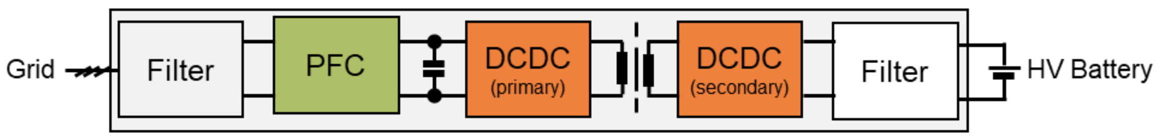

Figure 2 Typical on-board charger system comprising a PFC and a DC-DC stage

An important requirement for the on-board charger system is to achieve high efficiency in the conversion by minimizing power losses. The advantage of the power loss reduction is twofold: a higher efficiency delivers more energy to the battery, and thus the charging process is faster. Secondly, higher efficiency also means lower power losses. This is beneficial for the end customer, but also on-board charger manufacturers since their systems could be built more compact, and thus the power density could be improved.

The conversion efficiency becomes particularly crucial 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 flows 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 should be small and compact but able to handle high power. The latest industry trends show that the chargers have become smaller for a

given power level or that the power level increases for chargers exhibiting the same mechanical dimensions.

Infineon's new high-voltage CoolMOS™ technology, the CoolMOS™ CFD7A product family, for automotive on-board power management systems such as on-board chargers and DC-DC converters has been developed to respond to these requirements. The new series is based on the seventh generation of CoolMOS™ technology tailored to the needs of the automotive industry and can be used in the PFC stage and the DC-DC stage of on-board charger systems and on-board HV-LV DC-DC converters. It offers 650 V breakdown voltage, a fast body diode, and outstanding performance in figure-of-merit comparisons.

With Infineon's long-lasting experience in high-voltage superjunction MOSFET, robustness is guaranteed by design. High conversion performance and high power density can be achieved using the CoolMOS™ CFD7A product family. Additionally, the new CoolMOS™ technology platform was tailored to meet the needs of the rough automotive environment, especially in terms of cosmic radiation. Cosmic radiation is tackled right from the beginning of the development process and the robustness of CoolMOS™ CFD7A is proven by experimental results. CoolMOS™ CFD7A is fully compatible with system voltages up to 475 V_{DC} (*according to voltage class "HV_2b" of "LV123: Electrical Characteristics and Electrical Safety of High-Voltage Components in Road Vehicles"*).

The new technology offers a broad range portfolio of available $R_{DS(on)}$ classes and different package solutions suitable for various power classes or applications.

Today's majority of 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.

4 Topologies in an on-board charging system

4.1 The power factor correction (PFC) stage

Due to the various interoperability requirements, many different PFC topologies are being used within the industry.

The vast majority of PFC stages in OBCs are being operated in continuous current mode (CCM). This leads to the requirement of 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. 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 works in combination with a SiC diode.

In the next chapters, we give 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 chargers systems.

4.1.1 Classical boost PFC

The simplest topology to achieve a power-factor-correction functionality is to use a simple boost converter topology, as shown in Figure 3. This topology is also known as “classic PFC” or “classic boost PFC”.

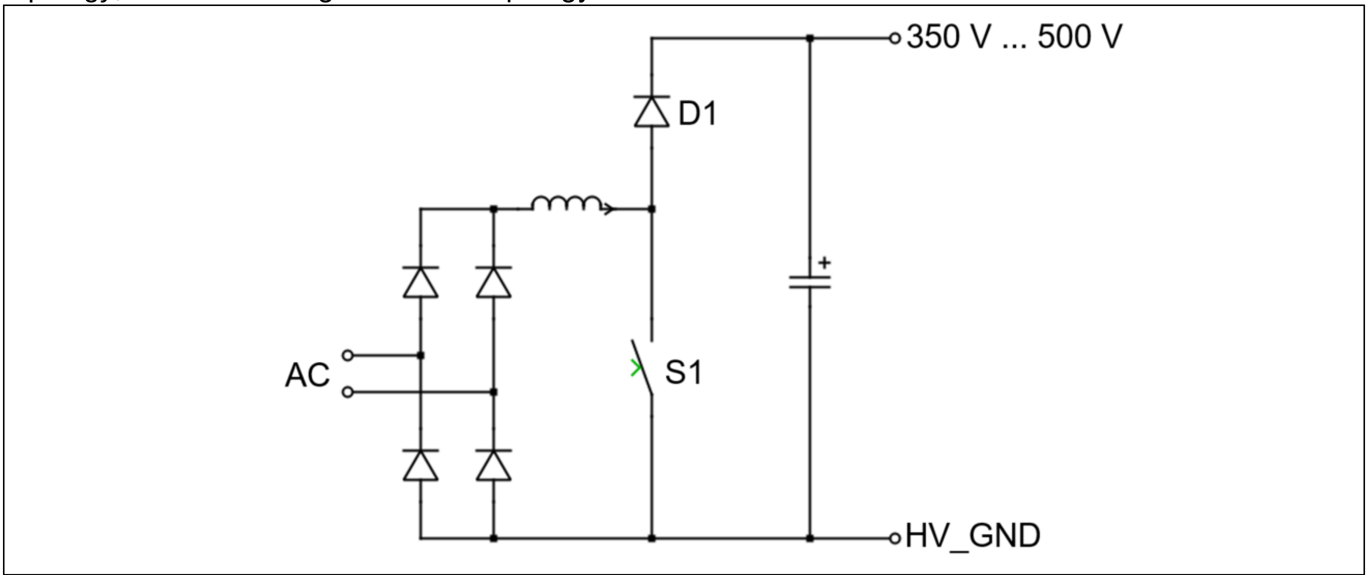

Figure 3 Principle of operation of a boost PFC (a diode across S1 is implied but omitted for a better understanding of the principle operation)

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 the 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.

As mentioned above, a hard commutation occurs within the half-bridge. Therefore, one requirement is that the semiconductors can 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. 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) is perfectly fitting to this topology if a SiC diode is being used as a counterpart. The MOSFET has the advantage of a resistive behavior in the channel, does not suffer from a tail current, and offers lower switching losses over temperature compared to an IGBT. All these advantages translate into lower power losses and, therefore, a higher conversion efficiency.

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.

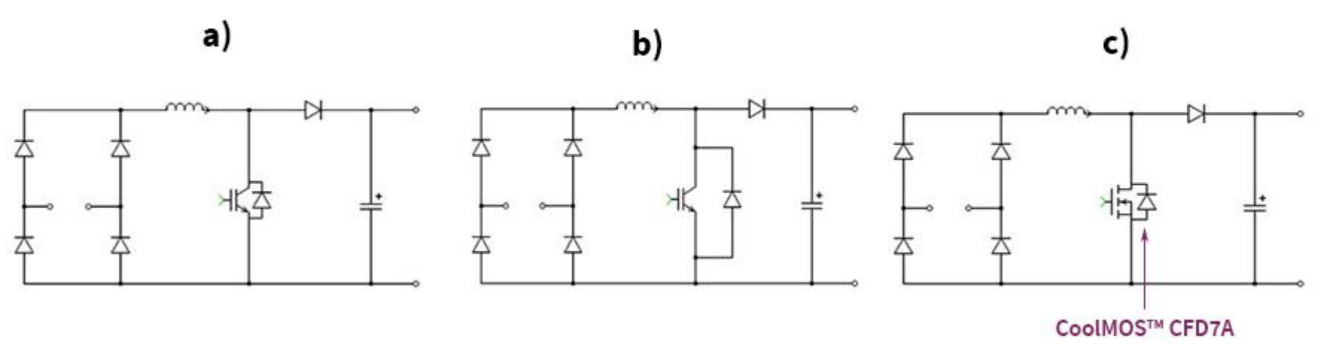

Figure 4 Example power-factor-correction stage for single-phase on-board charger: a) IGBT with integrated SiC diode, b) single IGBT with external protection diode, c) CoolMOS™ CFD7A (with intrinsic body diode)

4.1.2 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 5 shows the “dual-boost PFC” topology, which is a prominent example of a bridgeless PFC rectifier.

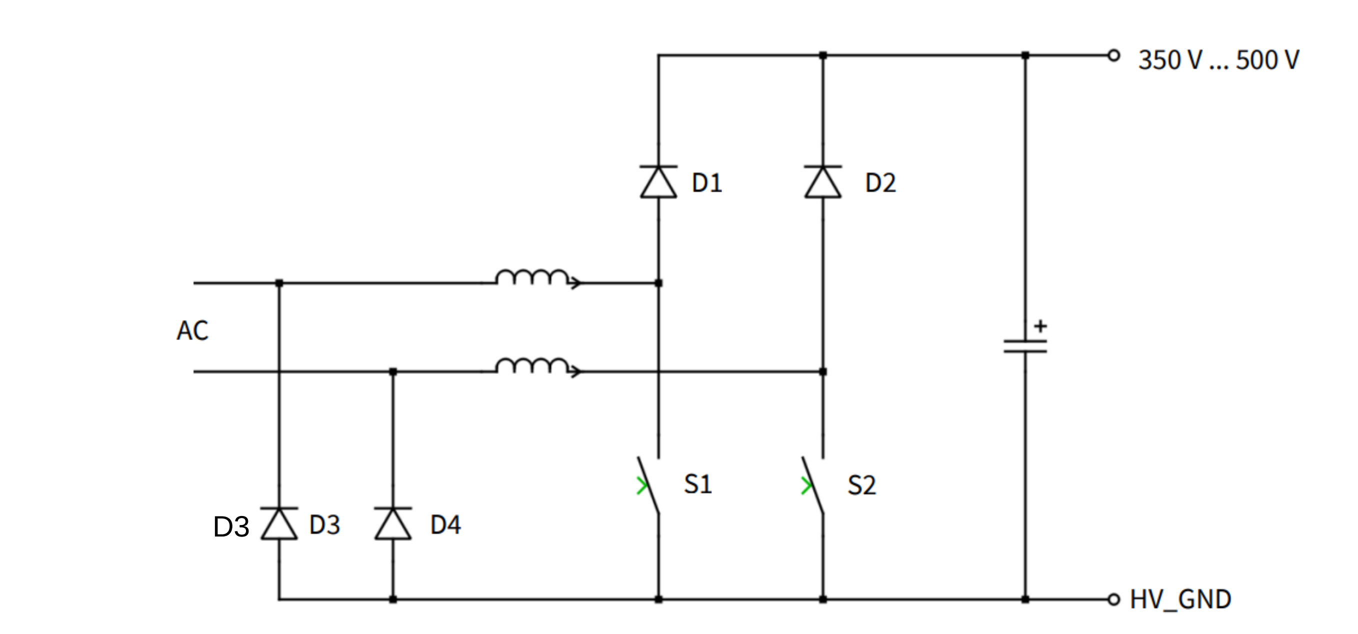

Figure 5 Dual-boost topology as a representative for a “bridgeless” PFC topology

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. The obvious difference on topology level is that each AC semi-cycle 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 is an optimal choice for “S1” and “S2”. The suggestion for “D1” and “D2” is to use the CoolSiC™ Schottky diode Gen5, whereas “D3” and “D4” could be PN rectification diodes. An additional lever to raise the efficiency is to use active switches in parallel to “D3” and “D42 for phase rectification.

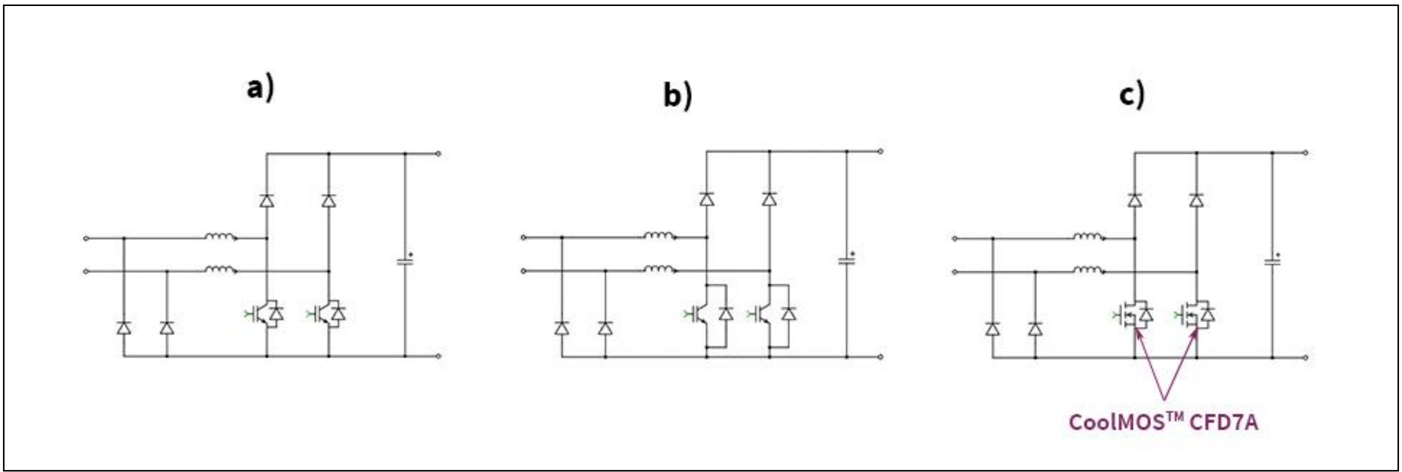

Figure 6 Dual-boost topology with a) IGBT with integrated SiC diode, b) TRENCHSTOP™ IGBT H5 with external PN diode, and c) CoolMOS™ CFD7A

4.1.3 Totem-pole PFC

A common topology for bidirectional on-board chargers is the so-called "totem-pole" PFC topology, shown in Figure 7. The concept of this topology is to replace all diodes with active power switches to enable a bidirectional power flow capability. Another advantage of using active switches instead of diodes is, that the efficiency rises as well. Nonetheless, this modification also raises the complexity, since more power semiconductors must be controlled within the circuitry.

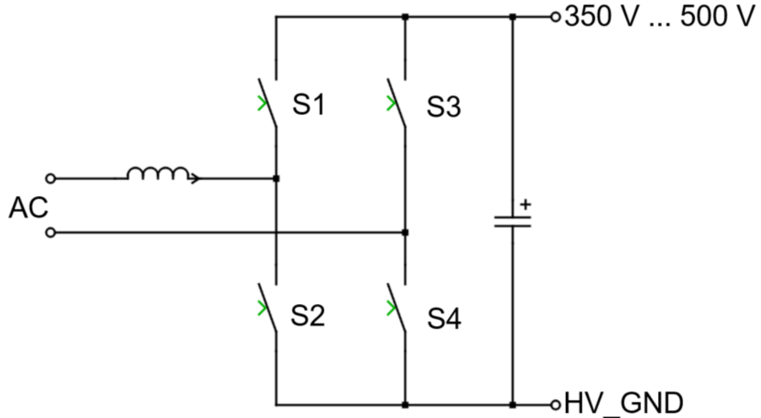

Figure 7 Totem-pole PFC topology

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 can withstand hard-commutation of the load current in between two active switches at high frequency. Therefore the best choice for "S1" and "S2" is to use the TRENCHSTOP™ H5 IGBTs or the CoolSiC™ MOSFETs.

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 crossings of the AC input (zero voltage switching).

One common way to realize a totem-pole PFC is to use for IGBT switches for positions "S1", "S2", "S3", and "S4". Infineon's high-speed TERNCHSTOP™ 5 IGBT is the best IGBT choice for on-board charger systems. It is recommended to use CoolMOS™ CFD7A for the slow switching half-bridge ("S3" and "S4") to leverage the efficiency further. This usage of superjunction MOSFETs in the phase rectification leg is possible due to the soft-switching nature at AC frequency. Thanks to their ultra-low reverse recovery charge, the CoolSiC™ MOSFETs can be used to realize a hard-switching totem-pole PFC comprising of four SiC MOSFETs. Another advantage of CoolSiC™ MOSFETs is that they are offered with 1200 V breakdown voltage. This enables support for higher DC link voltages (above 650 V).

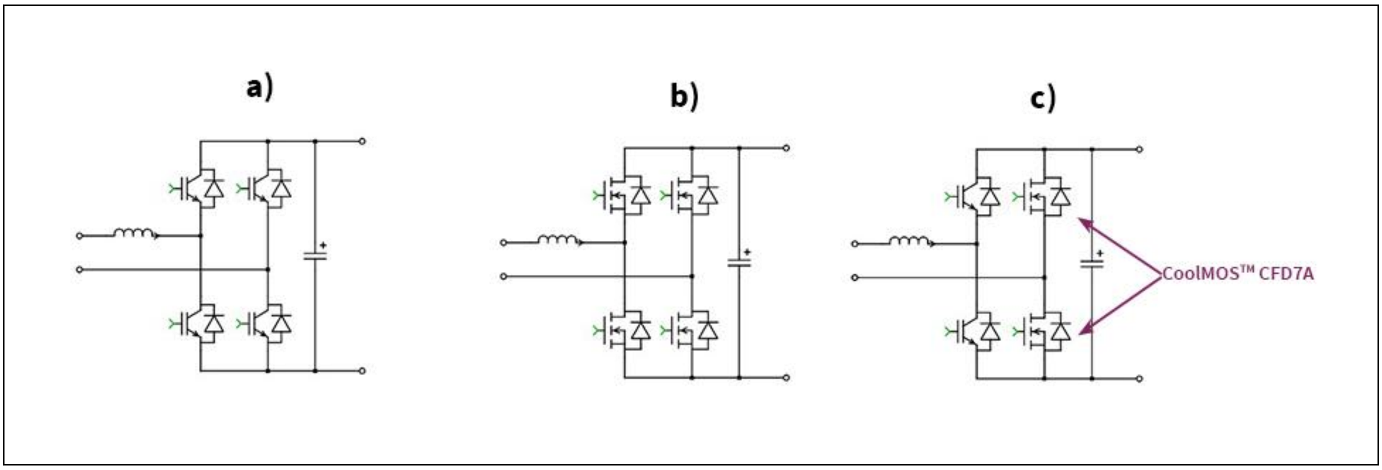

Figure 8 Totem-pole PFC with a) IGBTs, b) SiC MOSFETs, c) with IGBTs and CoolMOS™ CFD7A (as phase rectifier)

An improvement in the conversion efficiency can be achieved if the soft-switching technique is exploited. Soft-switching also enables the usage of CoolMOS™ in full-bridge topologies. 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 decreases in comparison to a CCM PFC. This could be compensated by an interleaving of several soft-switching PFC stages.

4.2 The DC-DC converter stage

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

The most common topologies are soft-switching phase-shifted full-bridge converters and LLC converters. Due to the superior switching speed, MOSFETs play a dominant role in modern DC-DC converters.

4.2.1 Phase-shifted full-bridge (PSFB)

A commonly used DC-DC topology, the so-called "phase-shifted full-bridge," is shown in Figure 9. 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.

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.

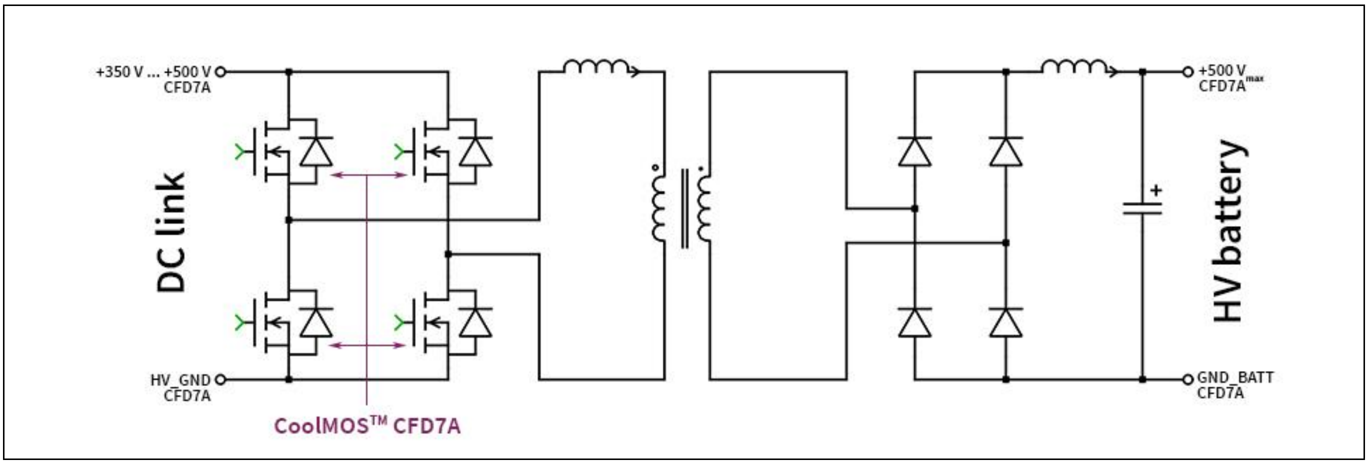

Figure 9 The phase-shifted full-bridge topology comprising diodes on the secondary side

A significant advantage of this topology is its high efficiency since it can be operated in soft-switching over a wide load range. That means that energy stored in the parasitic capacitances of the MOSFETs could be re-cycled, which lowers the power losses, reduces heat dissipation, and elevates the conversion efficiency. An additional inductor on the primary side (L_r) ensures the soft-switching of the MOSFETs in cooperation 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 MOSFET 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 the 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 being 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 is able to achieve a wider conversion ratio than the LLC converter.

The secondary side has the task to perform 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 9) or a center-tapped transformer. For both variants, either diodes or active MOSFETs are commonly used.

The phase-shifted full-bridge 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 10 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.

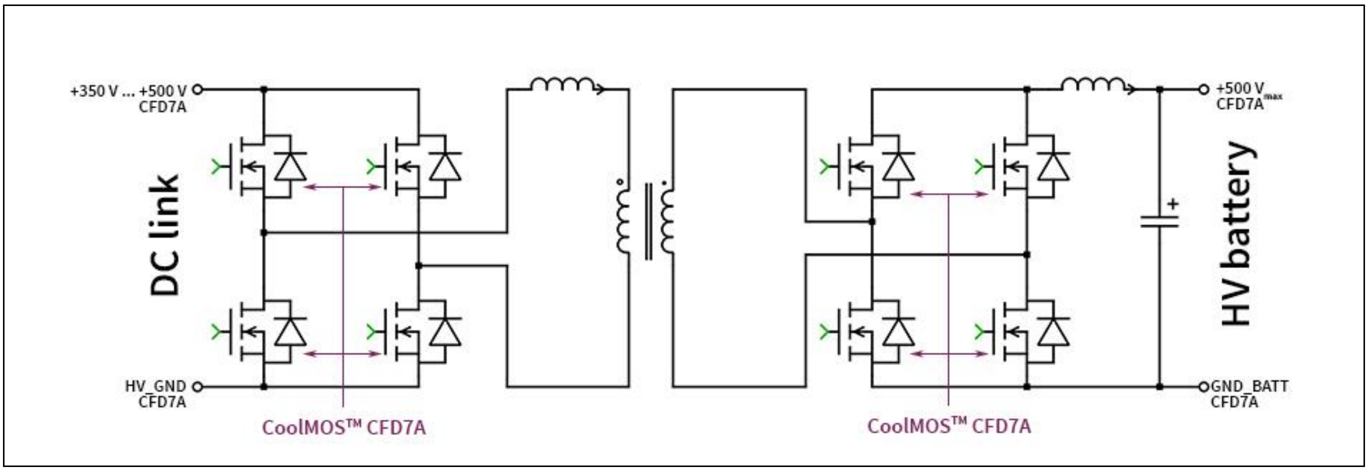

Figure 10 Phase-shifted full-bridge topology for bidirectional usage

4.2.2 LLC topology

The LLC topology is ideal for reaching highest conversion efficiency. Compared to the PSFB, this topology is able to achieve an even higher efficiency resulting in lower losses during operation. Thus, even higher power density converters could 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 factor two higher voltage compared to a half-bridge LLC converter. Due to the doubled voltage, it is possible to transfer the double amount of power for a given transformer size. Nonetheless, this principle is valid for all half-/full-bridge converters and not a unique feature of LLC converters. Nonetheless, it is more common to use half-bridge LLC converters for lower-power applications.

Another advantage of well-designed LLC topologies 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. The CoolMOS™ CFD7A is the perfect choice for this topology as well 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 a variable duty cycle of a pulse-width modulated control signal. Due to the required frequency range, the design for EMI filters might become more challenging. Furthermore, synchronization of parallel stages of LLC converters become more complex because it is difficult to dictate current sharing. Also, the LLC topology suffers from a somewhat limited conversion rate.

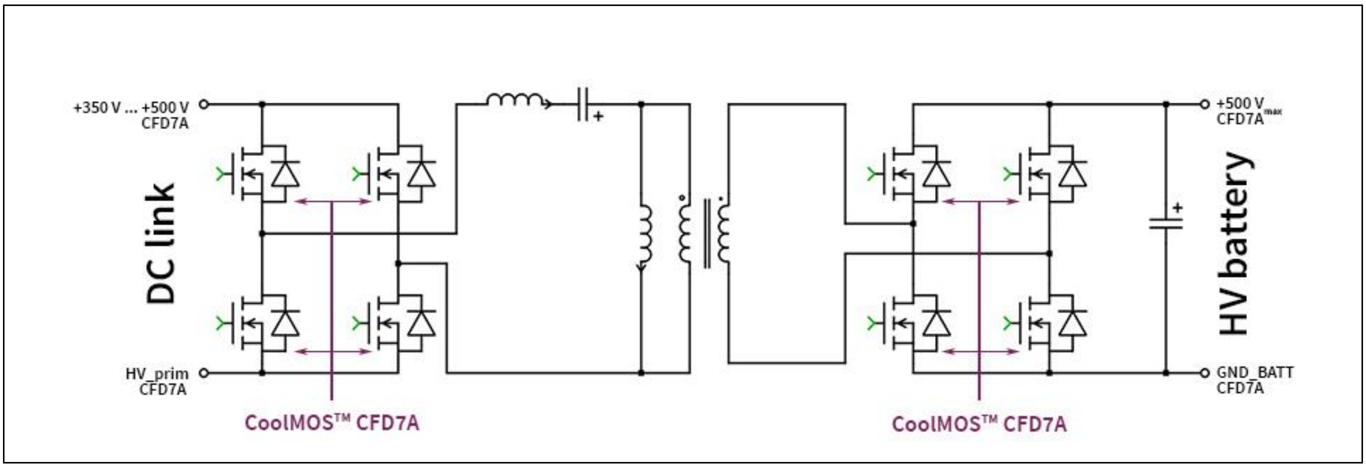

Figure 11 Full-bridge LLC converter for unidirectional operation (with active synchronous-rectification on the secondary side)

Figure 11 shows a typical full-bridge LLC converter used in on-board chargers. The secondary side of the converter is also designed as a full bridge. To achieve the best performance, CoolMOS™ CFD7A MOSFETs should be used on the secondary side instead of diodes.

4.2.3 CLLC topology

If the on-board charger is required to support bidirectional power flow, a small modification of the LLC's resonant tank is required: additional passives on the secondary side leads to a symmetrical resonant tank behavior.

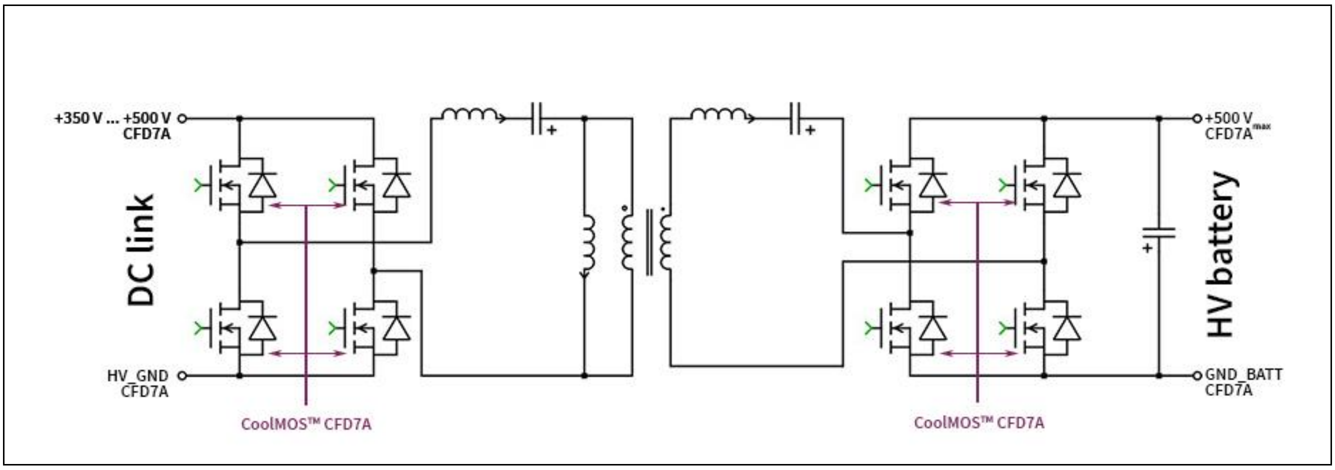

Figure 12 Full-bridge CLLC converter for bidirectional operation

4.3 On-board chargers with three-phase AC input

As aforementioned, 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.

4.3.1 Three-phase PFC

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

4.3.1.1 Stacking of single-stage modules

A common way to achieve three-phase support is to “stack” individual single-phase modules. This is being achieved by referring the AC phases to the neutral line on the input side.
Figure 13 gives an example of this stacking. It shows three single-phases 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 14.
The big advantage of this concept is that it can support single- and three-phase operation: a phase-switch on the AC input selects to operate the modules in parallel for single-phase or in a three-phase configuration as shown below. Also, the DC link voltage remains in the range of 400 V, which enables the usage of a subsequent single-stage DC-DC utilizing 650 V devices.

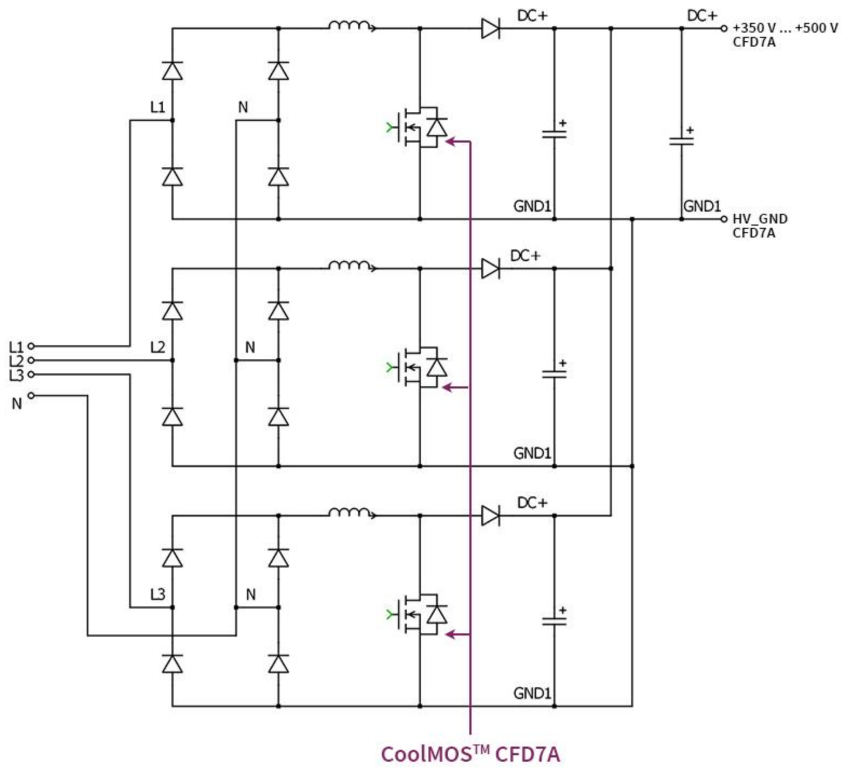

Figure 13 A three-phase PFC stage realized by stacking three individual single-phase PFC stages. The single stages are classic boost PFC comprising CoolMOS™ CFD7A

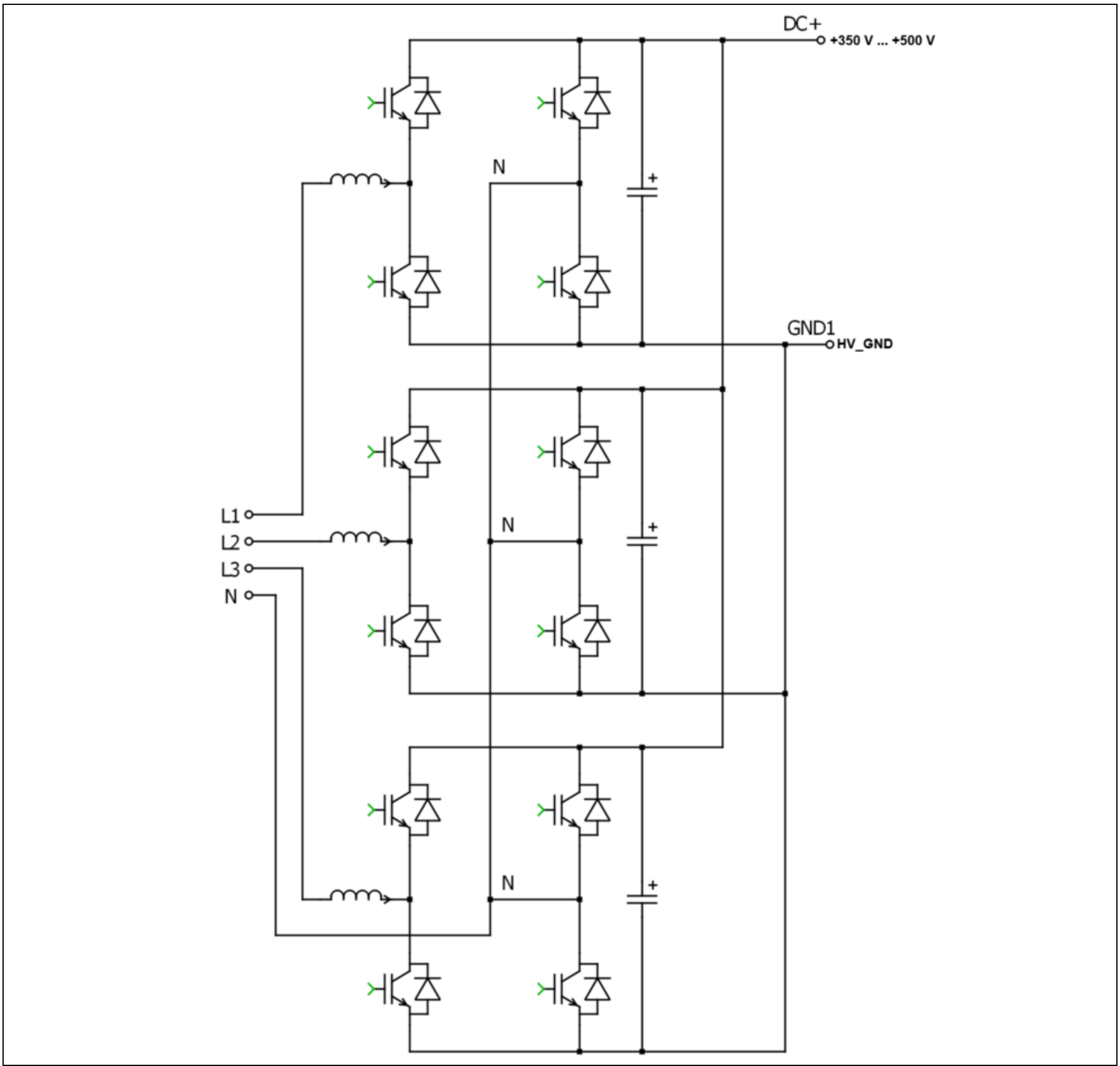

Figure 14 A three-phase PFC realized by stacking three individual totem-pole stages

4.3.1.2 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 a “three-leg bridge”. Figure 15 shows this topology for 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 16 depicts this extension.
Commonly, the operation mode is continuous current mode – therefore, semiconductors such as SiC MOSFETs are required to withstand the continuous hard commutation.

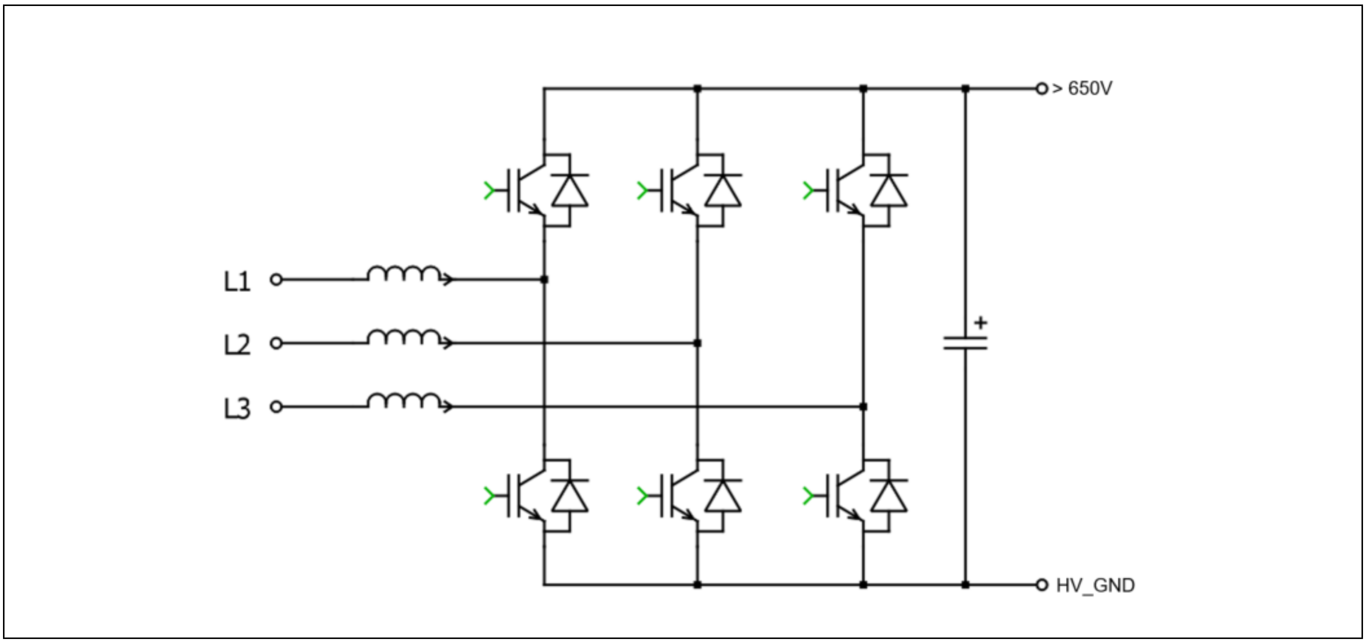

Figure 15 A "true" three-phase PFC topology (without using the neutral line)

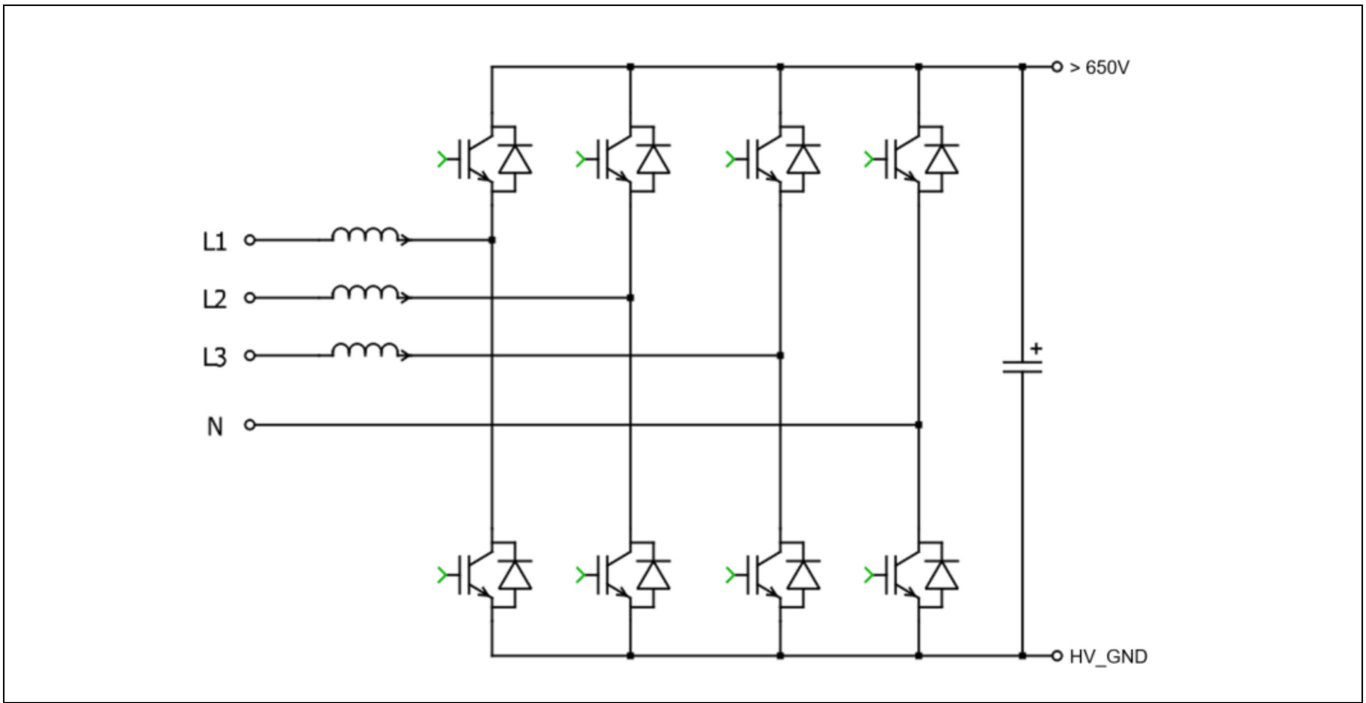

Figure 16 A three-phase PFC topology with support for single-phase operation comprising the neutral line

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 MOSFET family for these PFC stages.

4.3.1.3 Vienna rectifier

Also, dedicated topologies for three-phase AC systems can be used besides these topologies. The Vienna rectifier topology is a renowned representation of a “true” three-phase topology.

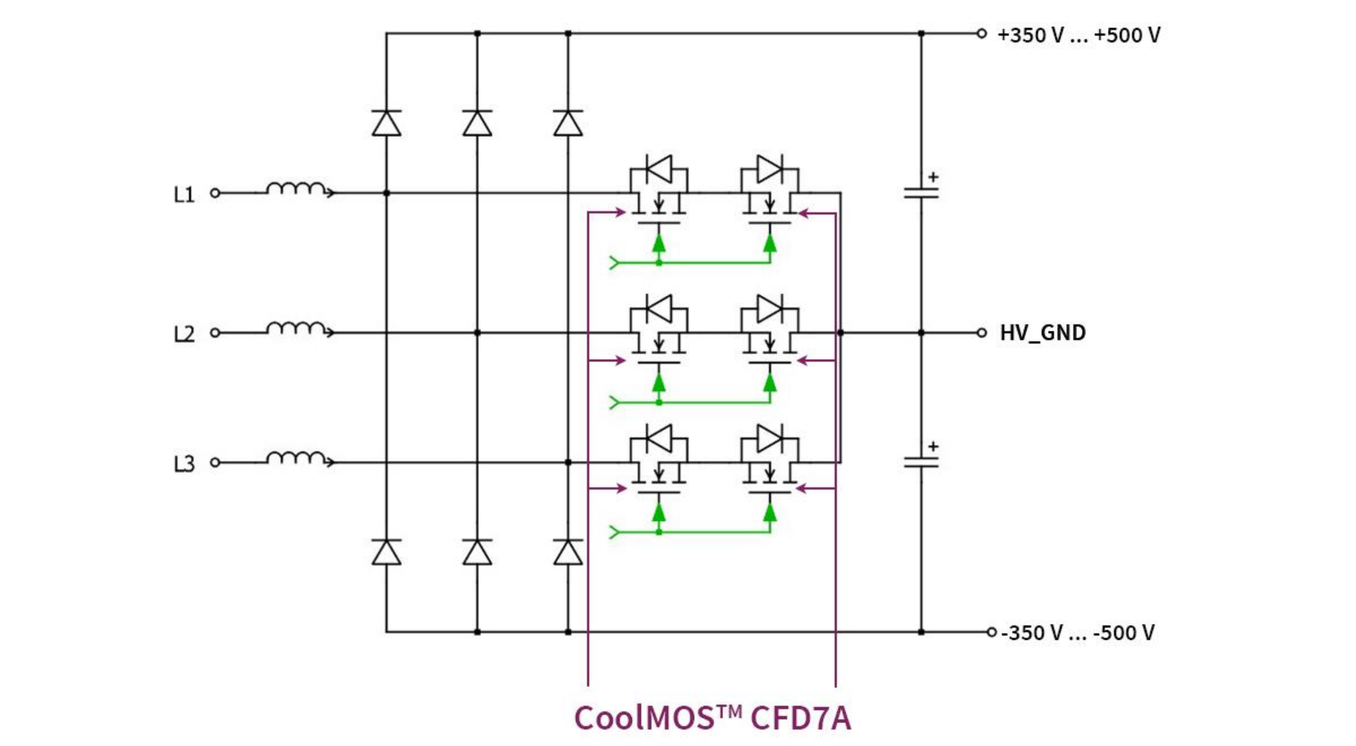

Figure 17 Vienna rectifier topology, a representative of a “true” three-phase PFC topology

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 could also be used for on-board chargers.
The topology utilizes 650 V semiconductor switches in a back-to-back configuration and SiC diodes with greater than 650 V blocking capabilities. Infineon’s recommendation is to use either TRENCHSTOP™ AUTO F5 topology or automotive CoolMOS™ CFD7A as power switches, and the 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. DC side. Due to this center connection, also the DC-DC stage can utilize the 650 V CoolMOS™ CFD7A devices. Figure 18 shows this arrangement.

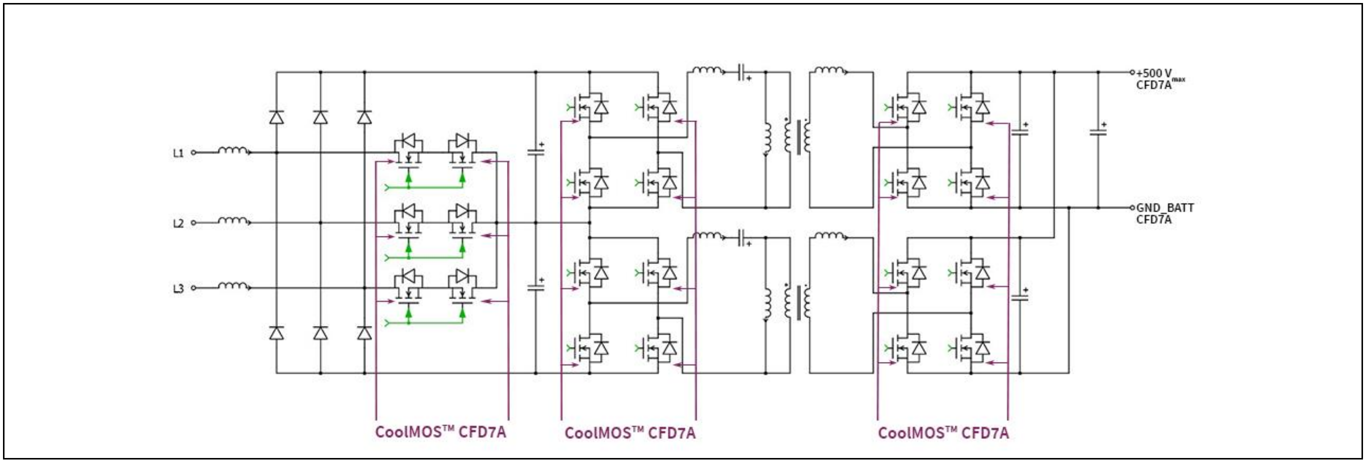

Figure 18 Three-phase on-board charger: Vienna rectifier PFC with subsequent LLC stages

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