Meeting the design requirements for bi-directional-capable on-board charging (OBC)

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Abstract

As the automotive industry shifts from internal combustion engines (ICE), powered by fossil fuel, to electric drivetrains, consumers must adapt their approach to 'fueling' their vehicles. In fact, there is no longer any requirement to use dedicated fueling stations. Instead, plug-in hybrid and battery electric vehicles (xEV) can be charged either at home, at the office, or while shopping using on-board charging (OBC) solutions. For automotive OEMs, efficiency, size, safety, quality, and weight remain design priorities, along with overall cost. In addition, they are increasingly planning to support bi-directional power transfer to support powering consumer appliances, vehicle-to-home, vehicle-to-grid (V2G) applications, and even jump-starting of other vehicles.

This white paper explores the changing expectations of OBCs, the semiconductor technologies used and their unique capabilities, and how such designs are tackled using today's preferred power conversion topologies.

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Introduction

Drivers rarely worry about running out of fuel between gas stations except in the most rugged and isolated areas, but range concerns for electric vehicles have existed since their inception. While charging stations are more common, both DC chargers and AC wallboxes are being integrated into new housing developments, there is still room to improve the range and charging speed of xEVs. The migration to electric vehicles also means looking at new use cases. With the move to higher battery capacity, an opportunity opens up to use bi-directional on-board chargers (OBCs), allowing use of xEVs as a power source when needed.

Role of OBCs in xEVs

OBCs address the anxiety associated with off-board charger availability. Although off-board chargers are fast, they are only available at dedicated charging stations. Sometimes they are proprietary (linked to a single automotive OEM), or access is limited (charged energy up to 3 times more expensive as normal household electricity price). Additionally, the journey and waiting time while charging may not be acceptable as part of the daily commute. The addition of support for bi-directional power flow in OBCs is expected to support an array of novel use cases, turning the xEV into a mobile power bank for grid balancing, jump-starting other xEVs, and even providing off-the-grid power in remote locations (camping, DIY, emergencies).

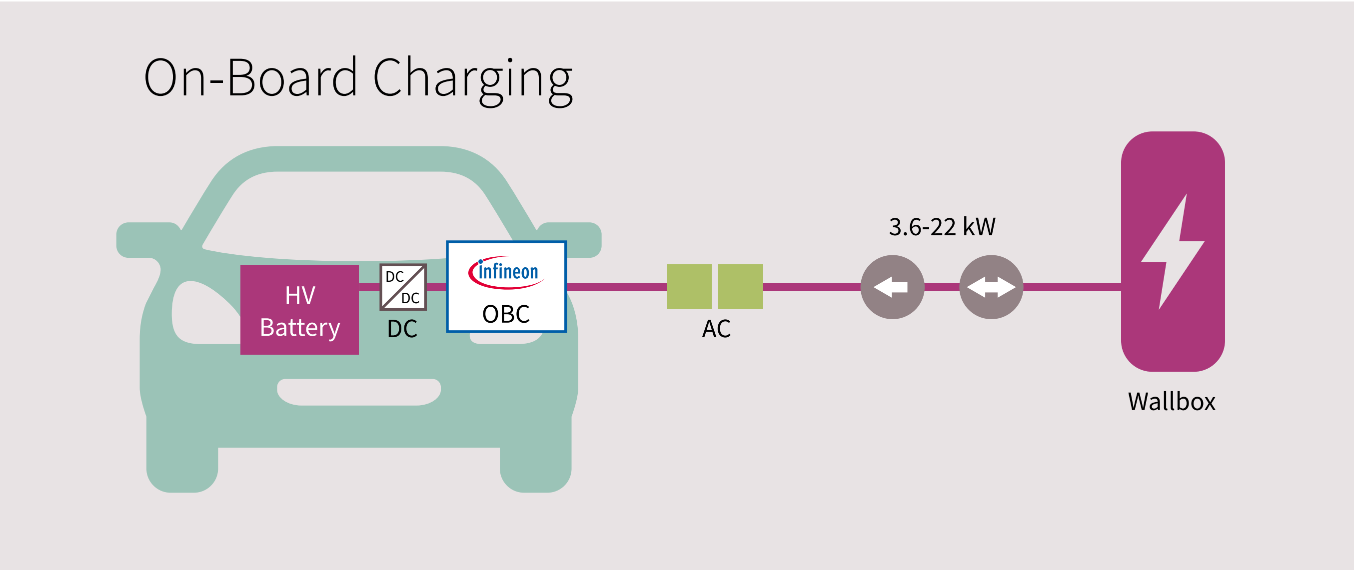


Figure 1: Overview of a typical AC-input on-board charging implementation as used at home or at a commercial parking lot.

OBCs target use at home, such as in a garage, or a parking lot, while working or shopping. A full charge takes around 6-8 hours at power levels of 7.2 kW. Charger power levels trend upward towards 11kW or even 22kW in the premium BEV platforms. Their operation principle is quite simple: 115 / 230 VAC with 1, 2 or 3 phase is taken from a wallbox, then converted into DC power for charging the batteries. The block diagram of a typical bi-directional OBC which consists of an active power factor correction (PFC) stage followed by a DC/DC converter.

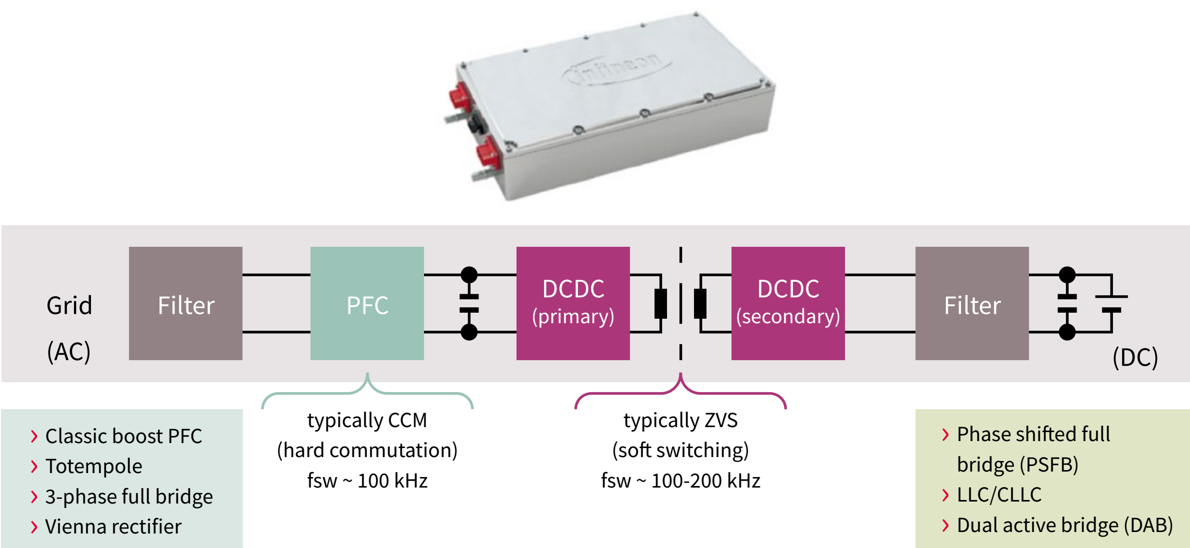


Figure 2: OBC block diagram with AC input on the left, active PFC, followed by a DC/DC converter providing the charge to the battery.

What makes silicon carbide suitable for OBC?

It is estimated that, within ten years, approximately 30% of all manufactured cars will be xEVs. Furthermore, emissions standards are tightening around the world. These changes, coupled with the expected massive rollout of xEVs, will result in an increased demand for both on-board (and off-board) charging systems. However, these charging systems cannot depend on yesterday's technology to meet tomorrow's needs.

One critical factor in modern charging system designs is the choice of a power semiconductor. While existing designs make extensive use of silicon power devices, the introduction of wide-bandgap (WBG) technology such as silicon carbide (SiC) opens up a range of new design approaches. Additionally, SiC-based designs achieve higher efficiencies over silicon-based designs, resulting in lower energy losses and related heat generation. This can be leveraged to construct OBCs needing less physical space. These smaller and lighter SiC based charging systems also offer faster charging times at a lower system cost. Due to the smaller volume required, OEMs have more freedom of vehicle design that supports their scalable xEV platform approaches, while the Tier suppliers can optimize overall system cost.

Figure 3 below compares the differences in material properties between silicon and SiC, highlighting how they translate to device- and system-level benefits. Additionally, the figure describes the value SiC can offer in the end-application.

Material properties

Parameter	Symbol	Unit	Si	SiC
Bandgap	E_g	eV	1.1	**3.3**
Critical electric field	E_c	V/cm	$0.3 * 10^6$	**$3 * 10^6$**
Electron saturation velocity	V_s	cm/s	$1 * 10^7$	**$2 * 10^7$**
Electron mobility	µn	cm²/V*s	1,350	**947**
Thermal conductivity	K	W/cm*K	1.5	**5**

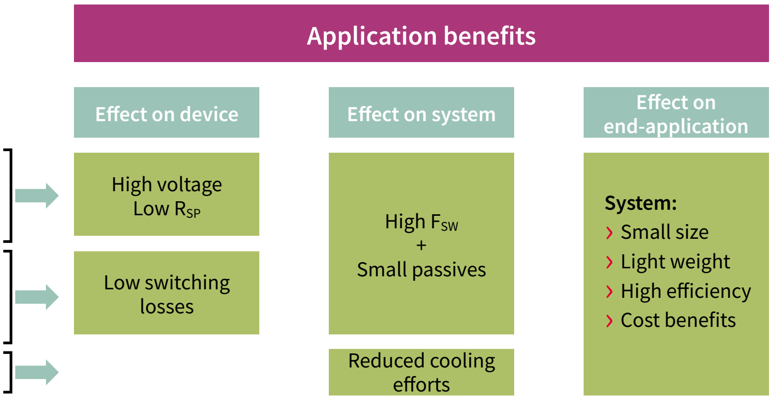


Figure 3: The physical properties of SiC show significant improvements over silicon power devices that translate into clear application benefits.

Compared to conventional silicon power devices, and depending on the topology used, SiC can offer increased power density, higher system efficiency, simpler cooling design and lower system cost. Although relatively few automobiles benefit from SiC today, the change within the automotive industry has only just started with the question being more "Where shall we use SiC next?" rather than "Why should SiC be used?"

With an extensive and competitive product portfolio, coupled with a global supply chain, Infineon Technologies is enabling its customers to define and design their OBC architectures optimally.

This is supported in a Product to System (P2S) approach by providing power devices with solutions for gate drivers, sensing, and control. Customers also profit from our team's application understanding and market insights. Infineon is already collaborating with its customers on next-generation SiC solutions and technology, tailoring ongoing development to specific target application needs.

Accommodating bi-directional power conversion

xEVs are still maturing as a product, and existing OBCs are still unidirectional, i.e. G2V (grid-to-vehicle) for charging the battery. However, the growing expectation is that OBCs will need to support bi-directional power conversion. The immediate and longer-term trends are:

- V2G (vehicle-to-grid) – stability of the electrical grid is a challenge in many parts of the world, especially at the extremes of summer and winter as citizens turn to cooling and heating appliances to make life bearable. Energy suppliers use various techniques to fill these jumps in demand, ranging from hydroelectric energy to fossil-fuel generators. One of the biggest challenges is providing electrical power quickly enough to avoid brown-outs. Several countries, notably Australia[1], already use of huge banks of batteries to respond rapidly to pending brown-out conditions. With potentially millions of xEV batteries connected to the grid, bi-directional OBCs could contribute by delivering or consuming (small amounts) of energy to help balance the energy supply under such conditions. xEV owners could even benefit from the contribution to grid stability (sale of vehicle's energy back to the grid).

- V2L (vehicle-to-load) – with a huge power source built into the xEV, it makes sense to enable drivers and their passengers to power their electrical appliances. Utility vehicles are a prime example and could be used during recreation to power entertainment equipment, electric grills, or even rice cookers while camping. Tradespeople and DIY enthusiasts can also use their electrical power tools in remote locations. This use case is currently more common in China and Asia Pacific than in other markets.

- V2V (vehicle-to-vehicle) – Jump-starting an ICE vehicle is much less challenging than for xEVs. Rather than provide enough power to turn a starter motor, a low-charge or discharged xEV requires recharging. V2V is a longer-term feature requiring bi-directional support from OBC implementations, along with standardization so that it is compatible across vehicle manufacturers.

- V2H Home storage in conjunction with home PV system.

- V2G Island Mode – In cases of catastrophe, such as extreme weather, power to homes and businesses could be lost entirely. Available xEVs could be used to provide electrical power in such situations until grid power is restored. (While this is theoretically possible with the availability of bi-directional OBC, it is a longer-term capability as it additionally requires a method for the OBC to synchronize with the restored AC grid before the breakers are opened or closed. Also needed for V2G and V2H).

1 https://www.bbc.com/news/world-australia-42190358

Bi-directional power converter topologies

Bi-directional power converters are well understood, but there are a range of challenges involved in bringing them to market in the context of the automotive space. Not only Reliability and functional safety are essential for automotive and electricity generation standards, but also for keeping the well being of the driver and occupants. Finally, the result must also meet the demanding pricing common to all automotive applications.

One approach is to develop two separate converters, each tuned to the specific needs of the application. The result, however, leads to a bulky solution with a high component count, making it challenging to meet the design needs of an automotive application. One optimal solution is a Totem-Pole PFC (TP-PFC) coupled with a Dual Active Bridge (DAB) topology, allowing the use of soft-switching and low device count while also offering high efficiency and the necessary galvanic isolation.

These half / full bridges are connected to an inductor and high-frequency transformer that also sets the conversion ratio, respectively. The control method varies according to the demands of the application and the voltage range supported on either side.

One typical approach is to control both bridges using a complementary pulse-width modulated (PWM) signal, typically from a microcontroller (MCU). Modification of the phase of the signals applied defines the direction of power transfer.

Another common topology is the CLLC resonant converter. This approach is suited to high-frequency switching also thanks to its galvanic isolation and support of soft-switching. Because of this, smaller passives can be used that result in a compact design. The use of capacitors on both sides of the full bridges supports bi-directional current flow.

The basic design for a resonant CLLC converter, as shown in Figure 4, is well suited to single-phase-input OCB designs supporting common charger power classes of between 3.6 kW and 7.2 kW. A DAB converter does away with C_{Pri}, C_{Sec}, and $L_{r\text{-}Sec}$ in the design shown. The diagram also includes the TP-PFC stage.

Currently, 650 V silicon superjunction MOSFETs, such as the CoolMOS™ series, are well suited CLLC-based DC/DC converters connected to 400 V batteries, one of the industry's current standard voltages. With the growing availability of WBG, designers are also considering 750 V CoolSiC™ MOSFETs as an attractive option, making use of their robustness, low and stable $R_{DS(ON)}$ over temperature, and higher V_{DS} as some OEMs move to 500 V batteries.

In the TP- PFC, 650 V TRENCHSTOP™ 5 + Rapid Diode Automotive IGBTs are a fair performance-low cost option, with CoolMOS™ MOSFETs in the return path. Alternatively, 650 V CoolSiC™ Hybrid Discrete IGBTs that combine the benefits of a SiC Schottky barrier diode co-packed with an IGBT can be used. These power devices exhibit a significant reduction in E_{on} and other switching losses compared to traditional IGBTs. As vehicles move to higher battery voltages (500 V), the 750 V SiC MOSFETs are the only option.

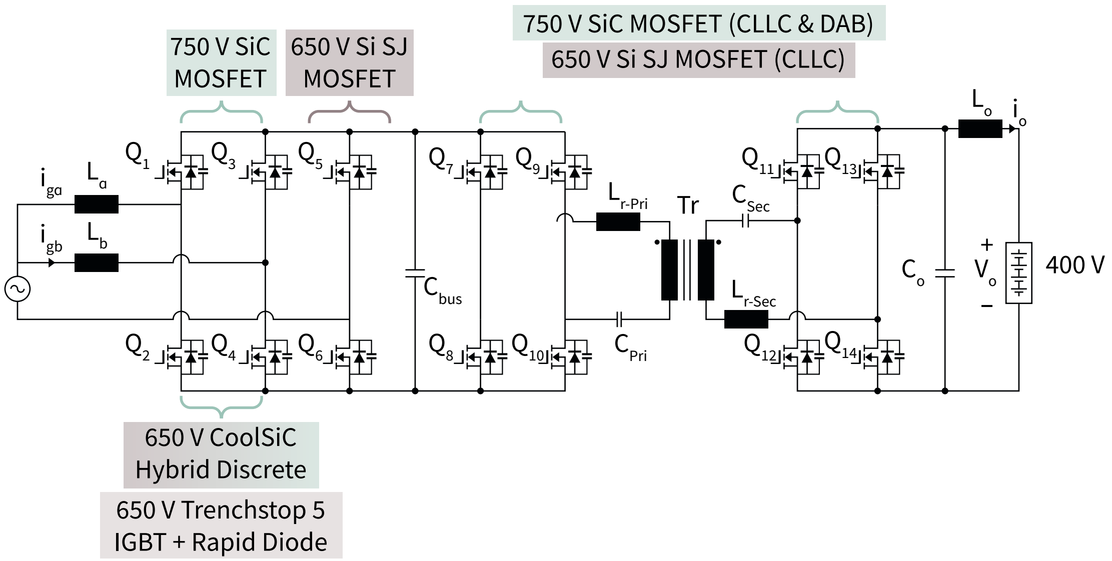


Figure 4: A PFC with CLLC topology suited to bi-directional OBC supplied by a single-phase AC supply. Stacked it can also be used with three-phase supplies.

Both the DAB and CLLC approaches are also suitable for three-phase OBC implementations by implementing parallel / stacked converters. This allows OBC power classes from 11 kW (3 × 3.6 kW) up to 22 kW (3 × 7.2 kW) to be covered.

OBCs supporting true three-phase AC grid inputs and higher voltage batteries, such as 800 V, benefit from the availability of 1200 V CoolSiC™ MOSFETs. Traditionally the domain of IGBTs, SiC MOSFETs enable higher switching frequencies to be used, leading to more compact and lower-weight designs. The improved efficiency and related drop in heat dissipation provide designers more flexibility in the overall design, especially thanks to innovative packaging that simplifies heat management. Like the single-phase design, three-phase designs can also be configured in parallel implementations to support higher power delivery and, thus, shorter charging times.

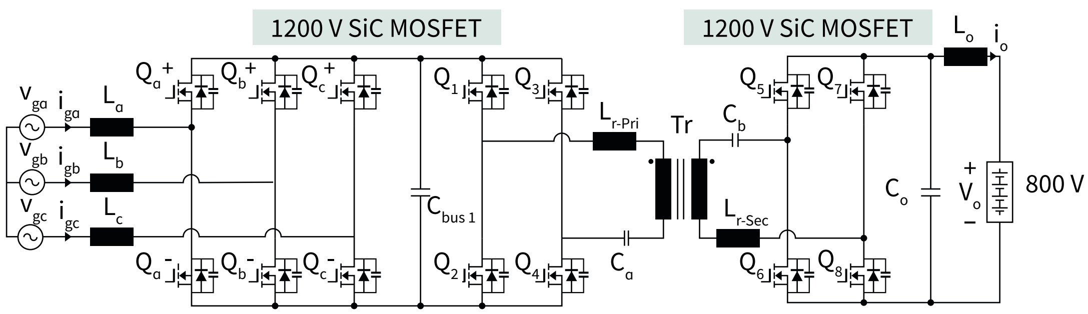
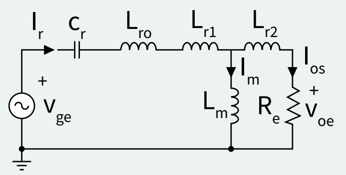


Figure 5: A three-phase PFC with CLLC DC/DC resonant converter targeting 800 V batteries using CoolSiC™ power devices.

Designing resonant LLC converters

LLC converter topologies have long been recognized as an optimal DC/DC conversion approach in applications converting AC grid power to a DC sink. Part of the attraction is their wide voltage adjustment range and handling of load variations. The option to use soft-switching offers a secondary benefit of minimal EMI (electromagnetic interference) challenges while the transformer delivers the required galvanic isolation. An analysis of existing OBC designs and ongoing research into automotive chargers confirms this approach. One of the challenges of an OBC is that the input side must handle a wide range of AC voltages and frequencies depending on the region of the world the xEV is used. The output side is, by comparison, more straightforward, as the load is known and remains unchanged over the xEV's lifetime.

In addition to quantifying the input and output requirements, designers also need to specify the power transfer planned and possible switching frequencies[2]. From here, resonant circuit components can be defined, including the stray inductance of the high-frequency transformer's secondary. It is essential to work closely with an experienced transformer supplier at this stage to perform accurate simulations of the design and attain the optimal transformer (Figure 6). Combining the LLC design with the transformer model allows rapid iteration to fulfill the design goals.



Equivalent AC circuit with the leakage inductance in consideration.

LLC transfer function

$$M_{gl}^{ac} = \left| \frac{(j\omega L_m)||(R_e + j\omega L_{r2})}{(j\omega L_m)||(R_e + j\omega L_{r2}) + j\omega L_r + 1/j\omega C_r} \times \frac{R_e}{(R_e + j\omega L_{r2})} \right|$$

If $L_{ro} = 0$ (no external inductance), primary stray inductance is used as resident inductance (but the secondary stray inductance has to be taken into account as well)

$$L_r = L_{r1} + L_m || L_{r2}$$

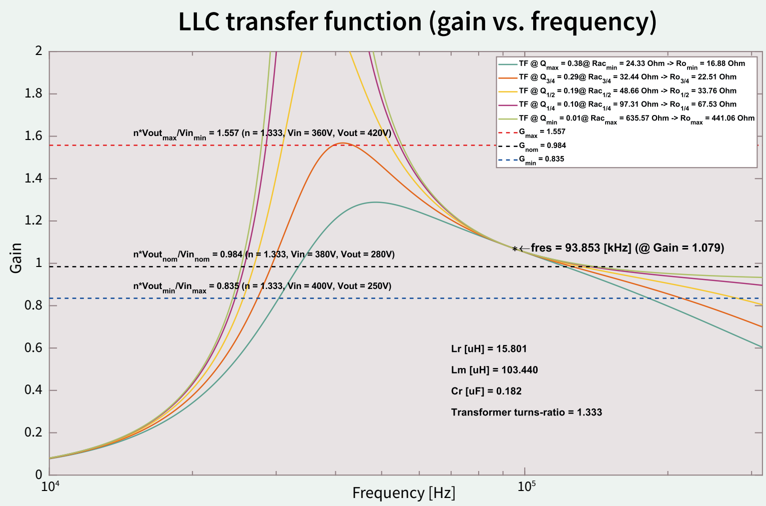


Figure 6: Design of the high-frequency transformer requires great care and support from experienced transformer suppliers.

2 S. Abdel-Rahman, "Resonant LLC Converter: Operation and Design", Infineon Technologies AN 2012-09, September 2012

A suitable control solution is required to handle both the real-time synchronous (closed-loop control) and asynchronous aspects (human-machine interface, monitoring, and emergency shutdown) of the OBC. In the design undertaken (Figure 7), the AURIX™ family of automotive microcontrollers (MCU) was selected powered by an OPTIREG™ PMIC. These powerful, 32-bit multicore MCUs feature a range of peripherals that simplify the high-frequency control of the power devices. The GTM (generic timer module) is ideal for generating dynamic PWM signals for such applications with its 24-bit timer resolution and 5 ns granularity. The integrated a deadtime function (DTM) and an advanced routing capability for data, avoiding CPU -dependent memory accesses. This combinations allows the AURIX™ to respond rapidly to voltage and current changes during OBC operation. The GTM running at 200 MHz can also support operation at up to 1 MHz OBC switching frequency if needed.

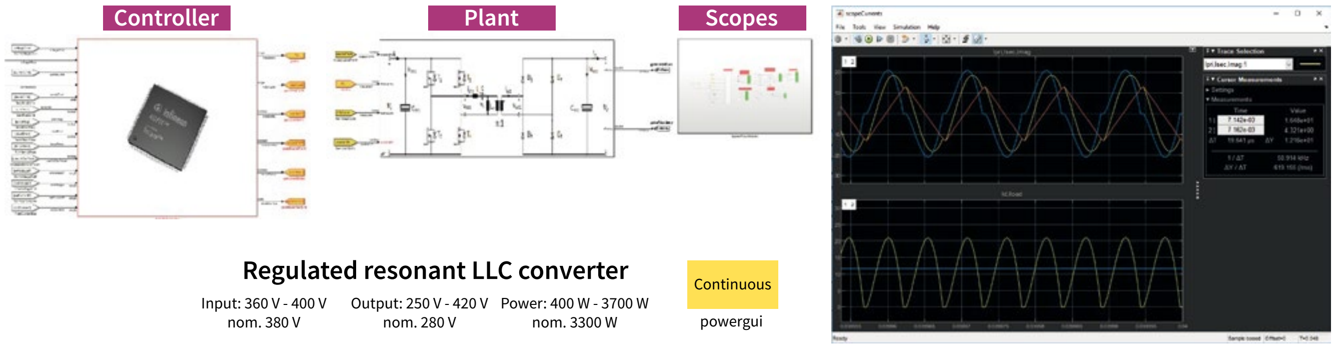


Figure 7: Block diagram of simulated resonant LLC converter as controlled by an AURIX MCU (left) along with the output (right).

The software architecture accommodate the timely update of the DC/DC converter's real-time control while also including the control aspects that demanded by a lower duty-cycle. The approach taken used several state machines (Figure 8). One was tasked with overall control (start-up, command decode, and execution, fault handling, status). A second dealt with handling the closed-loop control (PI controller), soft-start, and driver bootstrapping.

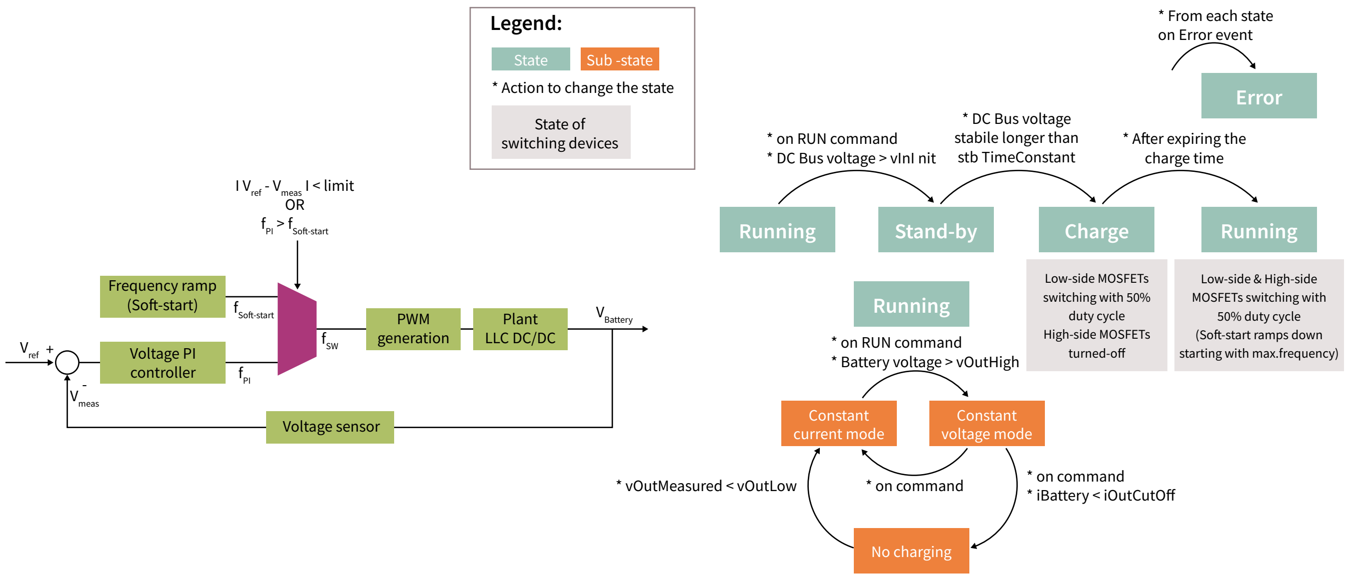


Figure 8: Bootstrapping of the gate drivers and PI control is handled in it own state machine (left), while the remainder of the application resides in a separate state machine (right).

The control interface is implemented in a PC-based graphical user interface (GUI) that provided control and output of status information. Connectivity uses the CAN interface via the transceiver of an OPTIREG™ Lite SBC (system basis chip).

This design uses 650 V CoolMOS™ CFD7A superjunction power MOSFETs in Easy1B press-fit modules for the resonant LLC. These assisted in a simplified heat dissipation concept and allowed an easy exchange for testing purposes. EiceDRIVER™ devices were also selected to drive the gates, providing isolation and level shifting. The LLC's secondary side utilized a self-controlled synchronous rectification gate driver that triggers based upon the forward voltage of the body diode.
To avoid damage during take into operation a software based and a second purely hardware based limit checking and shutdown mechanism was implemented. (outside the specified limits, a fast shutdown was implemented using a hardware sensing approach.) The board was designed in 6-layer 70 µm copper with surface-mount components on the top side and the through-hole components (capacitors, transformer, and power modules) on the bottom. An Control add-on board with AURIX™(-based module allowed the) MCU is placed on top of the LLC. (to be exchanged if required.) During testing, the design demonstrated efficiencies of around 96 % to 97 %.

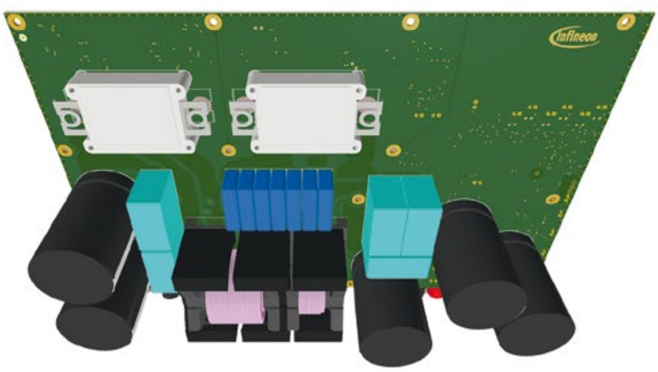


Figure 9: LLC prototype top side (left) and bottom side (right) showing CoolMOS™ CFD7A Easy1B press-fit power modules.

Moving to a bi-directional CLLC

The proof-of-concept approach described is an ideal first step to developing OBCs according to existing uni-directional power-flow requirements and 400 V batteries. The move to support V2G and V2L requires only a few changes on the secondary side. The first is to enable the MCU to control the full-bridge with gate drivers by replacing the synchronous rectification circuitry. The software also requires adaptation in the closed-loop control and support for setting power flow direction. Finally, the secondary side needs the addition of resonant capacitors and an inductor. Support for higher battery voltages or input voltages can be accommodated by moving away from silicon to CoolSiC™ power modules.

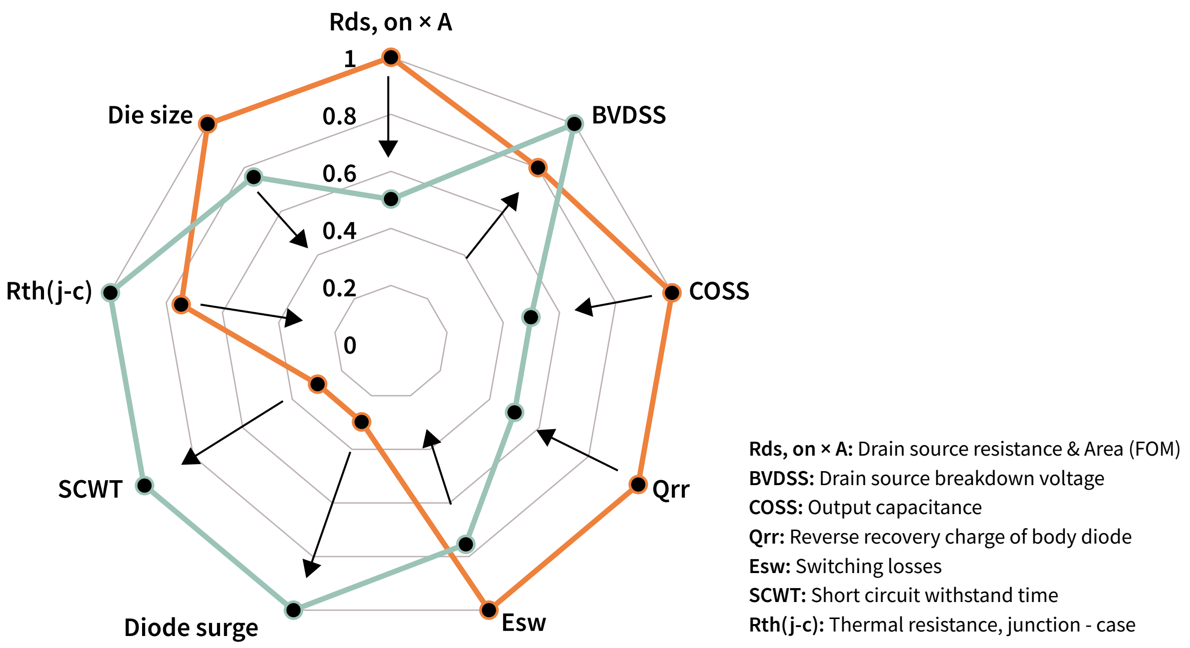


Figure 10: SiC MOSFET characteristics and their potential direction of evolution for OBC application. (Orange indicate situation today, green potential future improvement)

Evolution of SiC MOSFETs OBC

While the current improvements in application performance delivered by SiC MOSFETS are impressive, development teams are already reviewing the requirements for next-generation OBCs. Fueled by market pressure to save energy and costs while increasing functionality, they are looking to future improvements in SiC to attain these goals.

Like any semiconductor technology, device parameter improvements are a collection of tradeoffs. The improvements in device parameters shown in Figure 10 are theoretically achievable and can be expected to appear as development continues. Not all improvements relate to reductions in losses, important as this is. Ruggedness, through higher breakdown voltages, and lower package thermal resistance, resulting in simplified cooling concepts and higher reliability, are both regularly requested. There is also known scope for improving package and SiC MOSFET cell design that will likely yield reductions in $R_{DS(ON)}$ and die area, reducing die capacitances and dynamic losses.

Gallium nitride transistors are another WBG technology driving innovation in power converters, especially in servers, telecom, wireless charging, adapters and chargers, and audio.

CoolGaN™ complements CoolSiC™ technology, supporting voltages up to 600V, and represents a better alternative to silicon for boosting efficiency. Its inherent high-frequency capability has been recognized for enabling miniaturization in applications as diverse as chargers, power supplies, and solar inverters. It is expected that the momentum behind GaN, coupled with customer expectation regards cost-effectiveness and reliability, will see acceptance of GaN across other industries and applications.

The vision of an energy-efficient future depends on using new semiconductor materials, such as WBG power devices. Bi-directional OBC for automotive is just one example that couples the application benefits these new materials deliver – such as greater power efficiency, smaller size, lighter weight, lower overall cost – with support for innovative, green-energy use cases, such as V2G. With its world-leading position offering silicon, SiC, and GaN technology, Infineon Technologies is working alongside its customers to enable this greener, more sustainable future.

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