The key design challenges and optimal solutions

for on-board chargers in electric vehicles

Electric vehicles (EV) are quickly gaining in popularity thanks to a combination of government environmental initiatives, more affordable EV pricing, and consumer climate concerns. While vehicle electronics have increased in sophistication over the years, electric drive trains introduce even more complexity. In addition to the need for high-power electric motor drives, EVs also require a reliable on-board charger (OBC) for recharging the batteries when parked at a public space, office, or at home. In this white paper, we investigate the implementation approaches of OBCs, along with some of the technical challenges associated with their design. The key components used within an OBC are also highlighted, reviewing the substantial impact silicon carbide (SiC) MOSFETs are having on their future implementation.

THE EV INDUSTRY TODAY

The automotive industry is going through its most significant upheaval since the mass-production of private vehicles began. Under pressure to reduce the industry's generation of greenhouse gases, it has been examining alternative motive solutions to complement and even replace traditional internal combustion engines (ICE) powered by gasoline and diesel. Automotive original equipment manufacturers (OEM) have invested heavily in the partial and full electrification of their drivetrains as a result.

Electrically powered vehicles are nothing new. In the late 19th century, electric vehicles (EV) made up around 38% of all automobiles in the US[1], outnumbered by steam-powered (40%) but more popular than gasoline models (22%). They were noted for being clean, quiet, faster to start than steam, and easier to start than the hand-cranked gasoline cars. However, as road infrastructure improved, their speed and range limitation compared to gasoline cars grew more noticeable. As mass-production manufacturing developed, the ICE vehicle rapidly dropped in price compared to the battery electric vehicles (BEV) of the day. By 1935, BEVs had all but disappeared[2].

While the 1960s onward saw a renewed interest in electric propulsion vehicles, it wasn't until mature lithium-ion battery technology became available that the BEV started to be taken seriously again. Advancements in silicon MOSFET and IGBT technology, followed by the availability of efficient wide bandgap (WBG) devices using silicon carbide (SiC) and gallium nitride (GaN), have enabled engineers to get closer to 100% efficiency in power conversion systems than ever before. Powerful, highly integrated microcontrollers (MCU) that form the digital control system of modern power converters, charging systems, and battery management technology have helped to accelerate the attainment of this goal.

In 2021, not only do all the major automotive OEMs now offer vehicles with some level of electrical propulsion, completely new manufacturers have been established to serve this market. Currently, xEVs make up around 12% of all new car sales worldwide[3]. This is predicted to reach 50% by 2031. Hybrid EVs (HEV), cars that combine electric propulsion and ICE, will make up around three-fifths of those sales, while pure BEVs will make up more than one-fifth (Figure 1). The remainder of xEV sales will consist of other alternatives (plug-in hybrid (PHEV) and fuel-cell (FCEV)).

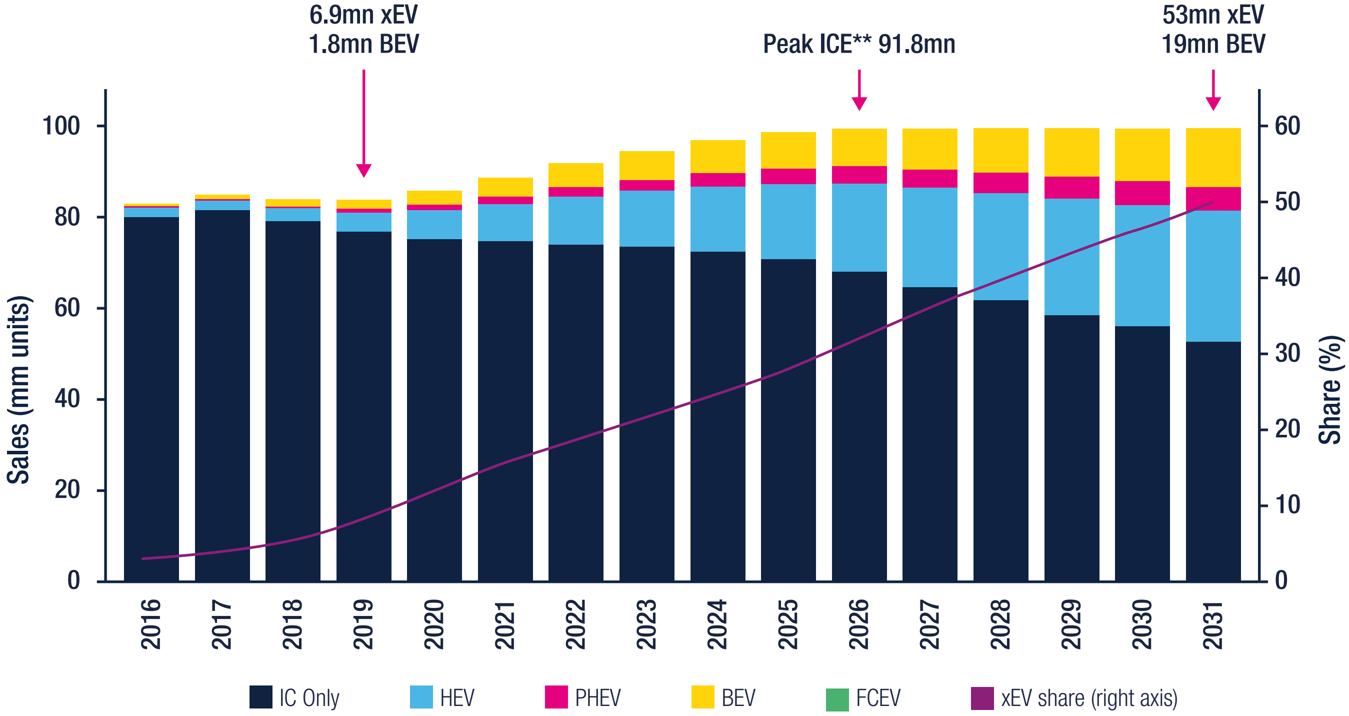

Figure 1: Predicted worldwide sales for xEVs (Source: LMV Automotive)

While some HEVs and PHEVs can still fall back on the ICE for motive power, BEVs rely solely on their battery. Range anxiety, a concern of how far an owner can drive in a BEV before the battery is empty, is a common discussion point. With today's BEVs reaching ranges of above 400 km[4], this concern has been displaced by charger anxiety, a worry of where the BEV can next be charged in a reasonable amount of time. This issue is composed of several parts. One element is infrastructure, making charging points available where they are needed so that the vehicle can be plugged into the electrical grid. Another is the charger in the vehicle, which converts AC from the electrical grid to the DC required by the battery. While the infrastructure is largely out of the hands of the automotive OEMs (much like gasoline stations), the charger, its implementation, and the power it can handle and therefore the rate at which range can be recovered, is.

THE NEED FOR ON-BOARD CHARGERS

The electrical system of the vehicle is changing significantly with the move to electrical traction. Motive force in BEVs is provided either by a central, three-phase electric motor or motors integrated into the vehicle's wheels (Figure 2).

The electric motors are powered by a traction inverter that sources energy from large, high-voltage (HV) battery packs. The inverter is either connected directly to the HV battery or through a DC-DC converter, depending on the battery's nominal voltage, 400V or 800V respectively, as shown in Figure 2. While technology may be changing rapidly in automotive, there are still plenty of systems that operate at 12 or 48 V_{DC}. These may be supplied from the HV battery pack via DC-DC converters.

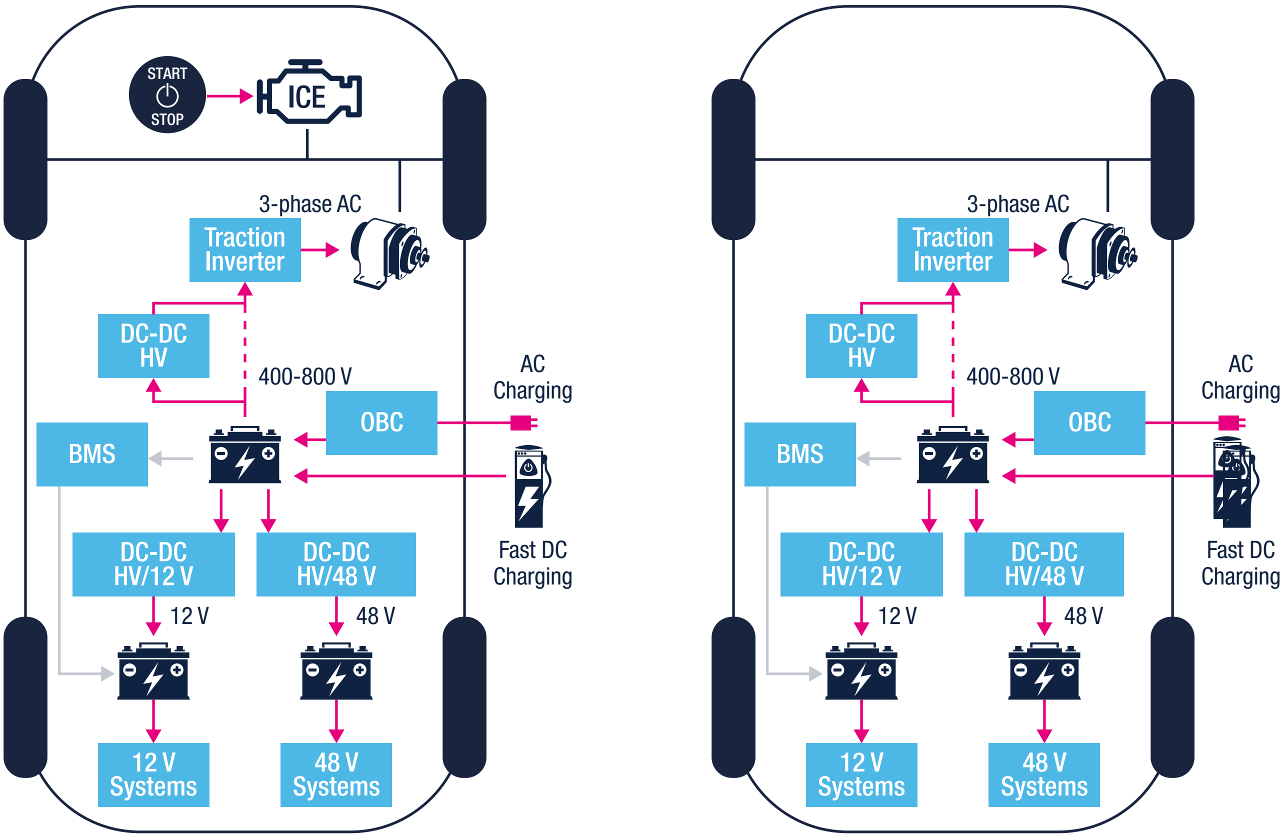

Figure 2: Generic PHEV (left) and BEV (right) architectures

The currents being drawn by some systems at 12 V_{DC}, such as door openers and lifters, heaters, and climate control systems, reach several tens of amps. There has long been a discussion about how to power such applications, and the trend is increasingly to replace 12V lead-acid batteries with 48V lithium-ion batteries in today's BEVs. This power line may also be generated by a DC-DC converter from the HV battery.

The state and monitoring of the HV battery are handled by the battery management system (BMS). It keeps track of charge levels for the entire battery, breaking down the management into individual modules and even providing information on individual cells. Charging requires a DC supply. This is not available in most homes and commercial spaces since electricity is transmitted over the electrical grid as AC. Thus AC needs to be converted into DC so that the BMS can control the charging of the HV battery.

There are two approaches to solving this issue. One is by using an on-board charger (OBC) that is permanently installed in the vehicle. Depending on its implementation, this can work from a single-phase AC, residential supply (100 to 230 V_{AC}), to a two- or three-phase supply (230 to 400 V_{AC}) that, in some countries, is available in residential properties and, in others, is limited to commercial properties. With a suitable Electric Vehicle Service Equipment (EVSE) box, the BEV's OBC is simply attached using a cable and region-specific charging plug. Thus, the EVSE is little more than a box that enables/disables its output and performs electrical-safety functions and monitoring (Figure 3). More advanced versions may also include a human-machine interface (HMI) for multi-party use along with a backhaul data interface (typically wireless) to handle service billing.

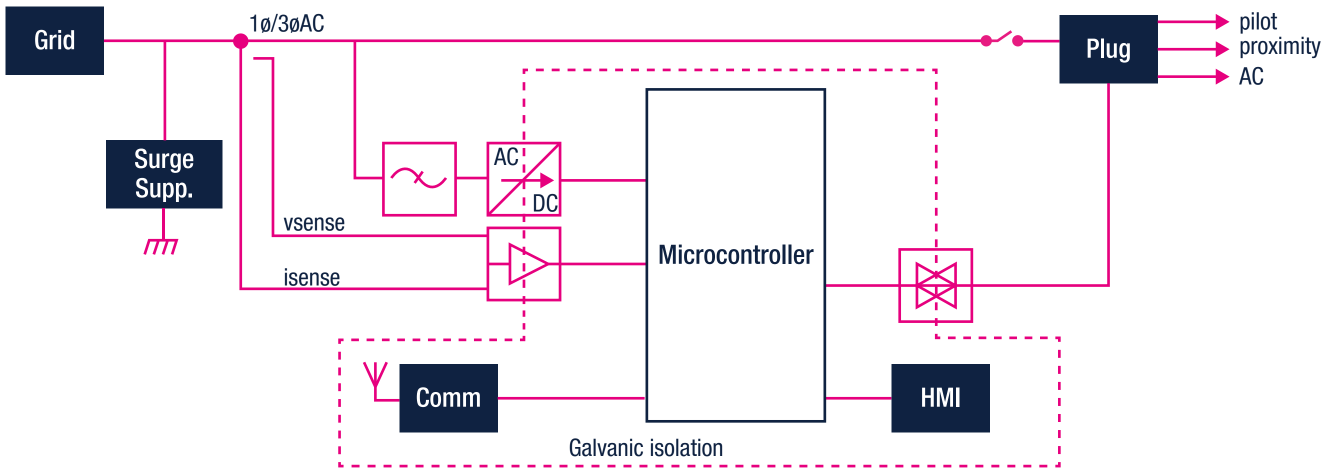

Figure 3: Basic EVSE block diagram

The second approach requires that the EVSE is responsible for converting AC to DC, which is then passed through the charging cable and connector to the BEV. Being DC, this can be used directly by the BMS, thus bypassing the OBC entirely.

Single-phase AC EVSEs are relatively cheap and are often known only as a ‘wall box’, delivering between 1.5 kW and 3 kW of power. However, due to these low power outputs, charge times of 10 – 20 hours can be expected to attain 100 miles[5] (160 km) of range (assuming 30 kWh of energy is required). Single-phase AC supplies that can handle higher currents of 16 A or even 32 A can deliver between 3.7 kW and 7.4 kW of power. This reduces the 100-mile range charge time to 8 or 4 hours, respectively. Finally, the availability of three-phase 400 V_{AC} at 32 A or even 60 A per phase can provide between 22 kW and 43 kW of power, reducing the same charge times to between 90 minutes and 42 minutes, respectively.

Due to the higher currents and voltages involved, such high-output-power EVSEs are more expensive. However, they remain significantly lower in cost than DC chargers (10% of the cost or less), which is why DC chargers remain the domain of commercial operators offering a fast-charge option on major highways for travelers to make long journeys (Table 1).

Mode	Capacity	Rating	Max Power (kW)	Cost ($)
AC Level 1 (L1)	120V@12A	15A	1.44	<1,000
	120V@16A	20A	1.92	
AC Level 2 (L2)	240V@80A	NEC 625	19.2	1,000-3,000
DC Level 1 (L3)	50V-1000V@80A	N/A	80	30,000
DC Level 2 (L3)	50V-1000V@400A	N/A	400	150,000

Table 1: EVSA SAE J1772 charge levels

THE ARCHITECTURE OF OBCs AND ITS CHALLENGES

The OBC design is very similar to that of other power conversion systems. The incoming single- or three-phase AC passes through a power-factor correction (PFC) stage and is converted to HV DC (DC link voltage). This is then converted by a DC-DC converter block to a DC voltage suitable for charging the battery. An MCU is typically employed to control these blocks using digital control methods. In addition to managing each of these stages, it is also responsible for handling safety, system monitoring, and communication with the EVSE (Figure 4).

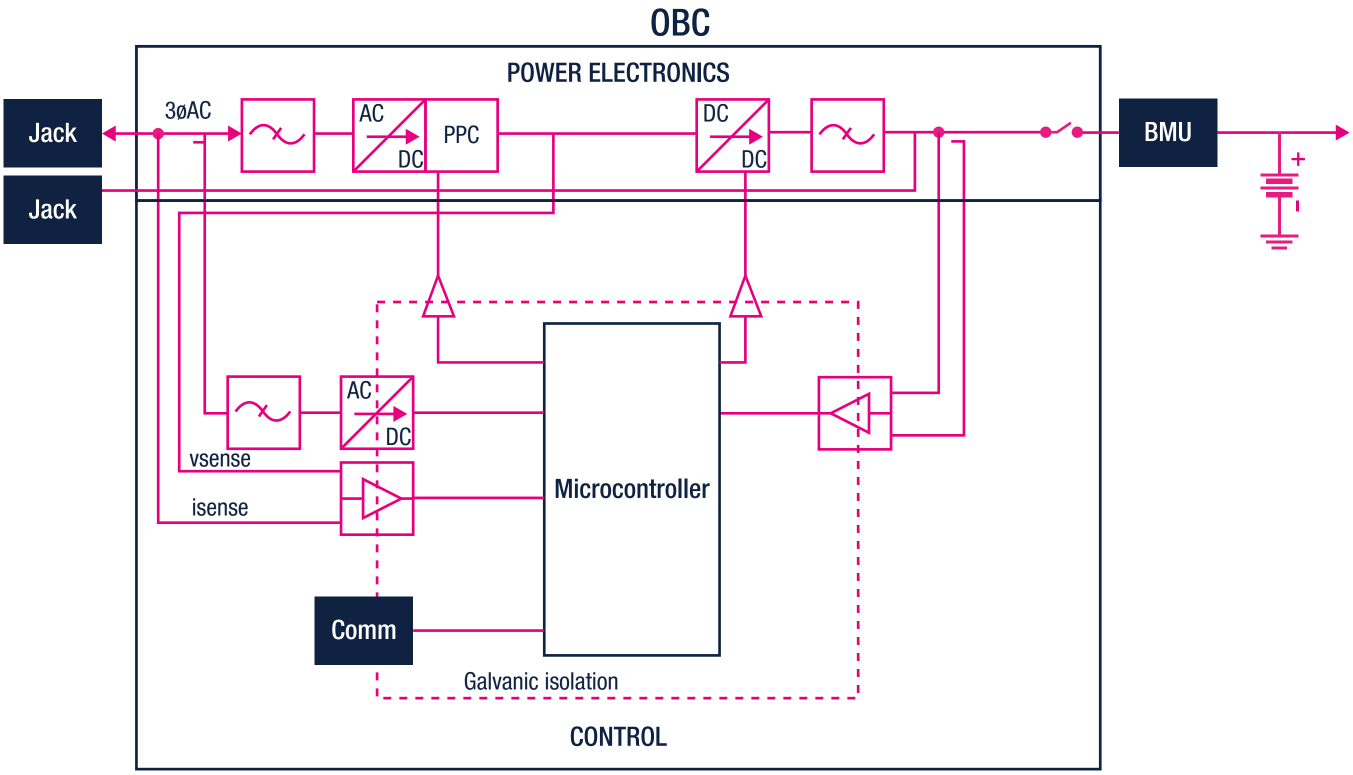

Figure 4: Partitioning approach for OBC power and control electronics

The precise implementation is dependent on a variety of factors. Firstly, it needs to be very efficient, as any losses will need to be dissipated as heat. Every 1% loss in efficiency in a 22 kW design equates to 220 W that needs to be removed as heat. The electrical grid is also a notoriously challenging environment with droops and surges that have to be dealt with. Integrated into the vehicle, the solution must also fulfill the strict requirements the automotive industry places on electrical components and systems. Finally, it needs to be as compact and lightweight as possible to minimize its impact on the vehicle's range.

The PFC typically switches at around 50 to 100 kHz and can be implemented either with a dedicated controller or digitally with a suitable MCU. Its goal is to ensure that the waveform of the current entering the OBC matches that of the incoming AC voltage. This makes the OBC look like a purely resistive load to the electrical grid and contributes to reduced conducted emissions. In turn, this reduces the complexity and cost of the electromagnetic interference (EMI) filters required. Done correctly, the apparent power seen by the electrical grid will closely match the real power consumed by the OBC, leading to a power factor (PF) close to the maximum value of 1.

Typically, the PFC and rectifier are integrated into a single circuit. This is achieved by using a boost regulator to convert the incoming AC into DC. The optimal choice of the topology depends on a range of factors, from the desired efficiency to solution size and cost. However, with the broad availability of silicon carbide (SiC) MOSFETs in recent years, hard switching topologies such as the Vienna boost converter are proving increasingly popular (Figure 5). The combination of high efficiency, lower losses in the switches, the higher switching frequencies supported by SiC devices (compared to silicon IGBTs), lower resultant heat dissipation, and smaller magnetic components tick many of the system designers' requirements.

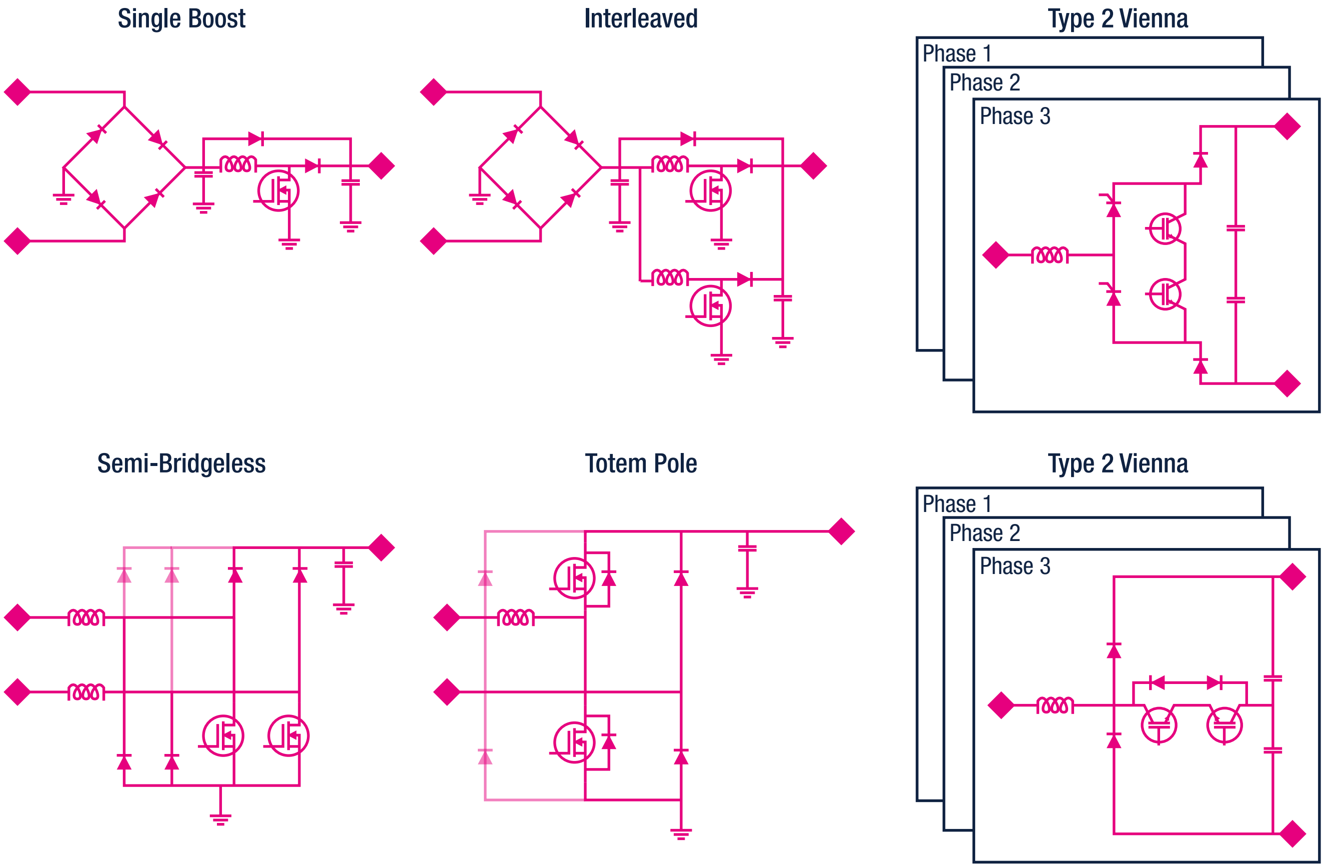

Figure 5: Basic rectifier/PFC circuits

The DC-DC conversion stage also needs to have low emissions and high efficiency and power density. A popular approach to this block is the LLC (using two inductors and one capacitor) resonant converter (Figure 6). The goal is to construct the LLC circuit's resonant frequency to match the power devices' switching frequency. This results in a more predictable emissions envelope due to the sinusoidal signal generated. As opposed to the generation of a pulse train with steep rise/fall times, the switches can be enabled at, or close to, the zero-crossing point of the sinusoidal signal, to perform soft switching commutations with very low switching losses. Today, Silicon MOSFETs with exceptional low on-resistance and supporting high voltages of up to 1200 V still remain ideal for such designs. The higher-cost SiC MOSFETs do not deliver significant benefits in this stage of the OBC design over current-generation silicon high-voltage MOSFETs.

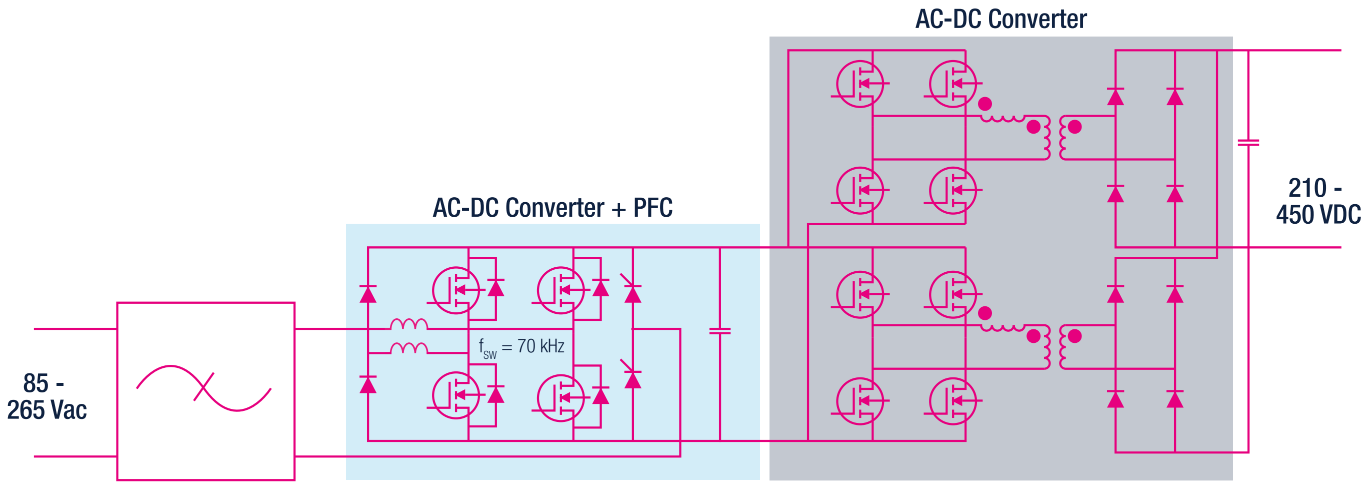

Figure 6: Example schematic for an EV on-board charger power device

OPTIMAL COMPONENT SELECTION

A new reference design (STDES-7KWOBC) will soon be available from ST that allows engineers to discover the benefits of various OBC design approaches and the implementation challenges. It can operate with both single-phase (85 to 265 V, 45 to 65 Hz) or three-phase (85 to 265 V) AC lines to neutral (45 to 65 Hz), allowing the investigation of single-phase Level 1 (16 A_{RMS}) and Level 2 (80 A_{RMS}) systems or three-phase approaches. The DC output is designed for a 375 V battery but can range from 250 to 450 V. The board includes a CAN interface, RS232 for debugging, and a UART for board-to-board communication.

Figure 7: STDES-7KWOBC reference design

The power stage board is built on an insulated metal substrate (IMS), forming part of the liquid-cooled heat dissipation concept, and is mounted with surface-mount components. It can handle 7 kW (Figure 8) and up to three modules can be used in parallel to construct a 21 kW charger suitable for either single- or three-phase operation, giving system designers scalability options.

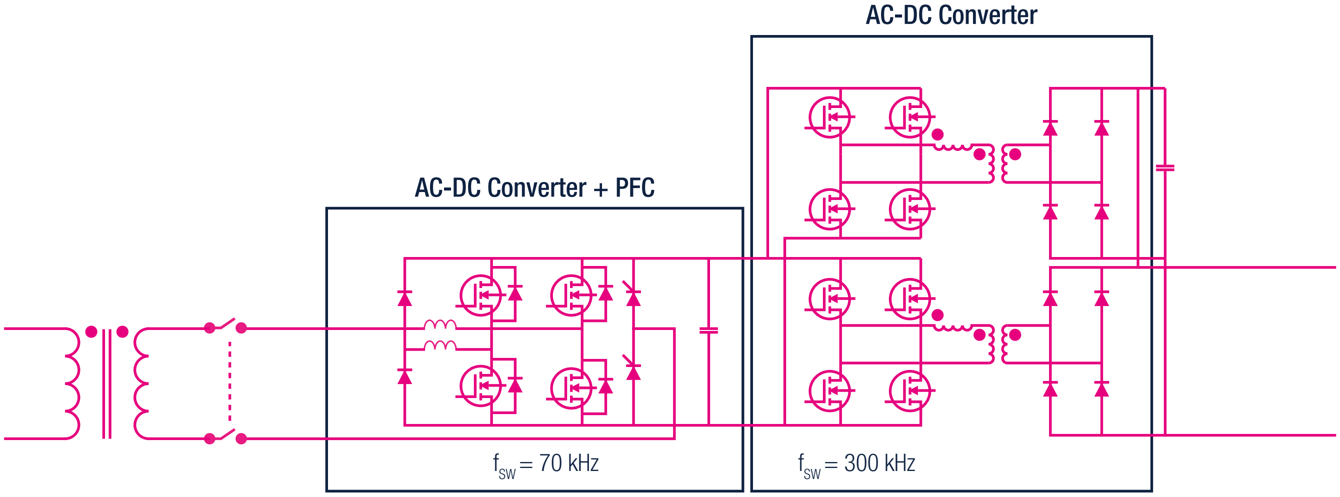

Figure 8: STMicroelectronics 7kW Charging Module

The interleaved Totem Pole block's switching element is implemented using 650 V STPOWER SiC MOSFETs. The 55 mΩ SCTH35N65G2V-7AG SiC power MOSFET is available in both H2PAK-7L and H2PAK-2L surface mount packages. Junction temperatures of 175°C are thus attainable.

The rectifier stage is implemented using a combination of diodes and thyristors (SCR). SCRs offer inrush protection when the filter capacitors are charged at power-on and are an alternative to a relay and inrush resistor combination that is not as compact. A suitable device is the 1200 V, 60 A TN6050HP-12WY SCR that is AEC-Q101 qualified and available in a D^2PAK package. The diode selected is the 30 A, 1200 V STBR3012G2Y-TR low-drop ultrafast diode that is also available in the same package.

In the final stage, an interleaved full-bridge LLC resonant DC-DC converter incorporates classic silicon MOSFETs together with SiC Schottky diodes. Here the AEC-Q101 qualified STPSC20065-Y SiC Schottky is well suited to the application. It offers a 20 A/650 V rating, has no or negligible reverse recovery, and also comes in a D^2PAK package. These are matched with the STB47N60DM6AG N-channel silicon MOSFET, part of the MDmesh™ DM6 series in STMicroelectronics's STPOWER MOSFET family. With a fast-recovery body diode and 70 mΩ typical $R_{DS(on)}$, they are well suited to zero-voltage switching (ZVS) topologies and come in a surface mount D2PAK package.

While much effort is spent on each component's electrical performance, improving its capability to match the demands of increasing innovative power converters, device packaging is another critical aspect. The packaging used can help or hinder the design's mechanical implementation as engineers work to develop the optimal heat dissipation approach.

Offering low electrical parasitic inductance and low thermal resistance, the ACEPACK™ SMIT is a novel packaging solution that delivers a flexible internal DBC design that enables various electrical circuit solutions from single switch to multi-die topologies in the 1 to 50 kW power range (Figure 9).

Featuring a Direct Bond Copper (DBC) metal-isolation-metal substrate placed on the top side of the package to improve thermal coupling with heatsinks, the ACEPACK™ SMIT frees the circuit board of silicon dissipation to allow operation at lower temperatures and a higher design flexibility. Additional freedom is represented by a wider technology selection. IGBTs and MOSFETs in both silicon and silicon-carbide are available for implementation on ACEPACK SMIT topologies, thus offering a full range of cost/performance solutions. The STGSB200M65DF2AG, a low-loss IGBT in an ACEPACK SMIT package, provides an optimal balance between inverter system performance and efficiency where the low-loss and the short-circuit functionality is essential.

While most switches place the metal slug on the PCB-side of the device, the new HU3PAK™ flips the approach by offering top-side cooling. This essentially removes the thermal resistance of the PCB, as the HU3PAK top side slug can now be connected directly to the cooler. The 650 V 20 mΩ SCTHU100N65G2-AG SiC MOSFET is available in this package, which also features a sense pin.

Figure 9: ACEPACK SMIT and HU3PAK packaging solutions

Driving the switches with an MCU requires the use of isolated gate drivers. As well as providing isolation between the low-voltage (LV) and high-voltage (HV) sections of the application, they also deliver diagnostic information to the MCU and offer a range of protection such as under- and overvoltage, Miller clamp, and overcurrent detection. Devices such as the STGAP1AS are ideal for this purpose, offering a 5 A sink/source current, 100 ns propagation delay, and are suitable for use with high-voltage rails of up to 1500 V (Figure 10). The device is also AEC-Q100 qualified.

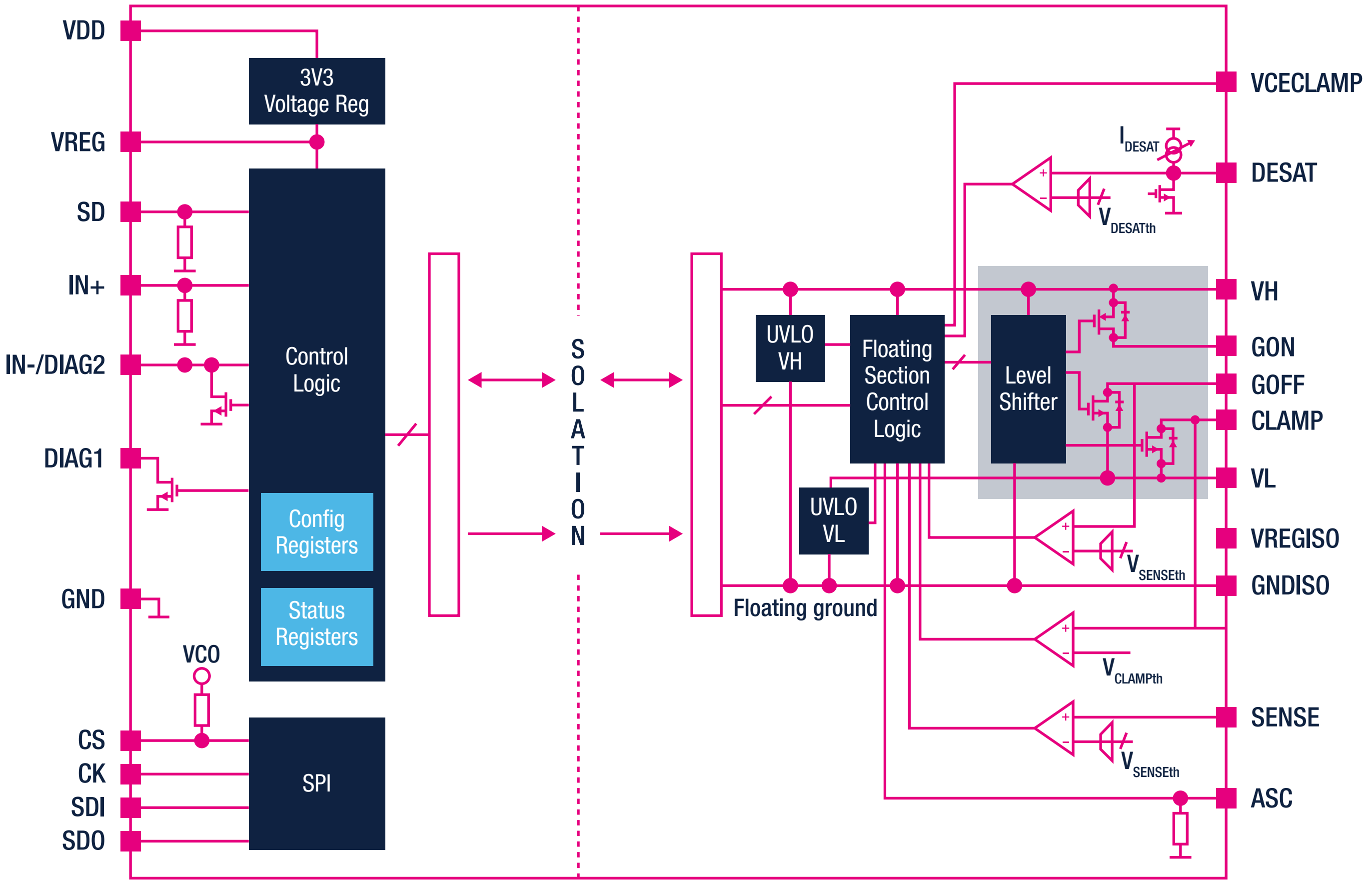

Figure 10: STGAP1AS galvanically isolated single gate driver block diagram

CONCLUSION

In the world of automotive, the final bastion of the mechanical has given way to the electrical, like many of the other systems found in the vehicle. Alongside the electric motor, battery, and traction inverter, the OBC is one of the most critical aspects of an EV's design and ultimate success. Huge battery capacity and highly efficient traction inverters cannot compensate for an under-dimensioned OBC that requires multiple hours to add 100 kilometers of range to the vehicle[6]. WBG power devices, such as SiC STPOWER MOSFETs and Schottky diodes as well as PowerGaN transistors in the next years, are making the life of automotive designers easier thanks to the highly efficient, low heat dissipation power converters they enable. Silicon STPOWER MOSFETs and IGBTs will continue to play a significant role in OBC designs, with the latest advancements in technology providing robust solutions with ultra-low $R_{DS(on)}$. Finally, innovation in packaging helps design engineers find optimal solutions to deal with any heat that is generated, despite the high levels of efficiency on offer. This can help move the OBC design to a higher power class and thus provide the BEV or PHEV owner with an improved EV experience through shorter charging times. With its broad palette of automotive-grade silicon and SiC devices for each stage of the power-conversion chain, STMicroelectronics remains the optimal partner for partnering on OBC designs.

ADDITIONAL RESOURCES

On Board Charger (OBC) [Application page]

STPOWER: A Webinar on the OBC and DC-DC Converters of Electric Cars [Blog post]

On-board Chargers in Electric Vehicles [Video]

REFERENCE DESIGNS

15 kW, three-phase, three-level Active Front End (AFE) bidirectional converter for industrial and electric vehicle DC fast charging applications [Reference design]

15 kW, three-phase Vienna rectifier with low cost mixed-signal control for power factor correction [Reference design]

3.6 kW PFC totem pole with inrush current limiter reference design using TN3050H-12WY and SCTW35N65G2V [Reference design]

1. https://www.britannica.com/technology/automobile/Early-electric-automobiles
2. https://www.thoughtco.com/history-of-electric-vehicles-1991603
3. LMC Automotive
4. https://autovistagroup.com/news-and-insights/ev-charging-anxiety-new-range-anxiety
5. https://www.spiritenergy.co.uk/kb-ev-understanding-electric-car-charging
6. https://autovistagroup.com/news-and-insights/ev-charging-anxiety-new-range-anxiety

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