



What's Under the Hood



COVER STORY:

The Batteries That Power EVs

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The Batteries that Power EVs

The battery pack accounts for 35% to 50% of a battery EV's (BEV's) cost¹ and is similarly a significant contributor to size and weight along with 100% of its range. A keen focus on battery prices and technology by EV makers as well as battery makers should therefore come as no surprise.

Consider this: Bloomberg New Energy Finance's (BNEF's) 2021 Battery Price Survey predicts that by 2024, the average pack prices could go below \$100/kWh. That is the price point at which automakers could manufacture and sell mass-market EVs at the same price and margin as comparable internal combustion vehicles and without subsidies.²

This chapter of Wolfspeed's What's Under the Hood series shines the light under the hood on the powerhouse of BEVs — the battery pack (Figure 1) — to reveal cell characteristics, battery chemistries, and architectures, as well as hazards, protections, and control.

BATTERIES AS ELECTROCHEMICAL FACTORIES

Rechargeable or “secondary” batteries convert chemical energy into electrical energy and vice versa. Cells (Figure 2) are the smallest individual electrochemical units within modules and packs.³

Industry names of battery chemistries generally refer to the electrode material. In a Li-ion battery, for instance, the cathode generally comprises lithium metal oxide particles and anode graphite particles. Both are physically separated by a membrane to prevent an internal short but are permeated with an electrolyte to aid movement of Li⁺ ions. During discharge, electrons travel from the negative electrode to the positive electrode external to the battery through the load, while Li⁺ ions travel in the reverse direction inside the cell.

During charging, the direction of electron and ion flows is reversed.

KEY BATTERY SPECS

Each cell is characterized by a number of parameters that are largely dependent on battery chemistry and packaging. They enable comparison of various battery packs and include:

- **Nominal voltage (V):** The reference or “normal” voltage of the battery.
- **Nominal capacity (Ah @ specified C-rate):** It is the coulometric capacity measured in ampere-hours delivered when a fully charged battery is discharged at a certain discharge current (specified by the C-rate).
- **C-rate:** This measures the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in one hour. Higher-voltage battery packs allow lower C-rate cells and faster charging and discharging by requiring lower current.
- **Specific energy (Wh/kg):** This is nominal battery energy per unit mass or the gravimetric energy density, which reflects on the driving range.
- **Specific power (W/kg):** The maximum available power per unit mass demonstrates the ability to deliver high current on demand that affects vehicle acceleration.

- **Energy density (Wh/L):** The nominal battery energy per unit volume or volumetric energy density. It determines the battery size required to achieve a given range for a given energy consumption.
- **Performance:** Typically, energy or power versus cycle lifetime, performance reflects the condition of the battery, especially when driving an EV in extreme temperature conditions.
- **Lifespan:** This is measured in charge-discharge cycle count. A Li-ion EV battery pack life is generally expected to be 10–12 years.

Cost is another parameter used to judge viability of battery technology. It not only includes technology, material, and manufacturing cost but also cost of secondary systems such as those for safety and battery monitoring and management.

EV BATTERY CHEMISTRIES

As mentioned above, battery chemistry drives the parameters that matter to EV applications. The nickel-cadmium (Ni-Cd) batteries utilized by early EVs have given away to newer battery chemistries. Although stable over a wide temperature range, Ni-Cd is beset by a number of issues, including a low nominal voltage of 1.2 V, low energy density, and a voltage-suppression problem known as “memory effect” that results in lower capacity when the battery does not complete charge-discharge cycles.

Among the more mainstream technologies are the Li-ion chemistries described below and compared in Figure 3.⁴

- **LCO:** Lithium cobalt oxide (LiCoO_2) offers high gravimetric energy density and a 3.6-V nominal voltage but has a low C-rate, short lifespan, stability issues over temperature, and high cost from cobalt use.
- **Nickel-based chemistries:** Although both nickel and cobalt significantly increase battery cost, lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA) are used heavily in EV traction as well as storage applications due to their high specific energy and a good nominal voltage of 3.6 V. NMC takes the lion’s share, with 71% of sales, with much of the rest taken up by NCA.¹ However, the industry is increasingly concerned about cobalt beyond its high cost — its supply chains is often tainted by difficult-to-track and questionable to illegal mining practices.
- **LMO:** Lithium manganese oxide offers both high C-rates and high nominal voltage (3.7 V) and has been used in older EVs. However, performance is lower than other chemistries.
- **LFP:** Lithium iron phosphate (LiFePO_4) is stable across a wide temperature range and is therefore safer. It has a longer lifespan and high C-rates but relatively lower

capacity and a lower nominal voltage of 3.2 V. LFP cells were also almost 30% cheaper than NMC cells in 2021.³ Since LFP cathode composition is close to that of the phosphates used as food additives with similar purity level requirements, it can leverage a well-established manufacturing environment practice and controls. Moreover, LFP does not have the supply chain issues associated with cobalt. EV makers are therefore increasingly turning to LFP battery technology, particularly for the more economical models.

- **LTO:** In these batteries, the negative electrode is a spinel-structured lithium titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$) instead of graphite. The positive electrode can be LMO or NMC. LTO batteries are much safer, have a longer lifespan, offer better performance, and have a lower cost. However, their specific energy is low. LTO batteries are used in Honda’s Fit EV and some Japan-only versions of Mitsubishi’s i-MiEV.⁴

CELL FORM FACTORS & PACK ANATOMY

Cells are packaged as cylindrical, pouch, and prismatic types. A cylindrical cell comprises sheet-like electrodes and separators sandwiched, rolled up, and packed into cylindrical cans. The 18650 (18 × 650 mm) is a popular format that is used by Tesla, and other common sizes include 21700 and 46800. They are well suited to running heat exchangers in the space between them in modules and packs.

Pouch cells have the electrodes and separator tightly stacked inside a sealed flexible foil container. They require a support structure and face thermal management and cell-swelling issues.

To achieve the prismatic format, sheets of electrodes and separator are sandwiched and either stacked or rolled up and press-fit into metal or hard-plastic housing. They offer high power and high current and are the most commonly used in EVs.

To form batteries, cells are arranged in parallel (P) and series (S), depending on voltage and current requirements. For instance, a 2P4S configuration has two cells in parallel for twice the current and four in series for 4X the voltage (Figure 5). Bus bars are used to connect cell modules to form the entire vehicle battery pack.

EV battery packs range from a few kilowatt-hours for hybrids to over 100 kWh for BEVs. The 400-V systems typically have 96–108 cells in series for 355- to 400-V nominal voltage and 454-V charging, whereas 800-V systems require about 198 cells in series to reach 733-V nominal voltage with 832-V charging.

LI-ION CELL HAZARDS & CONCERNS

Li-ion batteries were developed to address the inherent instability of lithium metal batteries. Li-ion cells are safe if certain precautions are taken. However, it is important to understand what can go wrong:

- **Dendritic growth:** The main cause of internal

short-circuits is lithium dendrite formation due to overcharging, discharging below a certain threshold, or charging at a lower-than-recommended temperature. Lithium dendrites grow due to electrodeposition (plating) on the negative electrode and eventually puncture the separator membrane to reach the positive electrode. This can cause excessive heat generation, combustion, and even explosion.

- **Thermal runaway:** Heating effects from internal self-discharge and internal resistance drive chemical reactions that further heat the battery. This vicious circle continues until the battery catches fire. Thermal runaway in a single cell can cause a chain reaction in the whole pack. Rapid discharging, overcharging, and current surges can cause a thermal runaway event.
- **Corrosion, crystal formation, and passivation:** Corrosion, the result of undesired oxidation of lithium, leads to increase in internal impedance. Particles on electrodes may develop large crystals, reducing the surface area that the lithium can bind to for normal electrochemical reactions. And a thin passivation layer may grow on the surface of electrodes, typically oxides or oxyhydroxides. These defects all impede desired electrochemical reactions, increase the cell's internal resistance, and reduce capacity.

Other issues with Li-ion include cell cracking and outgassing. Like dendritic growths, these problems can cause catastrophic failure that may result in fire or hazardous electrolyte spillage.

BATTERY PROTECTION AND CONTROL

Operated under optimum conditions, electrochemical cells can continue functioning for a long time. For instance, the Oxford Electric Bell comprised of two brass bells, each positioned beneath a dry battery, has been chiming continuously at 2 Hz since it was setup in 1840 — for over 180 years.⁵

For Li-ion, unique cell characteristics must be considered when monitoring battery conditions to ensure longevity. Its discharge voltage versus state of charge (SOC) is nearly flat between 20% and 80% charge, making it difficult to gauge SOC. Compounding this problem, the Li-ion charge-discharge cycle exhibits “hysteresis” following slightly different voltage versus SOC curves (Figure 6).

Cell monitoring is essential for battery protection. The following conditions are monitored, and if a fault condition is detected, protection measures, like disengaging contractors to open the circuit, are taken.

1. **Cell balancing:** While cells are matched during manufacturing, variation in capacity and internal resistance is a natural outcome of charge-discharge cycles. When multiple cells are stacked in series, the weakest cell limits the current drawn from the stack. Cells are balanced by bypassing strong or weak cells during charging and discharging cycles (Figure 7).

2. **Overcurrent:** This condition must be ascertained to trip contactors and protect the cell from overheating.
3. **Voltage:** Overvoltage and undervoltage conditions are measured at the cell level as well as battery pack level to ensure longevity.
4. **Cable insulation:** The cable insulation resistance is measured by passing a very low current so that insulation breaks can be detected.

The cell control methods are usually implemented over the wired CAN bus such that each module talks to a central microcontroller unit, which in turn processes the monitoring information and initiates protection measures such as engaging or disengaging contactors.

CONCLUSION

Given its importance to the BEV market growth, significant R&D is focused on bringing about new battery technologies. A silicon-carbon anode material from Group14 Technologies, for example, is claimed to increase gravimetric energy density by nearly 25% to 330 Wh/kg.⁶ Other research into solid-state batteries could eliminate fire risk.

To further your knowledge of the EV powertrain with tutorials such as this one, visit the Power [Products Knowledge Center](#).

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Article Spotlight

DESIGNING WITH SILICON CARBIDE IN BIDIRECTIONAL ONBOARD CHARGERS

Electric vehicle (EV) onboard chargers (OBCs) can take several forms based on power level and functions. Charging powers vary from less than 2 kW in applications such as electric scooters to 22 kW in high-end EVs. Traditionally, charging power is unidirectional. Bidirectional charging is gaining traction in the recent years. This paper will focus on bidirectional OBCs and discuss the advantages of Silicon Carbide (SiC) in both medium-power (6.6 kW) and high-power (11-22 kW) OBCs.

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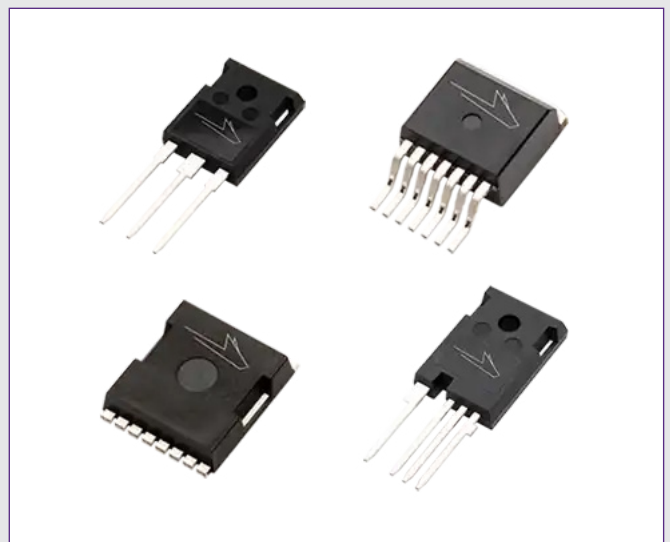
SILICON CARBIDE MODULES UNLOCK HIGHER POWER DENSITY IN MOTOR DRIVES

The traction drive is where nearly all of an electric vehicle's (EV's) energy is put to use. The drive system must, therefore, perform with the highest possible efficiency while occupying the smallest possible space with the lowest weight — all to maximize the EV range. With the use of dual drives to enhance traction as well as an 800-V architecture to reduce losses, the industry needs inverters that increase output power from smaller size to deliver power density well beyond the capability of silicon (Si)-based technologies like IGBTs.

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650 V SIC MOSFETS EXTEND WOLFSPEED'S AEC-Q101 QUALIFIED E3M RANGE

The rapid growth expected in the electric vehicle (EV) market — expected to be as much as 25% CAGR over the next decade¹ — is driven by environmental concerns and government support and enabled by Silicon Carbide (SiC) device technology that addresses the requirements of high efficiency and power density.

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What's Under the Hood?

EV Architectures & Inverters

The electric vehicle market is among the largest and fastest-growing business opportunities for Silicon Carbide (SiC) device manufacturers. Ten million EVs were on the world's roads in 2020, according to the International Energy Agency (IEA), an organization that urges mass adoption of light-duty EVs this decade to combat climate change.¹

As the leading supplier of Silicon Carbide discrete Schottky diodes and MOSFETs as well as power modules, Wolfspeed facilitates success in this market.

This chapter of Wolfspeed's What's Under the Hood series introduces various levels of architectures for vehicle powertrain electrification before focusing on two key components in the battery EV (BEV) drivetrain: motors and inverters. We discuss the types and placement of electric motors as well as Silicon Carbide-based inverters and their switching schemes.

END OF THE ICE AGE?

The internal combustion engine (ICE) market is in decline, according to industry observers. No major announcements on new ICE R&D investments or addition to roadmaps have been made recently by auto OEMs. This knowledge, combined with an estimate of 41 million EVs and hybrid EVs (HEVs) expected on the road by 2026,² points to the end of the ICE age.

OEMs have been transitioning to the electric powertrain for years, with the 1997 Toyota Prius introduced in Japan as the first HEV and the 2008 BYD in China as the first plug-in HEV (PHEV). The road to BEVs is thus paved with various levels of "hybridization" that depend on the power of the motor drive:

- Micro and mild hybrids: These "eAssist" systems have belt/integrated starter generators with 12-V "micro" and 48-V "mild" systems with <5-kW and 5- to 13-kW motors, respectively, that deliver the torque required to move the vehicle from a standstill. This architecture is often used by large trucks and SUVs.
- Full hybrids: With 20- to 40-kW motors, HEVs charge purely from their ICE blocks and regenerative braking. The motor and the ICE work simultaneously most of the time.
- Plug-in hybrids: The 50- to 90-kW motors in PHEVs allow electric-only local commutes, with a typical range of 10–50 miles (16–80 km) on a single charge from AC wall power.

HYBRID ARCHITECTURES

Hybrid drivetrains have architectures similar to BEVs, except they have additional energy sources and smaller onboard electric energy storage. A common feature in all hybrid architectures, where Wolfspeed's SiC modules

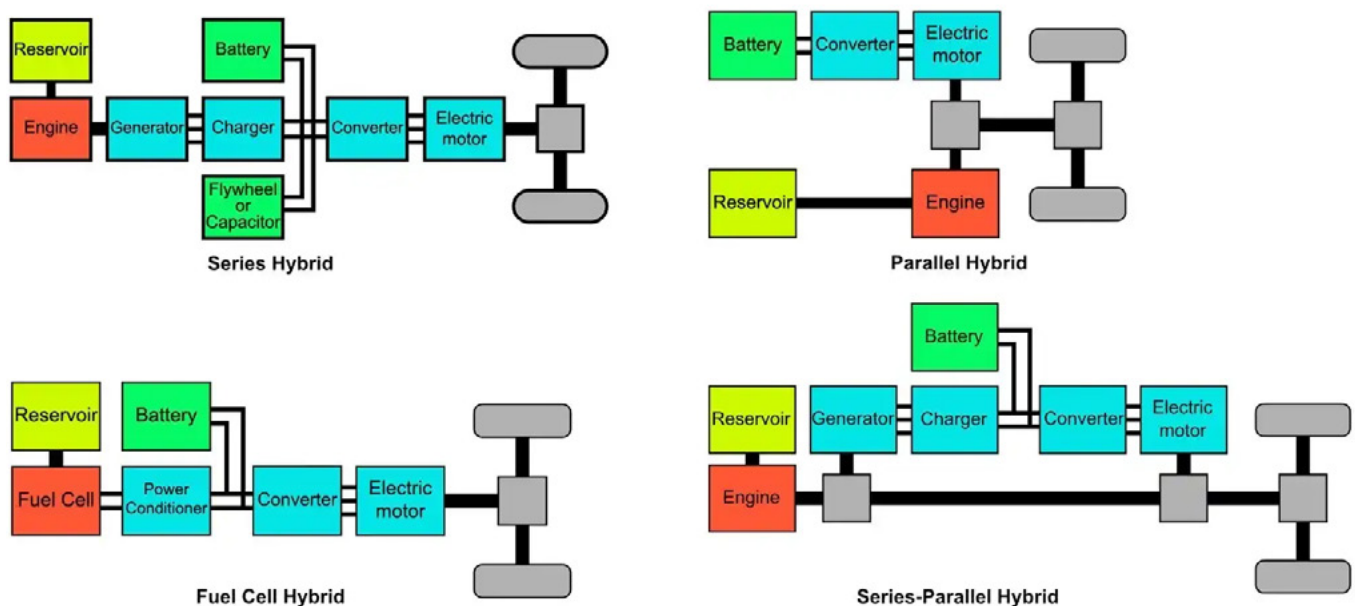


Figure 1: The various types of architectures used for hybrid EVs. Source: Illustrations by Peter Van den Bossche, Fred the Oyster, [CC BY-SA 4.0](#)

shine, is the bidirectional inverter that allows the ICE and regenerative braking to charge the battery. There are, however, four major drivetrain arrangements (Figure 1), including series, parallel, fuel-cell, and series-parallel.

The series hybrid, such as the Nissan ePower, Chevy Volt, BMW i3, and some models of the Toyota Prius, comprises an ICE that is in line with the battery and electric motor. The vehicle wheels and the ICE are thus mechanically “decoupled.” A significant portion of the design is that of a BEV with the motor driving the wheels directly. When the onboard battery is depleted, the ICE drives a generator that both charges the battery and powers the electric motor. Whenever a large amount of power is required, the motor draws electricity from both the battery and the generator.

Four illustrated examples of architectures used in hybrid EVs..

On the one hand, the two energy conversions — mechanical to electrical to mechanical — result in higher

The parallel hybrid architecture, as found in the Ford Fusion, Honda Civic, and some models of the Toyota Prius, consists of the ICE in parallel to the electric drivetrain. The vehicle is propelled by both the ICE and the electric motor connected to a mechanical transmission that usually comprises a planetary gear system. The power distribution between the ICE and the motor is changed such that they both run in their optimum operating region as much as possible. When the electric motor does not supply rotational power, for instance, the ICE takes over.

Because both the electric motor and, therefore, the inverter are smaller than those in the series architecture, parallel hybrids have lower costs.

The power-split, or series-parallel, hybrid is a combination of both series and parallel architectures, with the intention of utilizing the benefits of both. Planetary gear systems are used to drive the shaft using both the ICE and the electric motor, and a generator to charge the battery is connected to the shaft as well.

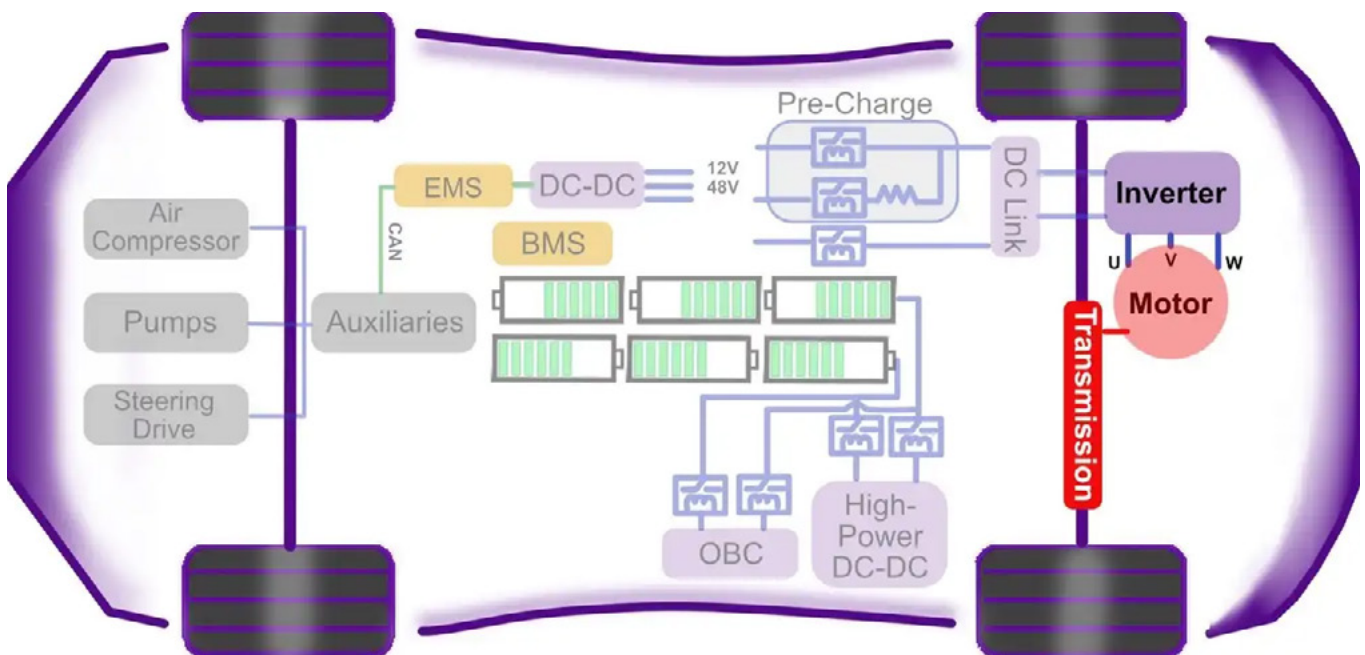


Figure 2: Diagram of a typical BEV showing the traction inverter, motor, and transmission among other functional blocks

losses,³ and on the other, the ICE size and speed can both be optimized for high efficiency. Both the battery pack and the motor in this architecture tend to be larger than in the parallel architecture, making it the more expensive hybrid.

The fuel-cell HEV (FCHEV) uses a design similar to that of the series hybrid, except the ICE and generator are replaced by the fuel cell and a power conditioner that helps the fuel cell output the appropriate voltage and current for the application, in this case charge the battery or drive power to the inverter.

All hybrid architectures, except FCEVs, have been seen by many automakers as a transition to the simpler BEV drivetrain (Figure 2), with the battery, motor, and inverter being the main components involved in traction.

BEV HUB MOTORS & E-AXLES

BEV motors can be classified as hub motors and e-axes based on their mechanical coupling to the drivetrain. Hub motors are mounted at the wheel to drive it directly. The resulting removal of the axle and mechanical gears offers the benefits of higher efficiency, smaller motors and inverters, and lower interior floors.

However, hub motors require special control to tune the speed of each wheel to changing requirements, such as when turning the EV needs outer wheels to rotate faster than the inner wheels. Because a differential pumpkin is not available in axle-less designs, the rotational speed differential must be handled by electronic motor control. With an inverter driving and controlling each motor, this design can get expensive. Another challenge is environmental protection from dust, debris, and water, which may require integrating and sealing off all electronics with the motor.

Suppliers of hub motors are fewer, including Protean, Elaphe, and Nidec, compared with those offering e-axes.

Mounting the motor in the center of the axle results in the e-axis design. While this usually requires only one motor per axle, there can be variations. Tesla's Tri-Motor, for instance, uses two motors on one of the axles.

Although the e-axis usually requires motors to be larger because they drive the full axle, it is cheaper and therefore more popular. It has fewer electronic components because some of the speed control requirements are replaced by cheaper mechanical parts.

MOTOR TYPES FOR EVS

BEVs do not use DC motors because of insufficient torque at high speed and rapid wearing out of commutators. Single-phase AC motors are also avoided because they do not deliver sufficient starting torque and have much lower power ratings, making them suitable for the lighter loads of home appliances. Three-phase AC motors, on the hand, offer BEVs high torque from middle to high speeds that can be further tuned to the needs of the drivetrain. BEVs use one of three types of three-phase AC motors — induction, permanent magnet synchronous, and permanent magnet synchronous reluctance.

The induction or non-synchronous motor has no brushes, which avoids wearing out of parts. Rotor windings generate the magnetic fields required — there are no expensive permanent magnets. The motor is directly controlled by the inverter AC output fundamental frequency with a small slip frequency. However, these motors have a low starting torque and are generally found in older BEV model architectures, such as the Tesla Model S.

The permanent magnet synchronous machine is the most common in BEVs, like the Toyota Prius, BMW i3, Audi e-Tron, and Nissan Leaf. Although they are easier to start than an induction motor, they require permanent magnets inside the rotor. With that extra cost also comes higher efficiency because the rotor does not draw current.

The permanent magnet synchronous reluctance machine is a newer motor that is more efficient than pure induction motors. They have a higher power density, but they are more complex to control. They are used, such as in the Tesla Model 3, for their lower inertia that helps achieve higher acceleration.

TRACTION INVERTERS

The traction inverter converts the high-voltage DC from the battery to the three-phase AC needed by the motor (Figure 3). However, not all designs use the boost converter shown in the figure.

Bidirectional inverters needed for regenerative braking are best implemented with SiC power modules because they allow for higher efficiency, greater power density, and simpler circuits compared with silicon IGBT components.

The inverter is usually required to output square waves with switching frequencies between 6 kHz and 24 kHz.

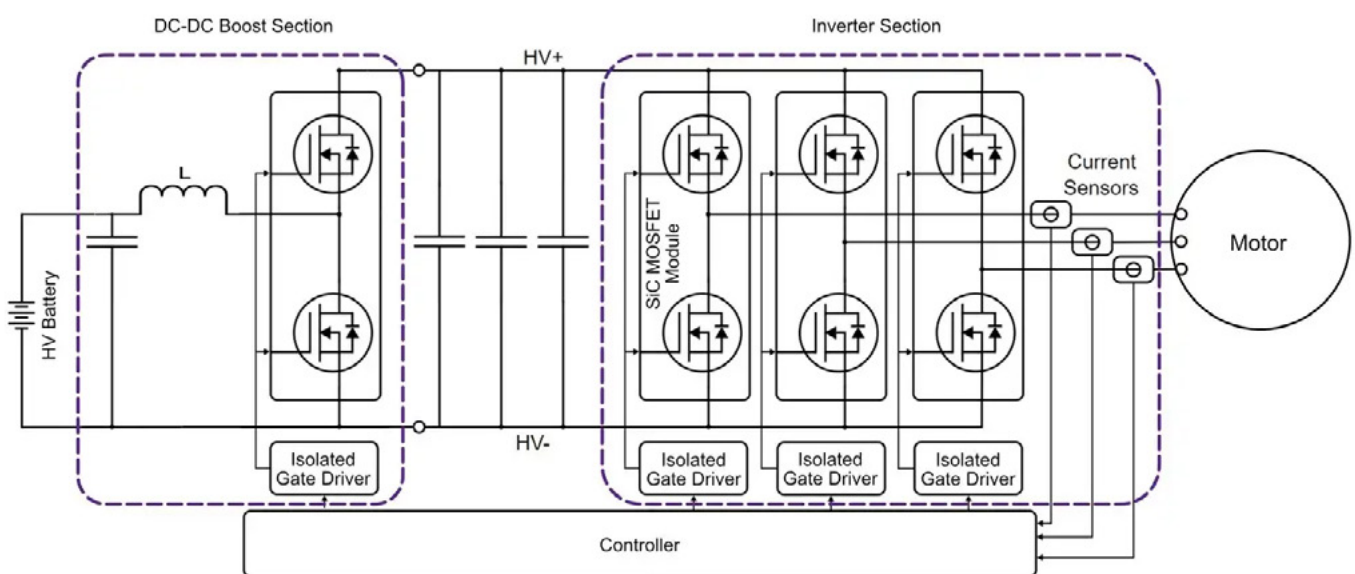


Figure 3: The 3-phase traction inverter using three SiC MOSFET-based half-bridge modules. The DC-DC boost converter, also implemented with SiC MOSFET modules, is not always needed.

This output is filtered by the motor's inherent inductance to provide a fundamental electrical frequency, which is also the shaft rotational speed for synchronous motors.

Although the classic pulse-width-modulation (PWM) scheme is used by most modern microcontrollers and is easy to implement for motor control, it is not common in traction inverters because it is not the most efficient switching scheme. Instead, the space-vector PWM (SV-PWM) is used in BEV applications. It allows overmodulation for attenuating the top of the sine waves so that a voltage higher than the DC-link bus voltage can be applied and greater current driven through the motor (Figure 4). This scheme also minimizes the switching transitions in the six switches of the inverter, thereby lowering switching losses and increasing efficiency.

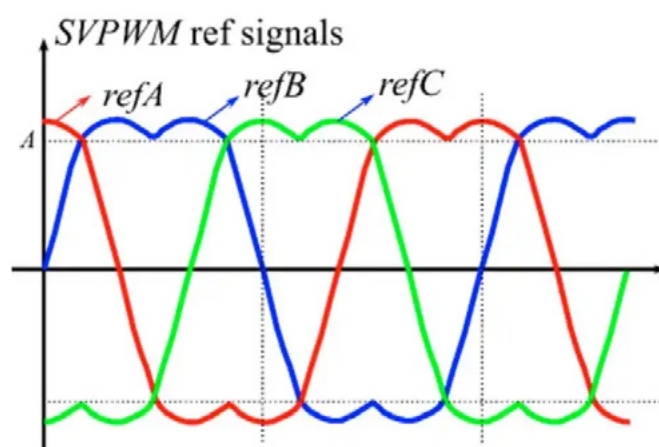


Figure 4: The three-phase SV-PWM waveforms

BEVs eschew the open-loop variable-frequency control in favor of the closed-loop field-oriented control (FOC) because the former uses a lookup table instead of feedback to get only low-precision speed control. The

FOC adds expense with rotor-angle position encoder and phase-current-sensing requirements but can set up the electric fields necessary in various operating modes — hill-hold, maximum acceleration, high speed, braking, and even faults.

An active short-circuit (ASC) feature is also used with inverters to handle faults, such as preventing very high power being delivered to the battery when regenerative braking is engaged at high speed. The ASC shorts the motor phases for the several milliseconds needed by contractors to open the circuit and protect the battery.

CONCLUSION

For less than \$1, a BEV travels the same distance that an ICE-based vehicle travels on a gallon of gas, according to the U.S. Department of Energy. Wolfspeed's SiC enables all critical and many auxiliary functions in BEVs.

To gain further knowledge of this important application and the functional blocks that Wolfspeed products enable, visit the [Power Products Knowledge Center](#).

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What's Under the Hood:

Contactors Implement EV Safety

Placed beside the more keenly discussed parts of the electric vehicle (EV) powertrain are electromechanical switches, called contactors. Despite their unglamorous existence under the hood, they are part of both functional and safety essentials that keep the EV running smoothly. Given that EV registrations grew by 41% in 2020 and each vehicle has several contactors, this is indeed an important component segment.

This chapter of Wolfspeed's What's Under the Hood series focuses on the switches that play various roles in an EV, from helping manage cell balancing and routing out onboard chargers (OBCs) in favor of fast charging to protecting batteries from overcurrent conditions.

WHAT ARE CONTACTORS?

They are electromechanical switches that, while similar to relays, perform heavier duty applications that require higher current carrying capacity. Contactors offer low-voltage control that engages and disengages a copper plate to connect or disconnect the leads of a high-voltage current path.

The devices comprise a solenoid (a cylindrical coil of wire) and a plunger rod of material that resists being permanently magnetized, such as steel. Passing current through the coil creates a magnetic field that attracts the plunger (Figure 1). Attached to the plunger are moving contacts on a thick copper plate that engage with fixed contacts of the same material, offering a very low resistance path, usually less than a milliohm, to the main circuit. The construction allows the switch to offer galvanic isolation between the control circuit and the main circuit being switched.

CONTACTORS IN ACTION

Today's EVs generally all use electromagnetic contactors that are either normally open (NO) or normally closed (NC). These devices find themselves in the path of anything that draws more than a few amperes from the battery — the motor drive, the OBC, even the DC-DC converter that supplies 12 V and 48 V systems.

The key contactors protecting the battery pack are placed beside it or embedded in it, depending on the OEM's choice. The battery and the inverter are isolated by these contactors for safety when the vehicle is switched off. The main positive contactor is placed between the battery's positive terminal and the inverter, and the main negative contactor is between the battery's negative terminal and the inverter (Figure 2). Electrical isolation of both rails is done for safety — to provide redundancy as well as to minimize accidental design-ins of alternative current paths.

The main contactors disconnect the high-voltage positive and negative leads in the event of a crash or another fault, such as when braking at high-speed causes a high back EMF from the motor to the battery. The contactors also allow mechanics to safely disengage the battery pack for replacement.

The pre-charge contactor, shown in Figure 2, has a resistor in series to limit current and both are placed in parallel with a main contactor. This setup is required because the traction inverter has a bank of filter capacitors, or DC link capacitors, that draw a high inrush current when the main contactors are closed. The inrush current can damage the battery and other components in its path. The pre-charge current path is therefore during initial power-up.

Battery EVs (BEVs) also have a pair of DC fast-charge contactors that bypass the AC OBC to establish a direct connection between the battery and the off-board fast charger. Similarly, the OBC has contactors as does the path from the DC-DC converter to low-voltage auxiliary systems, such as the heater, the air compressor, the pumps, and the steering drive.

THE FAULTS IN FAULT TOLERANCE

Although contactors are used primarily to increase the BEV system's safety and fault tolerance, they are themselves not without operational drawbacks and reliability issues as described below.

Bounce: Whenever a contactor is opened or closed, spring action in the device causes the contacts to bounce several times before coming to a rest in the new position. This damages the contacts in the long run and causes immediate voltage spikes (Figure 3) in the circuit that can damage other components. The physical damage roughens the contact surfaces and worsens sparking. The voltage spikes can be dampened by capacitive loads but cause problems with inductive loads.

Inductive load dump: When contactors are opened to break a high-current-carrying circuit, inductive loads in the path, such as the traction inverter and motor, cause a high back electromotive force (EMF) or voltage overshoot in the circuit. The inductive action momentarily causes a much higher voltage than was originally applied, which can cause damage to both the contactors and other components. Note that contact bounce can also exacerbate this problem.

Hold current: The electromechanical switches generally need a continuous current flowing through the solenoid

to hold the switch closed (or open in case of NC contactors). Although the energy needed for this is low, for an application that seeks efficiency above all else it is an important consideration.

Stored energy: Since the contactor itself is operated by an inductor, the solenoid, the problem of stored energy arises in the low-voltage control circuitry as well. This inductive energy must be dissipated with a freewheeling diode (Figure 4) or a high-side MOSFET.

Latch-up: When a contactor is “latched” or closed as part of its normal operation, it requires a magnetic force in the opposite direction to open the high-voltage terminals carrying high currents. Switching very high currents can sometimes lead to contact welds so that the contactor remains latched up. In the event of a fault, this can lead to catastrophic failure, including fire.

Sparking: This happens when a high-voltage circuit in the EV is closed or broken. Current bridges the gap between contacts leading to sparking. Contactors are typically packaged in tough housings to prevent the sparks from affecting the surrounding environments. However, sparking can cause a high enough power dissipation in the module to destroy copper interfaces and cause higher resistances. The electromagnetic interference (EMI) on the surrounding components can also affect their functions.

OEMs may have to choose from between two mitigating options — contactors filled with an inert gas that helps minimize or extinguish the spark or those with an additional electromagnet that “stretches” the spark away from the contacts and into a chute where it is “blown out.”

A FUTURE OF SOLID-STATE CONTACTORS

To address the disadvantages described above, the industry, including Wolfspeed’s design team, is investigating the use of solid-state switches, such as high-performance Silicon Carbide MOSFETs, to replace electromechanical contactors. The MOSFET-based

contactor would offer a low-voltage control of the high-current path via a low-voltage isolated gate driver input.

A solid-state contactor, like this, would offer significant advantages:

- There are no moving parts subject to mechanical wear and tear, thereby increasing lifespan
- Avoidance of contact bounce, sparking, and contact oxidation increases reliability
- Exponentially faster switching — in nanoseconds compared to milliseconds of electromechanical counterparts — offers greater system safety and fault tolerance
- Lighter and potentially smaller footprint

Before such contactors can go mainstream, however, certain challenges must be overcome. The first of these is related to resistance. Since electromechanical contactors offer $<1\text{ m}\Omega$, several solid-state switches may be required in parallel to achieve the same performance. The MOSFET surge-current capabilities are also much lower than those of mechanical switches. The inductive load-dump issue, which challenges electromechanical switches with very high voltages across the air gap, may cause the MOSFETs to break down.

When Wolfspeed and EV makers find a solution to these problems, yet another EV functional block will open up for Silicon Carbide technology to address.

Learn more from Wolfspeed’s application notes and tutorials in the Power Products Knowledge Center.

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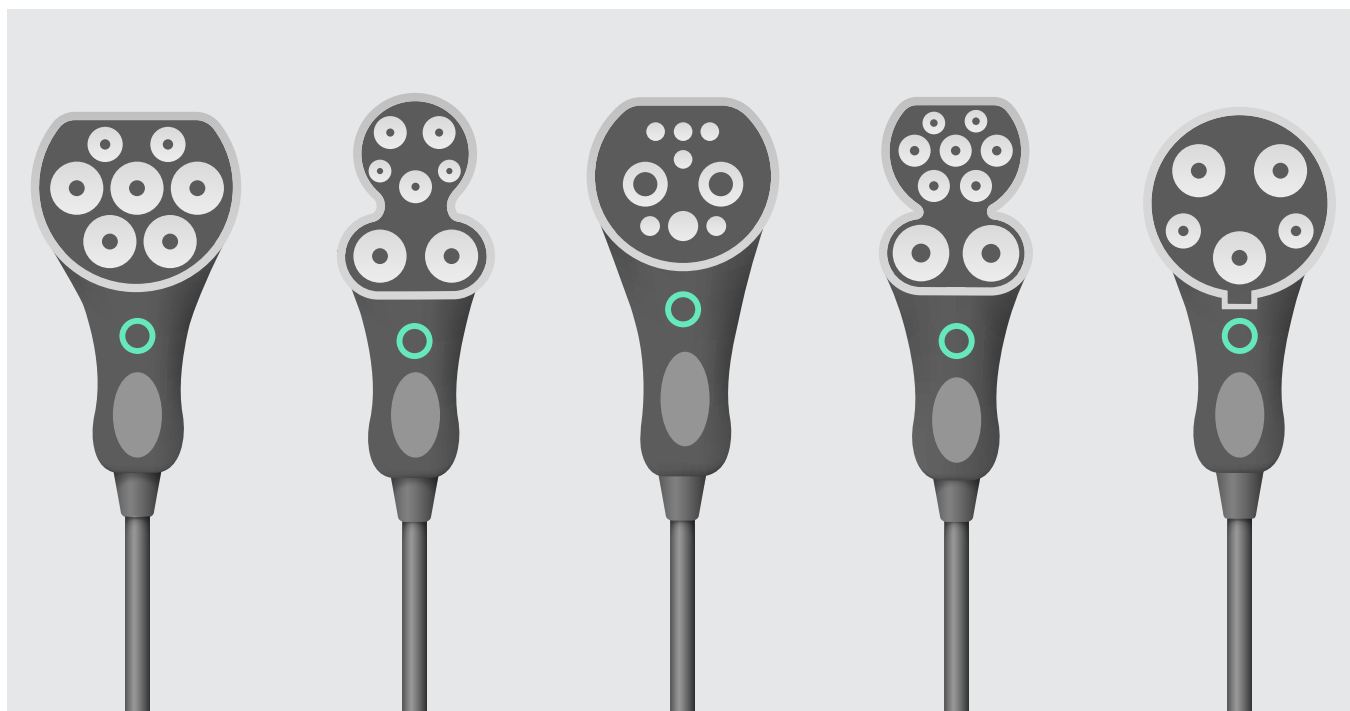
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What's Under the Hood?

EV Chargers: A Tale of Standards and Many Connectors



Rapidly growing electric vehicle (EV) sales are fueling growth in charging infrastructure and expected to be valued at \$40 billion per year by 2030 across all power levels. This will offer tremendous opportunities for companies along the EV charging value chain.¹

In this chapter of Wolfspeed's What's Under the Hood series we introduce various standard charging power levels and describe the variety of EV charger plugs used globally. Finally, we discuss the types and standards of communication between vehicle and charger, and charger and grid.

Although the most common type of EV charger is one that plugs into a standard wall outlet at home, there are standards for different AC power levels and DC fast charging (Figure 1). The first two charging power levels are based on AC supply and use the EV's onboard charger (OBC) to convert AC power from the conventional AC grid to DC.

Each level typically uses plugs and communication pins and protocols governed by international (IEC and ISO) or national standards, or Tesla.

LEVEL 1 CHARGING

Level 1 equipment utilizes single-phase 120 V AC, typically from a standard household outlet that is rated

for a maximum of 15 A with 12 A derating with circuit breakers. This limits the maximum available power to 1.4 kW, but dedicated 20 A outlets can take that up to 2.4 kW.

Level 1 is used mainly in North America, because the lowest domestic mains voltage in the rest of the world is about twice that level. This level of charging delivers a driving range of about 4-6 miles (6.4-9.7 km) per hour, taking 40-50 hours to fully charge from empty.^{2,3}

LEVEL 2 CHARGING

AC Level 2 equipment offers charging with household 240 V in Europe and other parts of the world. At 3.3 kW to 22 kW, it can deliver about 12-54 miles (19.3-86.9 km) per hour. From empty to a fully charged EV, Level 2 charging takes anywhere from 4-10 hours.²

The specification provides for up to 80 A (19.2 kW maximum) on a single phase, but most outlets are rated 30-40 A. At 40 A, the available maximum power is only 9.6 kW. However, with special multi-phase circuits, such as those provided at commercial U.S. charging locations, up to 22 kW can be achieved. More than 80% of the public EV supply equipment (EVSE) in the U.S. is estimated to be Level 2.³

LEVEL 3 CHARGING

At Level 3, also called DC Level 2 or DC Fast Charging

(DCFC), EVSE can charge an EV from empty to 80% in just 15-45 minutes, typically adding anywhere from 100 to more than 200 miles (160.9-321.8 km) of driving range in one hour.

Utilizing three-phase AC-to-HVDC (vehicle battery voltage), these chargers require dedicated infrastructure to deliver 50-300+ kW, which is particularly useful for medium- to heavy-duty EVs like vans and trucks, as well as passenger EVs on long road trips.

About 15% of public EVSE ports in the U.S. are estimated to be able to support DC fast chargers.³

STANDARDS AND PLUGS

The EV industry has not agreed on a single AC or DC connector, and there are significantly more plugs (connectors) than power levels for EV charging. Depending on the EV brand and country, the connector varies in shape, size, and pin configuration.

In general, all connectors use two or more large pins for power—L1, L2, L3 for AC phase lines, N for neutral, AUX for auxiliary, and PE or GND for protective earth or ground—and several smaller pins for communication control pilot (CP), proximity pilot (PP), and controller area network (CAN), as well as proprietary pins (Figure 2).

SAE J1772: The J1772—J-plug or the Yazaki connector—is specified in IEC 62196-2 as an implementation of the Type 1 connector for charging with single-phase AC. Although specified for both Levels 1 and 2, it is mostly used in the U.S. and Japan. Tesla plugs can use an adapter to charge using the J-plug.

The Type 1 connector has a round housing with five pins; there are two AC power pins, an earth wire, and two signal pins: PP and CP.

Mennekes: Defined as the Type 2 connector by IEC, it is standard in Europe for Level 2 charging. Tesla uses the Type 2 connector in Europe for AC and DC charging. The connector has five power pins for neutral and three AC line phases and earth, allowing use for both single- and three-phase charging. It also has two small signal pins for CP and PP.

GB/T: This is short for guojia biao zhun/tuijian, meaning it is a recommended (but not mandatory) national standard. China's GB/T 20234-2015 standard adopts an AC connector that is similar to but not compatible with the Type 2 Mennekes connector. The plug allows AC charging at 8 kW or 27.7 kW with currents 10/16/32 A at 250 V or 16/32/64 A at 440 V.

For DC charging, GB/T has a different plug that is unique in its ability to simultaneously charge both the low-voltage auxiliary battery and the high-voltage traction battery in the EV.

CCS: The combined charging system (CCS) standard unites AC and DC charging into a single connector that

has been widely adopted in the U.S., the E.U., and South Korea. In the U.S., CCS 1 places two additional DC power pins below the AC J1772 configuration. The E.U. uses CCS 2 that similarly combines the AC Type 2 connector with the DC power pins. Also called combo, the CCS connector complies with IEC 62196-1, 62196-2, and 62196-3 standards.

CHAdemo: This standard for DC fast-charging developed by a consortium of Japanese companies, including Toyota, Nissan, and Mitsubishi, has been published as IEC 61851-23, 61851-24, and 62196-3 as well as IEEE 2030.1.1TM-2015. However, in the U.S. only Nissan and Mitsubishi sell EVs with this connector.

CHAdemo uses “Type 4” EV connectors that have three power pins and six signal pins.

Tesla Connector: This proprietary plug supports Levels 1 through 3 of charging conditions. The plug, the only option available with Tesla cars in the U.S., uses three power pins (including earth) and two signal pins. Tesla plugs are unique in using the same connector and pins for both AC and DC charging.

In Europe, however, Tesla supplies a Type 2 cable with all models and a CCS 2 adapter with Model X and S (Model 3 uses CCS 2) and separately sells a CHAdemo adapter.⁴

COMMUNICATION PROTOCOLS

The way the vehicle, charger, and grid talk to each other is standardized and focused on two main communication flows—between vehicle and charger, and between charger and grid. The information that needs to be conveyed by the signal pins in the various connectors discussed above is guided by the standards IEC 61851, ISO 15118, DIN 70121, and VDV 261, which define multiple levels of functionality. Each function uses a different communication method and provides different levels of features and status support (Figure 3).

Low-level communication (IEC 61851): It provides limited functionality related to charging state and maximum current and uses the proximity pilot pin to determine the status.

Medium-level communication (IEC 61851-1): It uses the control pilot and pulse-width modulated (PWM) signals that alternate between two defined levels. The EVSE specifies the maximum charging current for the EV via the duty cycle. The IEC 61851-1 standard defines the applicable duty cycle values. While the functionality is similar to that at the low level, high-level communication can be forced.

High-level communication (IEC 61851-1): A requirement for DC charging, this level uses IPv6-based protocol structure and power line communication (PLC) technology over dedicated pins, such as CP and PE in CCS. Two common protocols are ISO 15118-3- and DIN 70121-compliant signal-level attenuation characterization (SLAC) and CAN, with the latter used by DC GB/T and DC CHAdemo.

Charger to grid: The charger-to-grid communication happens over ethernet (or wirelessly through cell networks) using the open charge point protocol (OCPP), an application protocol that allows EVSE to talk through a central management system. The vision of OCPP is to make any EV charger work with any charger management software, and possibly support value-added services.

CONCLUSION

EV charging infrastructure landscape currently has a large number of connectors and siloed service providers, which limits “charger roaming” or the ability to use any charging station closest to the EV owner. But this last challenge to widespread and rapid EV adoption is already being addressed through industry effort. For instance, more than 50% of EVs in the U.S. have now adopted the CCS standard⁵, and Tesla, which prohibits U.S. non-Tesla EVs from its chargers using software validation, has opened access to its vast charging infrastructure in Europe.⁶

As this market continues to evolve and place new requirements on designers, keep abreast of the latest application trends and solutions at Wolfspeed’s Power Knowledge Center.

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WOLFSPEED SILICON CARBIDE

Powering the electrification revolution



What's Under the Hood?

Onboard Chargers:

Filling Up The Electric Ride

The electrification of transportation is built on innovative developments, not just in battery technology and fast chargers, but also in onboard chargers (OBCs) that support up to Level 2 charging from ever smaller, lighter, cooler, and cheaper solutions.

In this chapter of Wolfspeed's What's Under the Hood series, shine a light on OBC functionality, architecture, and learn how they are so important to maintaining battery health.

THE OBC'S JOB

The OBC (Figure 1) handles the critical function of charging the high-voltage (HV) DC battery pack from an infrastructure power grid when an EV connects to a Level 1 or Level 2 wall outlet or electric vehicle supply equipment (EVSE) with a suitable cable. Simple as it seems, there's more to this functionality:

- **Power conversion:** The OBC takes Level 1 or 2 AC input, converts it to DC and outputs the appropriate voltage and current. Depending on the EV battery pack architecture, the DC output may be anywhere between 200 VDC and over 900 VDC. The OBC delivers 1.3-19.2 kW for single-phase AC home charging or 11-22 kW for multiphase AC such as in commercial charging. Additionally, there is a trend toward bidirectional OBCs so that EVs can act as energy storage systems (ESS) for home or back-power the grid.
- **Communication:** The OBC is responsible for communicating the battery's remaining charge status, any faults in the system, and the plug-in/ongoing charging status. This communication is important, for instance, to disable EV traction while the vehicle is plugged in.
- **Li-ion charging profile:** The charger handles the battery pack's charge profile that may comprise 3-4 stages. The OBC monitors the charge being delivered by measuring the current flowing to the battery pack or, in the case of bidirectional functionality, to the grid.

LI-ION CHARGE PROFILE

The OBC controls the current and voltage at which the battery is charged to extend battery lifespan. This is done by offering either constant current or constant voltage charging, depending on the charge state of the battery.

As shown in Figure 2, a typical Li-Ion charging profile¹

comprises modes that correspond to charge states:

- **Pre-charge:** This pseudo-healing mode allows for recovery of the passivation layer that may dissolve when the battery stays for long in a deeply discharged state. In this mode, the OBC charges the battery at a low C-rate, typically 0.1C at a specified current of IPRE, until the cell voltage reaches the threshold VPRE of 2.5-3 V.
- **Constant current:** This fast charge mode uses constant current regulation, usually at 0.5C to 1C (ICHG) and contributes to most of the cell charge.
- **Constant voltage:** To avoid the risk of overcharging, which would reduce battery life, the OBC enters a constant voltage regulation stage close to the peak cell voltage of 4.2 V. The battery is usually 65-70% charged at this point and current begins to taper off at fixed voltage.
- **Charge termination:** When charging enters its completion mode, current delivered into the battery pack (IEND) is decreased to 3-5% of the rated capacity (Ah) or 0.02C and charge delivery is eventually stopped to avoid overcharging.
- **Recharge:** When the battery voltage drops, from system use or from a long period of disuse, and reaches a recharge threshold voltage, VRECHG, a "top-up" charge is started.

OBC ARCHITECTURE

The key components of the OBC include an AC-DC rectifier that may be integrated with a single- or three-phase power factor correction (PFC) stage that ensures real power, as opposed to reactive power, is passed to the battery. After this an isolated DC-DC converter, which typically uses a resonant architecture and soft switching for lower losses, provides the isolation and a controllable voltage source. A microcontroller offers the control necessary to handle the complex requirements of the charging profile, faults, and communication (Figure 3).

Let us take a closer look at these components.

POWER FACTOR CORRECTOR

The PFC stage is often integrated into the input stage that comprises an EMI filter, a full-bridge, bridgeless, or totem pole rectifier, and one or more capacitors; parallel-connected capacitors being the main components

handling PFC. But why is it important?

AC voltage and current are sinusoidal and change continuously in both magnitude and direction. AC power at any instant is given by the product of the voltage and current at exactly that instant. Reactive components in an AC circuit, cause the voltage and current to go “out of sync.” (Figure 4).

This means that significantly more current is delivered during a low voltage part of each AC cycle. Therefore, even as low “real” power is being transferred, the circuit must carry large currents to deliver reactive power that is given back by the load in the next cycle. For instance, a 120 V outlet delivering 12 A at 50% reactive power (PFC = 0.5), delivers real power of just 720 W instead of 1.44 kW. This reactive power can also cause excess heating in the system that is avoidable and could lead to thermal issues.

The full-bridge rectifier, the smoothing capacitor, and capacitive and inductive loading on the DC output cause high reactive power. Active PFC uses a boost converter to align the current and voltage waveforms with the help of an inductor. Designers choose from one of several topologies – full-bridge boost, bridgeless for lower losses by avoiding the input diode bridge, totem pole with or without diodes, and interleaved to accommodate multiple phases for higher power.

Modes of operation to control the current include:

- **Continuous Conduction Mode (CCM):** It is the most common for high-power applications, like the OBC. It continuously passes current to a switching reactor, the inductor.
- **Transition Mode (TM):** Also called Critical Conduction Mode (CrCM or CRM), it allows the inductor current to reach 0 A. It employs zero current switching (ZCS).
- **Discontinuous Conduction Mode (DCM):** Current drops to 0 A and remains off for a certain interval. However, it requires higher peak currents.

BIDIRECTIONAL DC-DC

The DC-DC converter offers a controlled output to the HV battery. Its topology is typically a resonant converter with soft switching to reduce losses. Bidirectionality is often implemented using the CLLC topology. The output voltage and current can change with switching frequency as the latter affects gain. A high-frequency transformer offers galvanic isolation between the DC-DC output and the AC wall source so as to protect against voltage spikes during fault events. Designers prefer to use higher switching frequency so that they can use a smaller, lighter high-frequency transformer.

The soft switching benefits over hard switching are shown in Figure 5. With soft switching, zero voltage (ZVS) and zero current switching (ZCS) can be achieved to ensure that voltage or current across the MOSFET are zero when it is turned ON or OFF. This reduces power loss during switching.

In the gain curve shown in Figure 5, current leads voltage and ZCS is achieved in region 1. Regions 2 and 3 offer ZVS operation. DC gain varies across these regions with quality factor, Q , changing depending on load level. Operation under ZVS may be preferred over ZCS because at very high input voltages, turn-on losses can reduce efficiency and limit switching frequency.²

DIGITAL CONTROLLER

The controller block implements control algorithms for both the PFC and the DC-DC converter using feedback loops (Figure 6). A typical controller card or sub-system includes a processor, its own power supply unit, amplifiers, sensors, and voltage and current feedback circuitry.³

The microcontroller itself often includes high-precision analog-to-digital converters (ADCs) for accurate current and voltage sensing as well as fault measurement. It has configurable and high-resolution pulse-width modulated (PWM) outputs for switching MOSFETs. It may have multiple processing cores to handle the complex math and additional features, such as fault triggers, as well as safety functionality like redundant cores.

CONCLUSION

Even as the basic functionality described here holds, this critical system of EVs continues to evolve toward higher power and three-phase performance with constant pressure to keep the size, weight, and cost down.

Find information on other EV systems and the changing application requirements as well as reference designs to meet them at Wolfspeed’s Power Knowledge Center.

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What's Under the Hood?

DC Fast Chargers: Delivering Rapid Top-Ups for EVs

If the EV charging infrastructure required waiting in long lines for hours, there would be no market for EVs. Thanks to public charge points that are trending toward increasing power delivery for ever shorter charge times, EVs are finding avid buyers. Moreover, the supporting charging infrastructure is expanding rapidly — the global EV fast-charging system market could reach \$10.82 billion by 2031, growing with a CAGR of nearly 16.6% during 2022-2031.¹

There are two ways to charge an EV — via a Level 1 or 2 AC onboard charger (OBC), often overnight at home or via a DC fast charger (DCFC). In AC charging, the OBC converts the AC to DC in the vehicle but with DC fast charging, the conversion takes place in the charging station. DCFCs can reduce charge times down to anywhere between 15 and 45 minutes for an 80% top-up. This does impact battery life, however, such ultra-fast charging is generally recommended for commercial vehicles with large battery packs or smaller EVs on long road trips.

In this final chapter of Wolfsped's What's Under the Hood series explore DC fast chargers, their power characteristics, architecture, communications, and interoperability.

FAST CHARGER FUNCTIONALITY

The DCFC delivers power at Level 3 (L3), the highest charger power level discussed in the article on charger standards.² DC fast charging bypasses the OBC to charge the battery directly and significantly reduce the time it takes to charge the EV. However, the OBC is still the “brains” of the charging operation that monitors and communicates with the fast charger the battery pack charge and system status, and handles protection triggers.

The fast chargers host connectors that are compliant with one or more standards or proprietary specifications — CCS, CHAdeMO, GB/T, and Tesla2 — and output about 200 VDC and up to the 900

-1000 VDC range to support a wide range of vehicles, including both hybrids and battery EVs (BEVs). The DCFCs take as input three-phase 400-600 VAC and, as such, are not meant for home use where the available single-phase AC at a lower voltage cannot support the targeted L3 output levels.

Today's DCFCs are available in broadly two types of implementations.

- **Standalone:** With the entire charger circuit and functionality from grid to vehicle in one box, these chargers output 50-250 kW of DC power. These units are fed directly by the medium voltage (MV) lines from the substation.
- **Split:** Sectioned into two as user unit and power as well as communications unit, the chargers deliver 175-350 kW to the vehicle. The user unit is fed over a [relatively] low-voltage (LV) DC bus from the power unit. The split charger allows the use of a large galvanic isolation transformer between the power unit and the MV line from the substation. The benefits are potentially lower noise and more available space at the user unit area.

HIGH-LEVEL ARCHITECTURE

There is significant customization in DCFC designs and there are probably as many architectures as there are charger brands (Figure 2).³ However, the basic architecture for all includes a three-phase PFC, DC-DC converter, and a digital controller — similar to the OBC architecture discussed in that tutorial.⁴ Other features typical in DCFCs include protection mechanisms such as ground-fault detection shown in Figure 2, connections to the network, and various user and mechanical functions.

The overall design is modular with “power blocks” paralleled to achieve the power levels desired. Each block is typically 100-120 kW and includes the PFC and isolated DC-DC, such as with an interleaved LLC circuit topology. This allows power savings by allowing selective turning ON and OFF of blocks to meet the output desired at any time.

Common topologies used for three-phase PFC are totem pole and Vienna (Figure 3) with the latter becoming the most popular because it allows for three-level switching that offers three distinct advantages. First, only half of the total output voltage is applied to the switches used in the circuit, resulting in lower switching losses. Second, the peak-to-peak voltage applied to the inductor is half the total output voltage leading to less current ripple, smaller inductors, and lower cost. Third, lower peak-to-peak switching voltages and currents means lower radiated EMI. Overall, this spells higher efficiency, lower voltage stress on components, and higher power density.

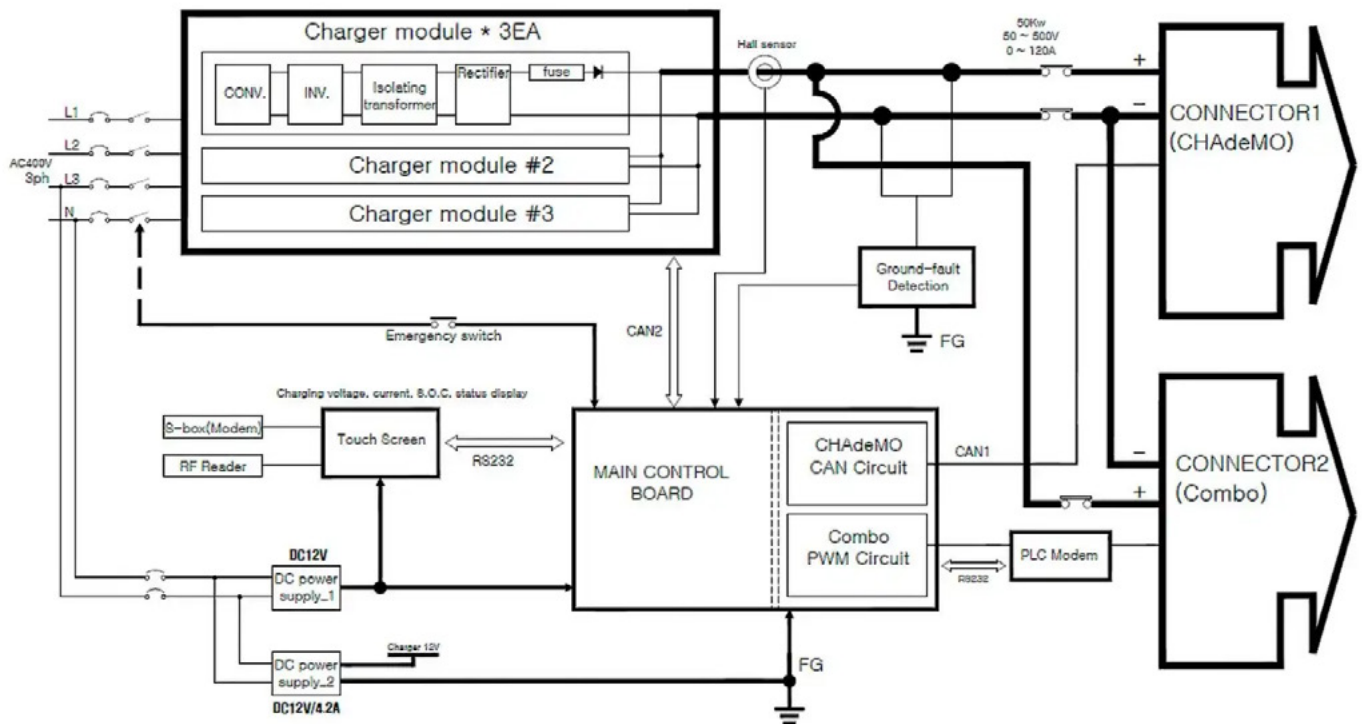


Figure 2: Block diagram of a standalone DC fast charging station. Source: Signet Systems Inc.³

The DC-DC converter is unidirectional, typically using a full-bridge LLC resonant topology (Figure 3) because DCFCs are not used to back-power the grid. The LLC circuit is interleaved to get higher power output per module. A single module, for example, might deliver 100 kW with 200 ARMS at 400 V or 125 ARMS at 800 V. Stacked with power modules, as shown in Figure 2, the charger block could then achieve much higher output — for example, 350 kW with 875 ARMS at 400 V or 438 ARMS at 800 V.

COMMUNICATIONS & INTEROPERABILITY

DCFCs need to inform central management systems (CMS) of their status and charge tracked for customer billing, and enable customer authentication and access, dynamic load management of the power grid, charge

station remote control, as well as remote firmware updates. While communication between EVs and charging stations is handled over IEC 61851 protocol, DCFCs use the Open Charge Point Protocol (OCPP) to talk to the CMS.

The OCPP, established in 2009 by the Open Charge Point Alliance, is used by EV Supply Equipment (EVSE) from over 40 manufacturers. An OCPP-compliant charging station can be networked through any available provider, wired or wireless. This network agnosticism allows for changing/upgrading of DCFC communication backbone with minimal disruption and at low cost. For example, charging locations typically prefer 4G and 5G cellular networks over the more cumbersome wired networks.

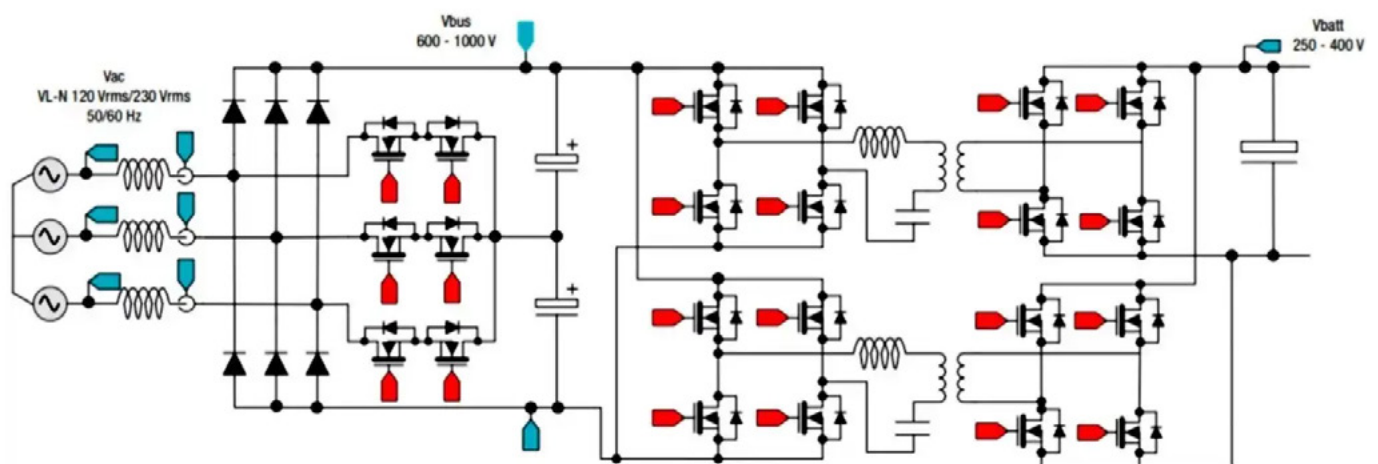


Figure 3: A typical power module comprises a three-phase PFC (Vienna topology shown) and an interleaved resonant DC-DC converter.

This interoperability forces the charging station manufacturers and network providers to compete on price, functionality and service, and innovation.

CONCLUSION

While the number of EVs on the road per public charging point globally rose to 9.2 at the end of 2021, this ratio is likely to continue growing and make it worthwhile for charging operators to install more fast chargers.⁵ There is already a wide variety of DCFC architectures, with many models offering multiple connector options, network-agnostic communication with the central management system, and up to 350 kW output for 80% charge top-ups within minutes.

To find more information on EV application trends and Wolfspeed's power solutions, visit the Automotive Applications Page.

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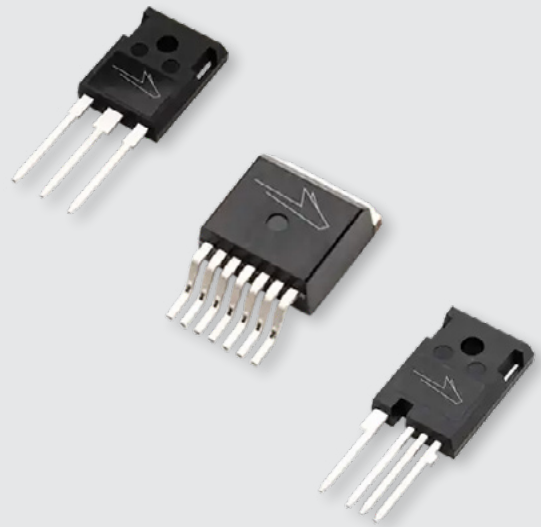
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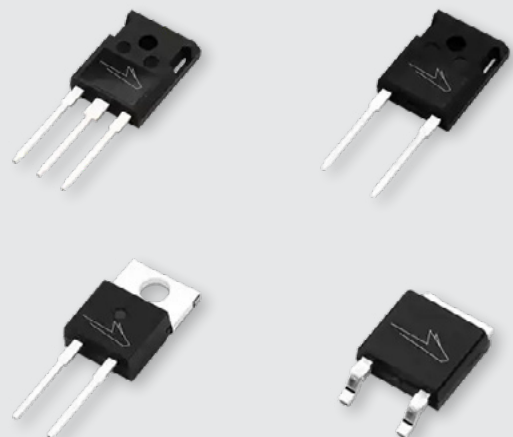
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1200 V DISCRETE SILICON CARBIDE SCHOTTKY DIODES

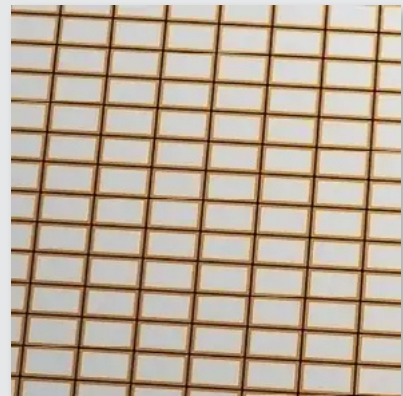
This auto qualified 1200 V Discrete Silicon Carbide Schottky Diodes feature the MPS design which is more robust and reliable than standard Schottky barrier diodes. Pairing Wolfspeed Silicon Carbide Diodes with Silicon Carbide MOSFETs creates a power combination of higher efficiency and reduced component pricing when purchased together.

[More Details](#)

Featured Products (continued)

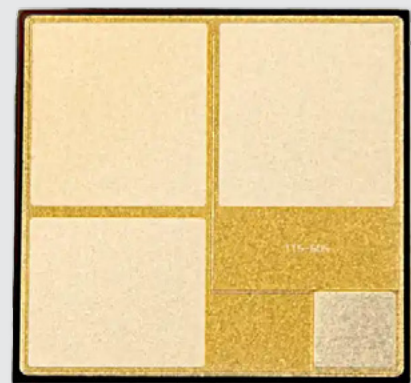
GENERATION 1200 V BARE DIE SILICON CARBIDE SCHOTTKY DIODES – E-SERIES

Wolfspeed's E-Series diodes are specifically designed to be robust and reliable in the harshest environments. As a result, the E-Series diodes are the industry's first 1200 V Silicon Carbide diodes to be automotive qualified for high-humidity/high-voltage/high-temperature tested. The E-Series family of diodes are ideal for onboard and off-board automotive charger applications.

[More Details](#)

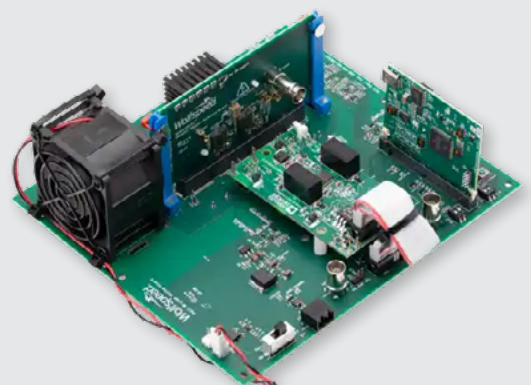
AUTOMOTIVE QUALIFIED GEN3+ 750 V SILICON CARBIDE BARE DIE MOSFETS

Wolfspeed's automotive qualified Gen 3+ family of 750 V Silicon Carbide MOSFETs are optimized for high power applications. This product is fully automotive qualified, with high blocking voltage with the industry leading low $R_{DS(on)}$ over temperature stability, enabling low conduction losses and highest figures of merit in the most demanding applications. Optimized for use in high power applications such as automotive drive trains and motor drives.

[More Details](#)

SPEEDVAL KIT™ MODULAR EVALUATION PLATFORM

Speed the transition from silicon to Silicon Carbide with the industry's most versatile modular evaluation platform providing a flexible set of building blocks for in-circuit evaluation of system performance. SpeedVal Kit's™ unique card-edge connection to the power daughter card enables users to change Silicon Carbide devices in seconds, meaning testing that once took weeks can now be completed in minutes.

[More Details](#)

Resources

REFERENCE DESIGN: 6.6 KW BI-DIRECTIONAL EV ONBOARD CHARGER

Wolfspeed's 6.6 kW Bi-Directional EV Onboard Charger demo board can accept 90 VAC- 265 VAC as an input and provide 250 VDC- 450 VDC at the output with >96% efficiency in both charging and inversion modes. Target applications of this reference design include the EV Charging Industry and the Energy Storage Industry.

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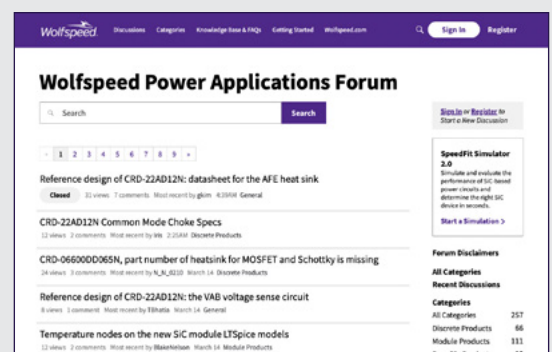
REFERENCE DESIGN: 30 KW DISCRETE INTERLEAVED LLC DC-DC CONVERTER

This reference design targets high-power-density, high-efficiency fast charger applications and features Wolfspeed's discrete 1200 V C3M Silicon Carbide MOSFETs and 650 V C6D Silicon Carbide Schottky Diodes. The reference design accommodates all levels of EV charging with a wide output voltage range of 200 V – 1000 V while maintaining a high power density of 6.5 kW/L and higher than 98% peak efficiency.

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POWER APPLICATIONS FORUM

Tap into more than 35 years of Silicon Carbide expertise at the Wolfspeed Power Applications Forum. Join our community and participate in technical dialogue that will help you advance your design. Access our knowledge base, ask technical questions in a community forum or reach us through private chat.

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Resources (continued)

SPEEDVAL KIT

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SPEEDFIT™ DESIGN SIMULATOR

Cut down on hours of comparative analysis with Wolfspeed's SpeedFit™ Design Simulator, a powerful online tool that allows designers to quickly evaluate different power conversion topologies and Silicon Carbide products. Our SpeedFit Design Simulator helps you:

- Select the right Wolfspeed Silicon Carbide product for your design
- Run simulations to predict and minimize conduction and switching losses
- Quickly compare different device and thermal configurations
- Generate circuit diagrams and a summary report to complete the design

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