Taking charge of electric vehicles – both in the vehicle and on the grid

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A plug-in hybrid electric vehicle (PHEV) requires a power electronic system between the power grid and the high-voltage battery pack located inside the vehicle. This electronic system is split into two parts: a charging station, which is also called electric vehicle service equipment (EVSE) or an off-board charger, and an onboard charger inside the vehicle.

A charging station is part of the grid infrastructure installed along a street, parking lot or in a home garage; its primary purpose is to supply the power to the PHEV for charging the battery. An onboard charger is responsible for the final stage of charging the battery pack. It takes the AC power source from the EVSE and transforms the power into the required battery-charging profile.

Despite having separate functions for charging a vehicle, similarities in the naming conventions ("on-" and "off-" board chargers) have caused general confusion about these two types of systems. While the onboard charger has to condition (convert to high-voltage DC) power from the off-board AC charger (**Figure 1**) before supplying it to the battery management system (BMS), the off-board DC charger works without an onboard charger and interfaces directly with the BMS.

In this paper, we will attempt to explain onboard chargers, how they work and why they're used. We will also explain charging stations and how they interact with onboard charger and EV BMS systems, along with various power-architecture implementations.

Onboard vs. off-board charging: power subsystems

The power subsystem (module) of an onboard charger and an off-board charger are split based
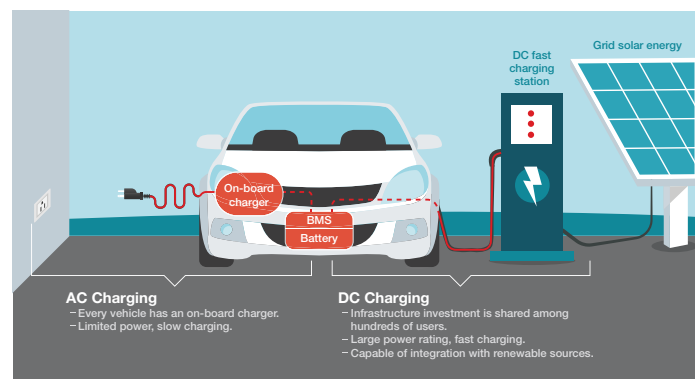
Figure 1. *The differences between AC/DC charging stations and onboard chargers.*

on the charging power levels, as shown in **Figure 2**. The power subsystem of an off-board (DC) charger is generally designed to transfer higher kilowatts of power and requires a more sophisticated BMS on the PHEV. In addition, it removes significant weight off the PHEV, which can increase the vehicle's overall efficiency. On the other hand, an onboard charger is generally designed for lower kilowatts of power transfer and adds significant weight to a PHEV.
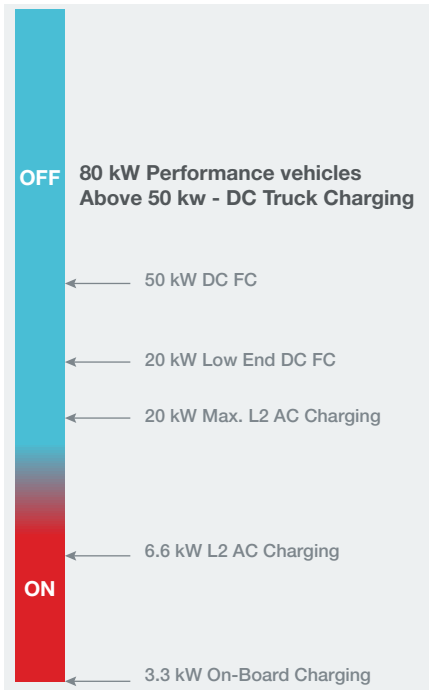
Figure 2. *Power and charging levels for onboard and off-board charging.*

The implications of charging levels, types, modes and charging time

Batteries all have different capacities; because they require different charging currents and voltages, both EVSE and onboard chargers must support different charging levels, types and modes, which ultimately determines the battery charging time. For example, a typical single-phase onboard charger converts the 3.5 kW power level, which requires 16 A of input current from a 220 V input voltage. An onboard 3.3 kW charger can recharge a depleted 16 kWh battery pack in a PHEV to a 95% charge in about four hours from a 240 V supply [1].

There are mainly two types of charging systems, as shown in **Figure 3**: AC and DC charging systems. An AC charger powers the battery through the vehicle's onboard charger, while a DC charger directly charges the vehicle's battery.

Let's first focus on AC charging stations, which the Society of Automotive Engineers (SAE) further characterized into standard levels.

A Level 1 EVSE (typically a residential charger) uses commonly available 120 VAC/230 VAC power sources, draws current in the order of a 12 A to 16 A range and can take anywhere between 12 to 17 hours to fully charge a 24 kWH battery.

A Level 2 EVSE (typically used in commercial spaces such as malls, offices, etc.) uses poly-phase 240 VAC sources to power a more robust vehicle charger and draws anywhere between 15 A and 80 A to completely charge a 24 kWH battery in about eight hours.

DC charging stations also happen to have an unofficial level not recognized by SAE, known as Level 3 DC. This type of charging station uses an external charger to supply high-voltage (300 V-750 V) DC at up to 400 A directly to the vehicle's battery.
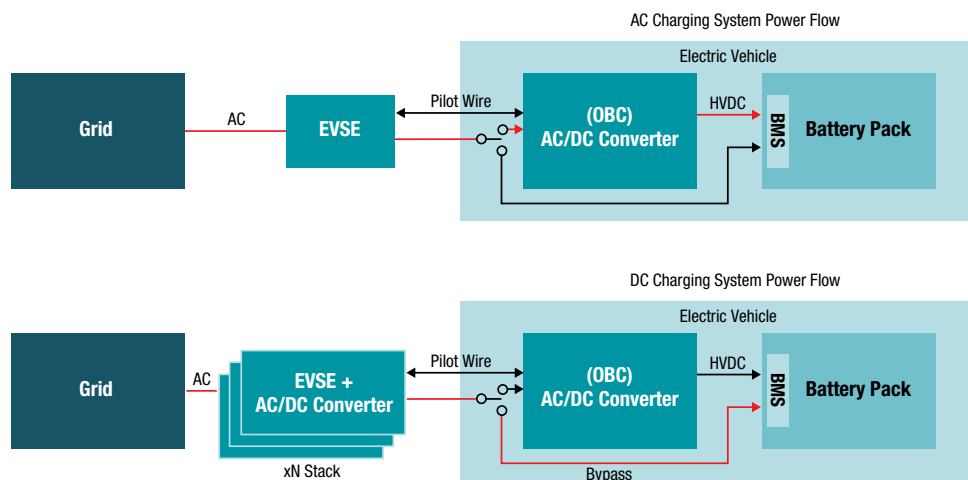

Figure 3. *The organization of charging levels 1, 2 and 3.*

Level 3 bypasses the onboard charger on the EV, as indicated by red line in **Figure 3**. Since high power is directly supplied into the vehicle, the overall time required to charge is much, much lower and explains why Level 3 has earned the name "fast charger." The charging time for a typical 24 kWH battery is less than 30 minutes, shown in **Table 1**.

As defined by International Electrotechnical Commission (IEC) modes definition (the IEC 62196 standard), there are four charging modes [2]:

- Mode 1 – slow charging from a regular electrical socket (single or three phase).

- Mode 2 – slow charging from a regular electrical socket, but equipped with an EV-specific protection arrangement.

- Mode 3 – either slow or fast charging using a specific EV multi-pin socket with control and protection functions (according to SAE J1772 and IEC 62196 standards).

- Mode 4 – fast charging using a special charger technology such as Charge de Move (CHAdeMO).

In addition, there are four plug types:

- Type 1 – single-phase vehicle coupler reflecting SAE J1772/2009 automotive plug specifications.

- Type 2 – single- and three-phase vehicle coupler reflecting the VDE-AR-E 2623-2-2 plug specifications.

- Type 3 – single- and three-phase vehicle coupler

equipped with safety shutters reflecting the EV Plug Alliance proposal.

- Type 4 – fast charge coupler for special systems such as CHAdeMO.

Safety codes and standards

Both onboard and off-board chargers need to comply with various specifications mandated by regional governments and utility boards depending on the location of deployment. In general, these are the key safety and operation requirements mandated:

- Electromagnetic compatibility (EMC) emission and immunity (U.S.: Federal Communications Commission Part 15 Class A; European Union (EU) European standard (EN): EN 55011, EN 55022 and IEC 61000-4).

- Efficiency (96% and up).

- Harmonics current total harmonic distortion (iTHD) <7% (complies with Institute of Electrical and Electronics Engineers [IEEE] 519 requirements).

- Enclosure protection (such as IP54).

- Connector types (CHAdeMO, combined charging system (CCS)1 (SAE J1772 combo), CCS2 (IEC 61851-23), GuoBiao standard GB/T.

- Safety compliance (in the U.S., Underwriters Laboratories (UL) 2202, UL 2231-1 and UL 2231-2. In Europe, IEC 62196, IEC 61851, Conformité Européene (CE) marking).

| EVSE type	Power supply	Charger power	Approximate charging time for a 24 kWH battery
AC charging station: Level 1 residential	120/230 VAC and 12 A to 16 A (single phase)	~1.44 kW to ~1.92 kW	~17 hours
AC charging station: Level 2 commercial	208/~240 VAC and 15 A to ~80 A (single/split phase)	~3.1 kW to ~19.2 kW	~8 hours
DC charging station: Level 3 fast chargers	300 to 600 VDC and max 400 A (poly phase)	From 120 kW up to 240 kW	~ 30 minutes

Table 1. The organization of EVSE levels 1, 2 and 3.
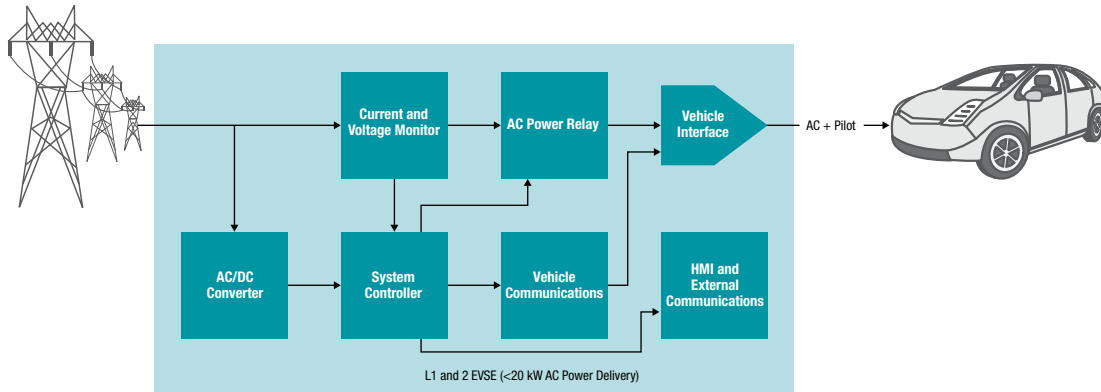
Figure 4. A typical block diagram of an AC charging station.

A systems-based approach to charging stations

Figure 4 shows a high-level block diagram for an AC charging station. This is a Level 2 commercial EV station where the AC charging station feeds the AC power from the grid directly into the EV. A current and voltage monitoring subsystem monitors the power transferred to the vehicle. An AC power relay makes or breaks the connection with the EV based on the discretion of the host controller. The vehicle interface analog front end controls the pilot signal coming out of the connector; this signal serves as a handshake between the EV and EVSE and enables negotiation with the EV for power status, available power and charge state.

The charger will include an AC/DC converter that provides the auxiliary supply necessary to power up various other components in these systems. As a system controller, a host microcontroller (MCU) typically manages all housekeeping services. A vehicle communication module could include interfaces like Controller Area Network (CAN), RS-485 and Ethernet to communicate with the EV as well as the charging station network. Most Level 2 charging stations also include a human-machine interface to improve the user experience with the charging station by providing visual status updates.

The main difference between AC charging stations and DC charging stations is the existence of the power factor correction (PFC) and DC-to-DC
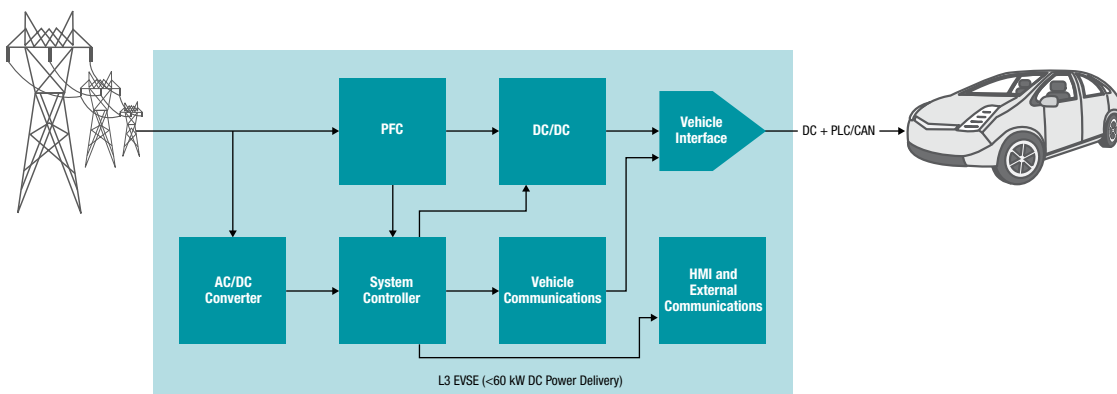
Figure 5. A typical block diagram of a DC charging station.

power stage, as shown in **Figure 5**. The PFC stage ensures that the input current is in phase with the grid voltage, thus improving the grid's overall power factor. Typically, a multilevel AC/DC stage takes the poly-phase AC from the grid and converts that to high-voltage DC. A second DC/DC stage can generate a stable DC for transfer to the EV, which bypasses the onboard charger power stage. Various power-stage architectures exist for the active PFC power stage: the two most popular are a single-phase architecture and a three-phase architecture.

Power architectures in EVSE and onboard chargers

As we discussed above, different charging levels yield different power ratings for the onboard charger or EVSE. This thereby divides the power electronics into a single-phase input architecture and a three-phase input architecture, respectively, where the biggest impact is on the PFC circuit.
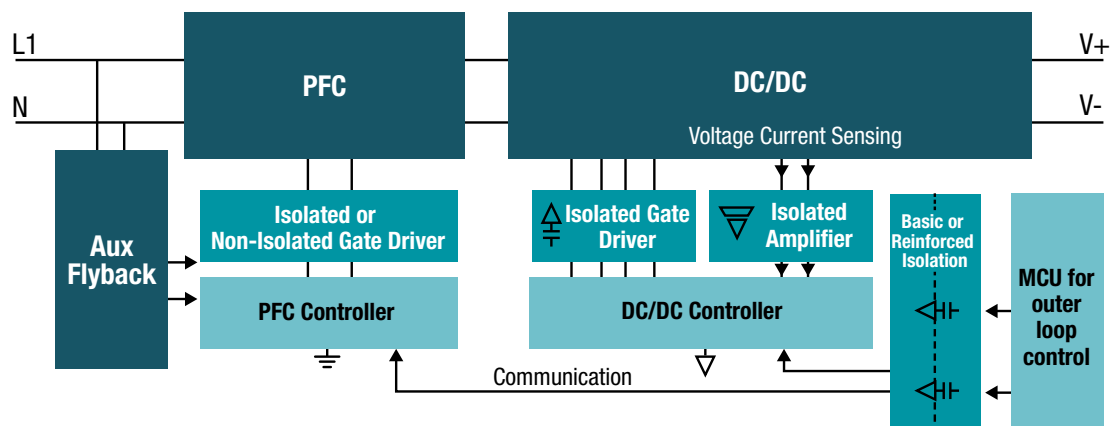
Single-phase architecture

PFC is the first step in an onboard charger/EVSE power stage. The aim of a PFC is to transform the input current close to a sinusoidal waveform that is in phase with the grid voltage, reducing the harmonics

injected to the power grid and improving the power factor to comply with various international standards. Second, the PFC generates a regulated output voltage to supply the downstream DC/DC converter.

Figure 6 is a block diagram of a single-phase input architecture. It requires a single-phase PFC, which takes one single phase and the neutral line as the input. You can use a single-stage boost PFC or an interleaved dual-stage PFC here. The single-stage PFC provides the benefit of simplicity and employs a low-cost controller. An interleaved topology benefits the input and output current cancellation, resulting in an easier electromagnetic interference (EMI) filter design, smaller storage elements and better thermal dissipation [3].

A DC/DC follows the PFC [1], provides the galvanic isolation [2] and generates the output [3], which strictly follows the charging profile of the high-voltage battery. The selection of a second-stage topology depends on the strength of the stresses on each active component [4]. You can choose from various topologies, including a resonant inductor-inductor-capacitor (LLC) half bridge, a hard-switched half bridge, a phase-shifted full bridge or a dual half bridge [5].

Figure 6. A single-phase input architecture.

Six other main subsystems include:

- An auxiliary power supply, which converts the line voltage input to auxiliary power rails. Examples include gate drivers, current-sensing circuits, voltage-sensing circuits and controllers. The topology is often an isolated, low-cost flyback topology.

- An isolated gate driver, which integrates a digital isolator and a conventional gate driver. It accepts a low-power input from the DC/DC controller integrated circuit (IC) at the low-voltage side and produces a high-current drive input for the gate of a high-power transistor at the high-voltage side. It may also integrate multiple safety features like overcurrent protection, Miller clamping and more.

- A non-isolated gate driver when isolation is not required because in a conventional continuous conduction mode boost architecture the PFC controller is referred to the same ground potential as the PFC power stage. There is a recent trend of moving towards a bridgeless architecture with the elimination of the traditional diode bridge, such as a totem-pole PFC. Isolated gate drivers are becoming more popular in PFC.

- The voltage sense, which monitors the voltage magnitude. A resistive divider normally divides the high voltage. The voltage drop indirectly represents the entire input voltage. Galvanic isolation is required to separate any electric hazard from the high voltage.

- The current sense, which monitors the magnitude and direction of the current flow at both the input and output of the DC/DC converter. It could be indirect current sensing using a Hall sensor, or direct current sensing using a shunt resistor.

- The signal isolation, which provides the galvanic isolation between two systems with different ground potentials. It allows the high-speed communication signals from the MCU located at the low-voltage side to the DC/DC controller or PFC controller located at the high-voltage side.

Three-phase architecture

Higher power delivery requires a three-phase input source at the grid. In order to maximize power transfer while minimizing the conductor volume, the grid usually supplies utility power in a three-phase manner, resulting in two architectures defined by whether or not they have a neutral connection.
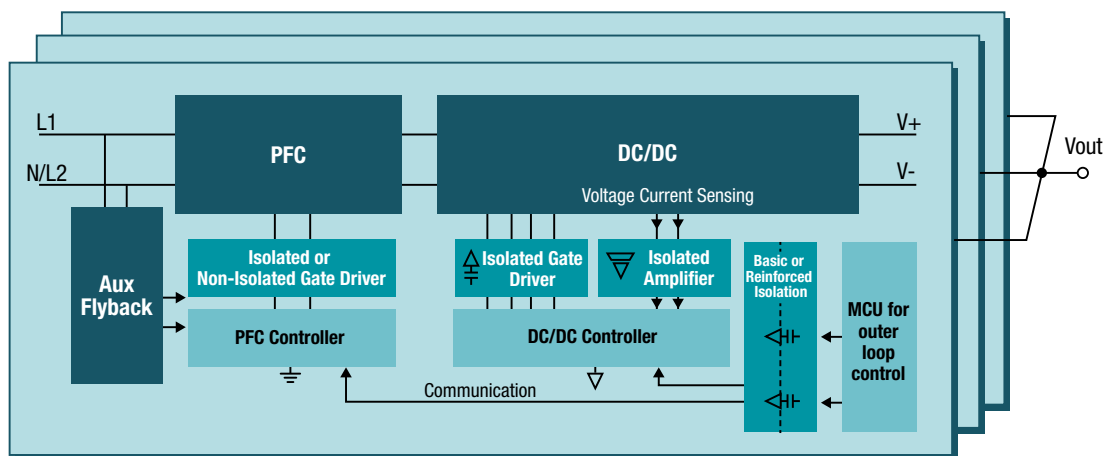

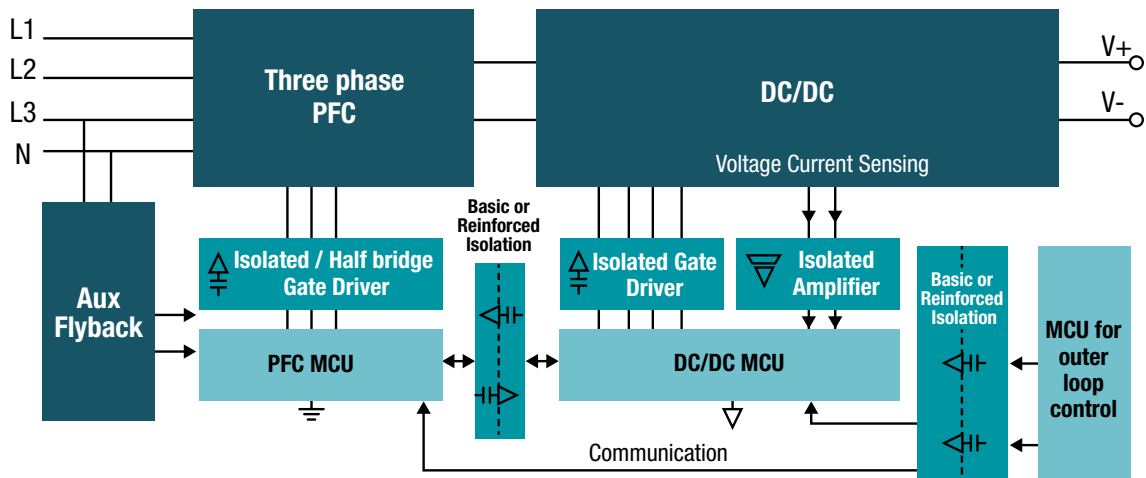*Figure 7*. The first type of three-phase input architecture.

Figure 8. *The second type of three-phase input architecture.*

Figure 7 illustrates the architecture of combining three single-phase modules. The input could be either from a phase-to-neutral voltage or a phase-to-phase voltage. The input single-phase modules provide the benefit of simpler and more efficient power-conversion circuits. All subsystems and requirements are similar to that of a single-phase-input on-board or EVSE charger, other than being multiplied by three. Although this structure might require an increased number of power transistors and sensing circuits, it reduces the current stress and filtering efforts. Therefore, you can use smaller components with a low profile. This modular combination also reduces stress on the PFC and DC/DC controlling resources, enabling you to implement the analog controller separately, with a lower cost and reduced control complexity for the central MCU.

Figure 8 illustrates the other architecture that connects all three phases (and optionally the neutral line simultaneously). The popular PFC topology here is three-phase active bridge, or Vienna rectifier [7]. In this case, the downstream DC/DC converter has to either work from around 700 VDC or connect in series to reduce the voltage stress on the power devices.

Additionally, the control algorithm becomes more complicated, which requires the design of powerful MCUs into the system.

Figure 8 also shows the example of using one MCU to control PFC (such as TI's C2000™ TMS320F280025 Real-Time Control MCU) and DC/DC (such as TI's C2000 TMS320F280049 Real-Time Control MCU), respectively. Unlike the single-phase modular approach, an isolated gate driver or half-bridge gate driver with high floating-voltage capability is required to drive the PFC stage. In **Figure 8**, you can use a non-isolated gate driver when a conventional boost architecture is implemented because the PFC power transistors are all located at the low side.

A complete onboard charger

Figure 9 shows a common analog control-based onboard charger power architecture with the power rating up to 3.3 kW. It accepts a universal input voltage of 85-265 V from the AC grid line and delivers an output DC voltage range of 200 V to 450 V at 16 A maximum. It includes an interleaved AC/DC converter with PFC, followed by a pulse-width modulation (PWM) analog-controlled phase-shifted full-bridge DC/DC converter. The DC/DC converter operates under zero voltage switching (ZVS) conditions to
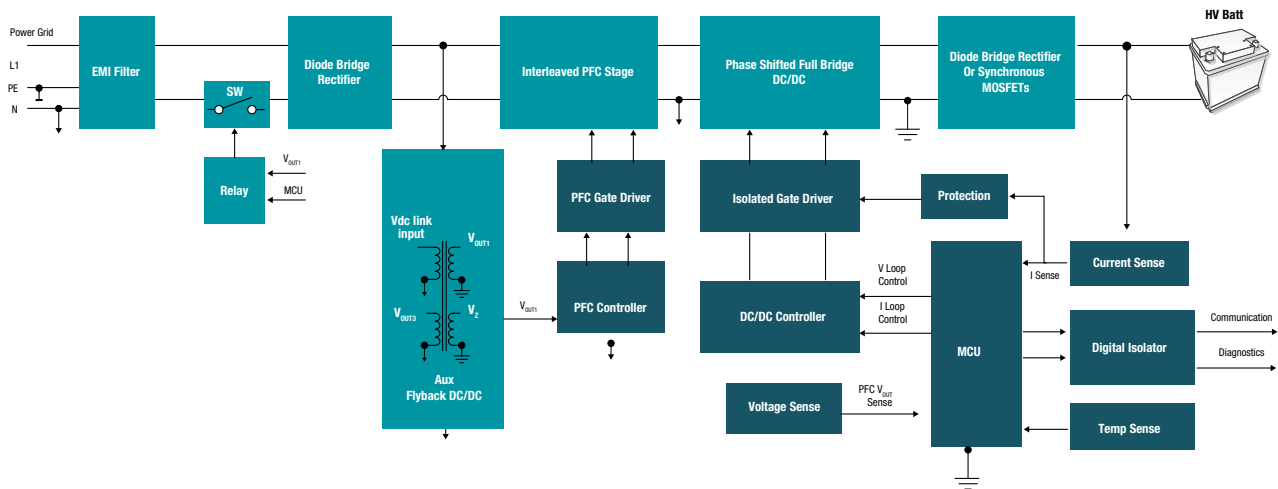
Figure 9. Analog control-based on-board charger reference diagram for a PHEV application. Click here to see detailed diagram in the Appendix.

increase efficiency and power density.

The interleaved PFC consists of two boost converters in parallel and operates 180 degrees out of phase. In this implementation, one bulky 3.3 kW PFC stage is split into two 1.65 kW PFC stages using more (but smaller) components for better heat distribution. Because the inductor's currents are out of phase, they cancel out each other and reduce the input ripple current. All of these advantages lead to higher power and a higher-density design. Other advantages of interleaving include easy scalability to higher powers and a lower profile.

The block diagram of the PFC stage consists of:

- The EMI filter, which aims to reduce differential-mode and common-mode noise in order to comply with EMC regulatory standards. It suppresses the EMI that may cause malfunction in other devices. It also protects the downstream power electronics against surge spikes and in-rush currents.

- The AC voltage input-sense function, which reads the input root-mean-square voltage. This information is important for the MCU to limit the input current in case the input voltage is lower

than the under-voltage threshold and to perform overvoltage protection.

- The interleaved PFC stage, which is controlled from an analog controller such as TI's UCC28070-Q1. This controller contains multiple innovations including current synthesis and quantized voltage feed forward to promote performance enhancements in power factor, efficiency, THD and transient response.

- A low-side gate driver, which accepts the low-power input from the PFC controller and produces a high-current drive input for the gate of a high-power transistor such as TI's UCC27524A-Q1. This driver is capable of delivering 5 A source and 5 A sink high peak current into the gate, along with rail-to-rail output and very small propagation delay (typically 13 ns).

- The unidirectional auxiliary power supply, which is controlled by a PWM controller such as TI's UCC28700-Q1. It converts from a high-voltage input of around 400 V down to multiple low-voltage rails. It supplies bias power to both the PFC side and DC/DC converter side. The typical values are 12 V for driving the metal-oxide semiconductor

field-effect transistors (MOSFETs), 16 V for driving the isolated gate driver and 6.5 V for powering the tracking low-dropout regulators (LDOs).

- The voltage and current sensors, which are directly done by the interleaved PFC controller. A resistor divider performs the voltage sense and a current-sense transformer performs the current sense.

A phase-shifted full-bridge topology with diode rectification at the secondary side is applied as the DC/DC. The block diagram consists of:

- The isolated voltage sense, which is placed at the input of the DC/DC converter is performed through an isolated amplifier such as TI's AMC1311-Q1. The isolated current sense, which is placed at the output of the DC/DC converter is performed through an isolated amplifier such as TI's AMC1301-Q1, plus an operational amplifier (op amp) such as TI's OPA376-Q1. The AMC1301-Q1 precisely reads the current input and converts it into a differential output, and the op amp converts the differential output to a single output.

- Temperature sensors such as TI's LMT87-Q1 are placed close to the power transistors in order to maintain the health of the power transistors during their active operation. Checking the case or internal temperature (depending on the position of the sensor) provides the protection. It immediately shuts down the system once the temperature rises above the threshold.

- The isolated gate driver, which could be either a single channel such as TI's ISO5451-Q1 or an isolated dual channel such as TI's UCC21520-Q1. It accepts the low-power input from the DC/DC controller IC at the low-voltage side and produces a high-current drive to the gate of the MOSFETs at the high-voltage side.

- The DC/DC converter, which takes the output from PFC and converts it into a dedicated DC output that strictly follows the battery-charging profile. The phase-shifted full-bridge controller, such as TI's UCC28951-Q1, drives all MOSFETs at the primary side. The phase-shifted full-bridge topology has the main advantage of being ZVS, significantly higher efficiency and low EMI.

- The MCU, which monitors the overall status of the system. It generates the output voltage and current references for manipulating the voltage and current-loop control of the DC/DC controller. It also reads temperatures, controls the fan and interfaces with the liquid crystal display (LCD) and user interfaces. Additionally, it interfaces digital data with other MCUs in the vehicle through a CAN hardware interface.

Conclusion

As more EVs and HEVs hit the road around the world, automotive system developers will need to improve efficiency and lower battery charging times in these vehicles, all without adding too much weight. Both the EVSE and the onboard charger will play critical roles in the deployment of battery-powered vehicles.

While industrial designers typically design the EVSE and automotive suppliers design the vehicle, the technologies must work seamlessly. With this in mind, in this paper we've attempted to dispel any confusion between onboard chargers and charging stations. It may seem like a simple distinction – an onboard charger is located inside the vehicle because of its lighter weight, role in charging the battery and safety compliance; a charging station stands outside the vehicle and supplies high voltage and high power to either the onboard charger or the battery directly via

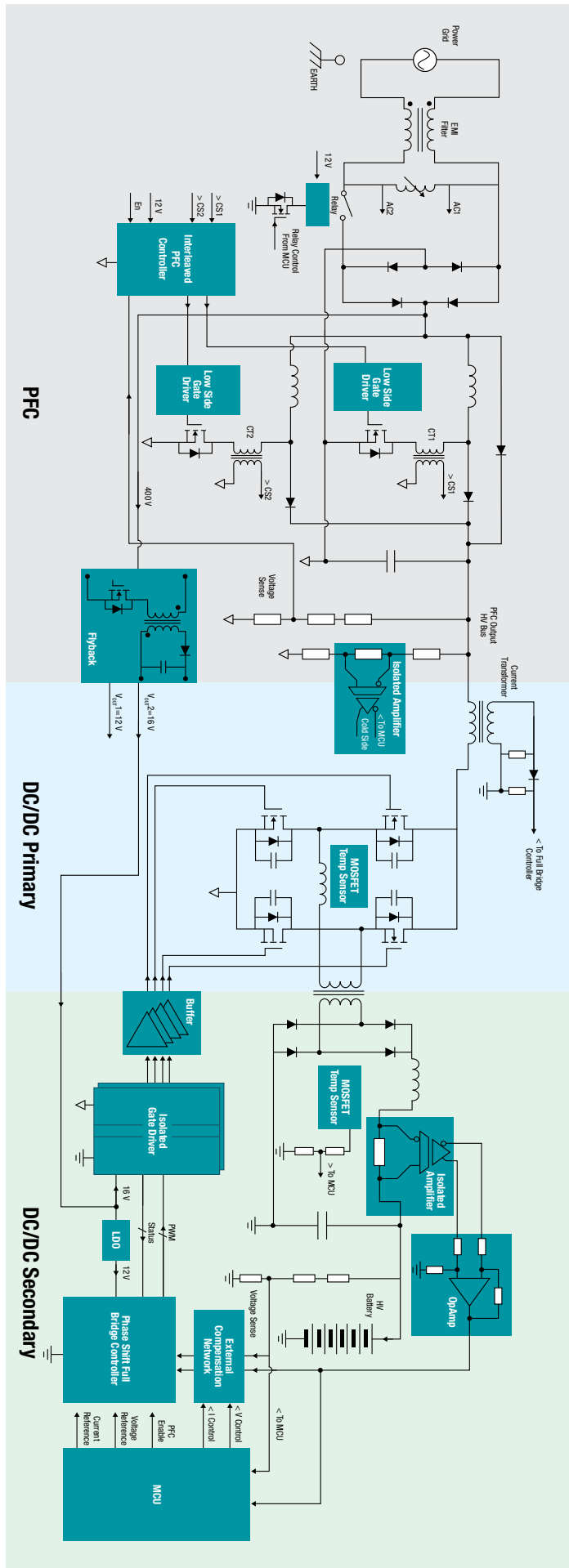a charging connector – there are more nuances to these systems.

Depending on the power-delivery capability, the charging station is categorized into various levels; the Level 3 charging station bypasses the onboard charger and supplies up to 240 kW directly to the vehicle's battery. Both the charging station and onboard charger implement a similar power architecture, where the input could be from a single phase or from three phases.

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