Optocouplers Ensure Safety and Enable Efficiency in Electric Vehicle Charging Stations

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White Paper

Abstract

The rapidly growing number of electric vehicles (EVs) on the road requires more charging infrastructures to top off energy so that EVs can get back on road quickly. An EV charging station is an important element in the charging infrastructure, which supplies electric energy to the EV and provides a network connection. The need for fast-charging systems results in several challenges, such as safety and efficiency, to charging station designs. This article descries how to use optocouplers in such designs to meet the aforementioned challenges.

Introduction of the EV Charging Station Market

The worldwide electrification of transportation process continues its fast speed through recent years. The global electric vehicle (EV) stock was about 180,000 by the end of 2012; soon this number grew by 3.7 times and reached at more than 665,000 through end of 2014, per International Energy Agency (IEA) Global EV Outlook reports. The report forecasts the global EV on the road to reach at 20 million by 2020 [1].

The rapid growth of EV fleets drives strong demand for charging infrastructures to extend the travel range of EVs. An EV charging station, also called an EVSE (Electric Vehicle Supply Equipment), is an important element in the charging infrastructure that supplies electric energy to the EVs and provides network connection. EVs in this context refer to plug-in electric vehicles, including all-electric cars or battery electric vehicles (BEVs), electric buses, and plug-in hybrids (PHEVs). Figure 1 shows an EV charging station charging an EV.

Figure 1 An Electric Vehicle Charging Station at Work

IHS Automotive forecasts the global EV charging stations installation base to skyrocket from 1 million units by 2014 to 13.6 million in 2020. The market-research firm estimates there will be 4.3 million units installed in the Americas, 4.1 million units in EMEA (Europe, Middle East and Africa), and 5.3 million in Asia (including Japan) [2]. Governments, for example, those in Germany, China, and the United States, are increasingly making funds available for the development of charging infrastructures. Recent development in China shows that China plans to deploy EV charging stations of 4.5 million units by 2020 [3]. This deployment will support the plan of cumulative production and sales of 5 million units of BEVs and PHEVs by 2020, reports the www.gov.cn, a website run by the central Chinese government [4], [5]. Comparing to 31,000 charging stations built through end of 2014 [5], the target of 4.5 million units implies a whopping compound annual growth rate (CAGR) of 129 percent.

Charging Station Standards

Along with the vast market opportunities of EV charging infrastructure, there are significant challenges that must be addressed. One of them is the lack of harmonized standards for key elements in a charging system, such as charge cords, protection mechanisms, power ratings, plug types, coupler configurations, and communication. This issue becomes more prominent for the fast-charging systems compared to the slower-charging AC because the fast-charging systems are often installed at public or semi-public areas and are meant to be shared; whereas incompatible systems make sharing difficult.

International Electrotechnical Commission (IEC) has a set of standards for EV charging. For example, IEC 61851-1:2010 EV applies to on-board and off-board equipment for charging EVs at standard AC supply voltages up to 1000 V and at DC voltages up to 1500 V. IEC 61851-23:2014 gives the requirements for DC EV charging stations. And IEC 62196-3:2014 specifies requirements for EV charging couplers [6], [7]. Globally, fast-charging systems currently face competing standards, one being the CHAdeMO protocol adopted by Japanese industry and the other being SAE International's J1772 Combined Charging System (CCS, also known as "Combo" standard) adopted by U.S. and German car manufacturers [1], [8]. They have different power rating specifications, coupler designs, and communication protocol between EVSE and EV. However, there are views stating "no standards war" as their charging systems feature all-in-one designs for both CHAdeMO and SAE Combo standards. One of the examples is the ABB's Terra 53 Charge Station [9]. Another relatively new competing standard is the Chinese GB/T 20234, which a revised version has been approved [10]. Some designs, such as Tesla's Superchargers, use proprietary charging technology [11].

Type of Charging – AC or DC

Putting aside the complication of standards, there are two primary ways to transfer electricity from outside the vehicle to the battery inside – AC or DC. The grid transmits power in AC form, and energy stored in the on-board battery is in DC; therefore, a charger is required to perform the conversion. Depending on whether the charger is installed inside of the vehicle, chargers can be categorized into an on-board charger (OBC) and an off-board charging station. An OBC accepts AC power source from the main supply available at home and workplace and convert to DC to charge the battery. AC charging normally is slow due to limited power rating of the charger because of limitation of allowable weight, space, and cost.

The DC charging method is often used in off-board charging stations. It supplies regulated DC power directly to the batteries inside the vehicle. As the DC charging equipment is installed at fixed locations with little constraint of size, its power rating can be as high as hundreds of kilowatts. For example, SAE J1772 specifies up to 100 kW for DC Level 2 [12]. CHAdeMO considers 50 kW as optimal output power, taking into consideration both factors of the cost of securing the maximum power at the charger location and the time it takes to charge the battery [13, p. "Optimal output power"]. Tesla's Superchargers consist of multiple Model S chargers that work in parallel to deliver up to 120 kW of DC power directly to the battery. This charging rate equates to 170 miles of range in about 30 minutes [11]. The DC fast-charging method shortens charging time from hours to minutes [11], [14]. Figure 2 illustrates the AC and DC charging methods. Table 1 lists the AC and DC charging power ratings and estimated charge time for reference.

Figure 2 AC Charging and DC Charging [15, p. 6]

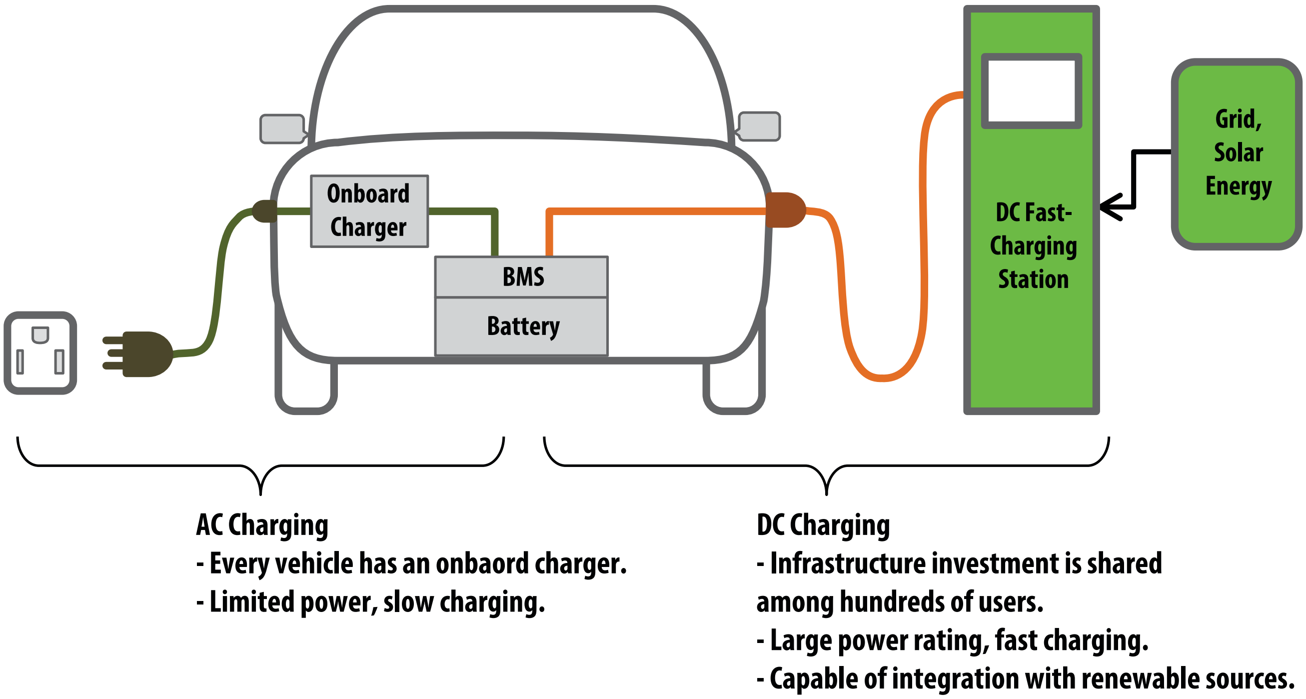


Table 1 AC Charging Electrical Ratings [14]

Charge Method	Nominal Supply Voltage	Maximum Continuous Current	Output Power	Estimated Charge Time[a]
AC Level 1	120 V AC Supply, 1-phase	12 A	1.4 kW	17 Hrs (OBC, SOC[b] - 20% to full)
		16 A	1.9 kW	
AC Level 2	208-240 V AC Supply, 1-phase	80 A	Up to 19.2 kW	SOC - 20% to full: 7 Hrs (3.3 kW OBC); 3.5 Hrs (7 kW OBC); 1.2 Hrs (20 kW OBC).
DC Level 1	200-500 V DC (EVSE Output)	80 A	Up to 40 kW	1.2 Hrs (SOC - 20% to 100%, 20 kW off-board charger)
DC Level 2	200-500 V DC (EVSE Output)	200 A	Up to 100 kW	20 min (SOC - 20% to 80%, 45 kW off-board charger)

a. For ease of discussion, only BEV (battery electric vehicle) examples are listed.

b. State of charge (SOC) is the equivalent of a fuel gauge for the battery pack in a BEV. An SOC of 0% means the battery pack is completely discharged; and 100% SOC means that it is fully charged.

NOTE

1. Rated power is at nominal configuration operating voltage and coupler rated current.
2. Ideal charge times assume 90% efficient chargers, 150W to 12V loads and no balancing of Traction Battery Pack.
3. BEV (25 kWh usable pack size) charging always starts at 20% SOC, faster than a 1C rate (total capacity charged in one hour) will also stop at 80% SOC instead of 100 percent.

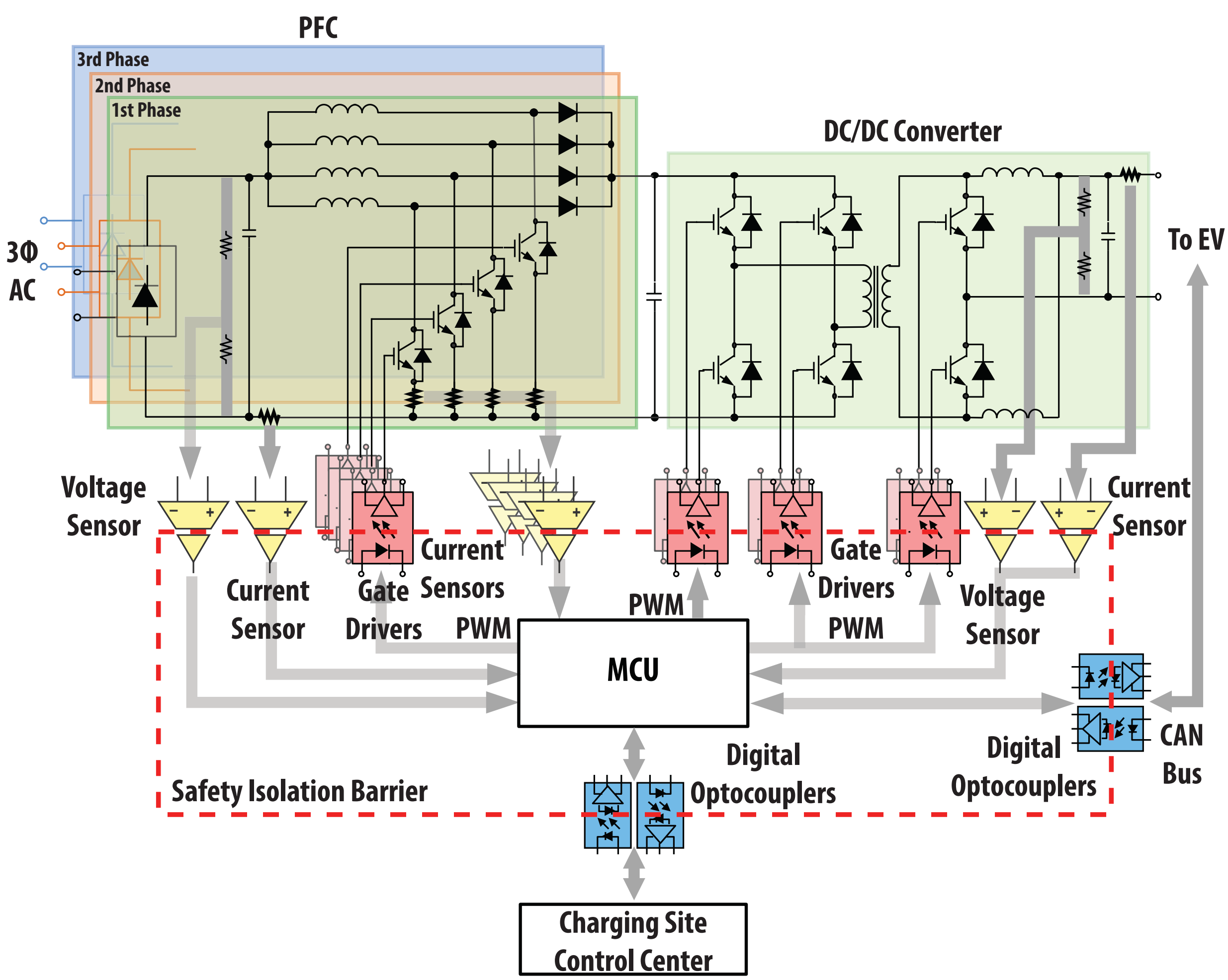
AC and DC chargers provide different charging speeds, and both are required to fit the EV drivers' different life styles. For example, an EV driver can use an AC charge in the scenarios where ample time is available, such as parking at home or at the workplace. DC fast charge has an obvious and important benefit as it can dramatically reduce charging time so that the EV drivers can continue their journey quickly. Fast charging is a key instrument in the successful roll-out of electric vehicles to reduce or eliminate range anxiety, especially for long-distance driving.

Charging Station Topology and Safety Isolation

Safety isolation need is present in all functions of the EV on-board electronic systems and EV charging stations. On-board systems include the high-voltage battery management system, DC-DC converter, electric motor drive inverter, and on-board charger [16]. For on-board systems, optocouplers, such as the R^{2}Coupler® product family from Avago Technologies, provide the complete range of automotive-grade devices with reinforced reliability and safety insulation capability, suitable for applications, such as gate driving, current/voltage sensing, and digital communication [17, pp. 25–29]. Discussions in this article focus on the isolation solution for off-board charger designs that often find that industrial-grade devices are sufficient.

An EV charging station typically includes functional blocks, such as an AC-to-DC rectifier, a power factor correction (PFC) stage, and DC-to-DC conversion to regulate the voltage level suitable to charge the battery in the vehicle. Figure 3 shows a simplified block diagram of a DC-charging station design. In a high-frequency isolation topology, galvanic isolation is provided in the DC-to-DC converter stage by a high frequency transformer and multiple isolation devices that provide various signal isolation functions while maintaining a safety isolation barrier between the high voltage power section and the low voltage controller section. Within all these stages, power devices such as MOSFETs and IGBTs, are used to perform switching function.

Figure 3 Block Diagram of an EV Charging Station



Located in the center of the system is the MCU, which controls the PFC, and the DC/DC converter with PWM signals. The control is based on voltage, current information, and other information, such as temperature, user inputs, and so on, to carry out calculations and control instructions to fulfill the designed functions. There are digital communication ports that communicate between the EVSE and the EV for charging control, and between the EVSE and the charging station control center and thereafter to the cloud for charging data reporting, remote monitoring, and diagnostics.

Optocouplers for Galvanic Isolation and Efficient Charging

As shown in Figure 3, a safety isolation barrier is built up along the line formed by optical coupling points of the various optocouplers. This is important to ensure that the design safety complies with regulatory standards. Besides galvanic isolation, the other key factor that often requires close attention in the power converter, including the one in EV charging station, is the power conversion efficiency. This paper introduces how to use several optocouplers from the catalog [17] to implement safety isolation in efficient charging station designs.

Gate Drivers

In an EV charger, a micro-controller unit (MCU) alters pulse-width modulation (PWM) signals to switch the power MOSFETs or IGBTs on and off and the duration of each status to regulate the output voltage/current according to the battery charging mode. A PWM signal from the MCU normally requires amplification to increase the output current to switch the power device at the desired frequency by driving the gate of an MOSFET or IGBT. Therefore, such a device is called a gate driver.

Gate drivers, such as those offered in the catalog [17] provide a complete portfolio, from basic gate drivers to feature-rich integrated gate drivers, to meet the design needs of efficient driving and protection. For instance, the ACPL-W346 gate driver features 2.5 A output current, rail-to-rail output voltage range, and a 55-ns very short propagation delay time. These electrical specifications are essential for designs with the aim of high power conversion efficiency. Packaged in an SSO-6 small surface-mount device, this part has an isolation voltage rating of 5000 Vrms for 1 minute per the UL1577 standard, and 1140 Vpeak per the IEC/EN/DIN EN 60747-5-5 standard. These standard approvals ensure the safety of the controller and the user side.

In EV charging station designs, besides choosing optimal power conversion topologies such as those described in [18], [19], and [20], choosing advanced power devices and appropriate gate drivers can help achieve efficiency goals. Recently, silicon carbide (SiC) MOSFETs are rapidly emerging into the commercial power device market that deliver several benefits over conventional silicon-based power MOSFETs and IGBTs. One of the benefits is that they reduce switching losses as a high voltage SiC MOSFET does not have the tail current losses found with IGBTs. In addition, the SiC MOSFET's high current density and small die size results in lower capacitance than those of silicon MOSFETs; hence, higher switching frequency operating is possible, which helps improve system efficiency [21]. Experimental results in [22] show that the improvement is significant. The experimental designs used the ACPL-W346 and ACPL-339J with suitable buffer stages, respectively, work with the CREE C2M SiC MOSFET in an 8 A SEPIC DC-DC converter operating at 100 kHz. As the results show in Figure 4, at a 600 V blocking voltage level, the SiC MOSFET-based system achieves 4 percentage points better efficiency than the conventional IGBT-based design. Figure 5 shows a simplified connection circuit using ACPL-339J to drive the SiC MOSFET.

Figure 4 Achieving High Efficiency with Avago Gate Drives and CREE SiC MOSFETs

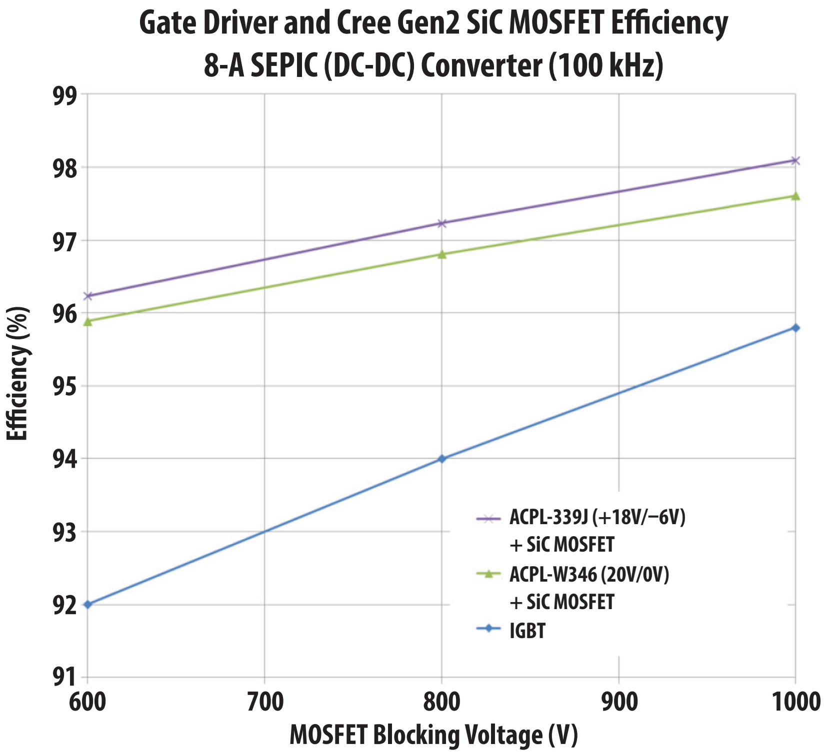
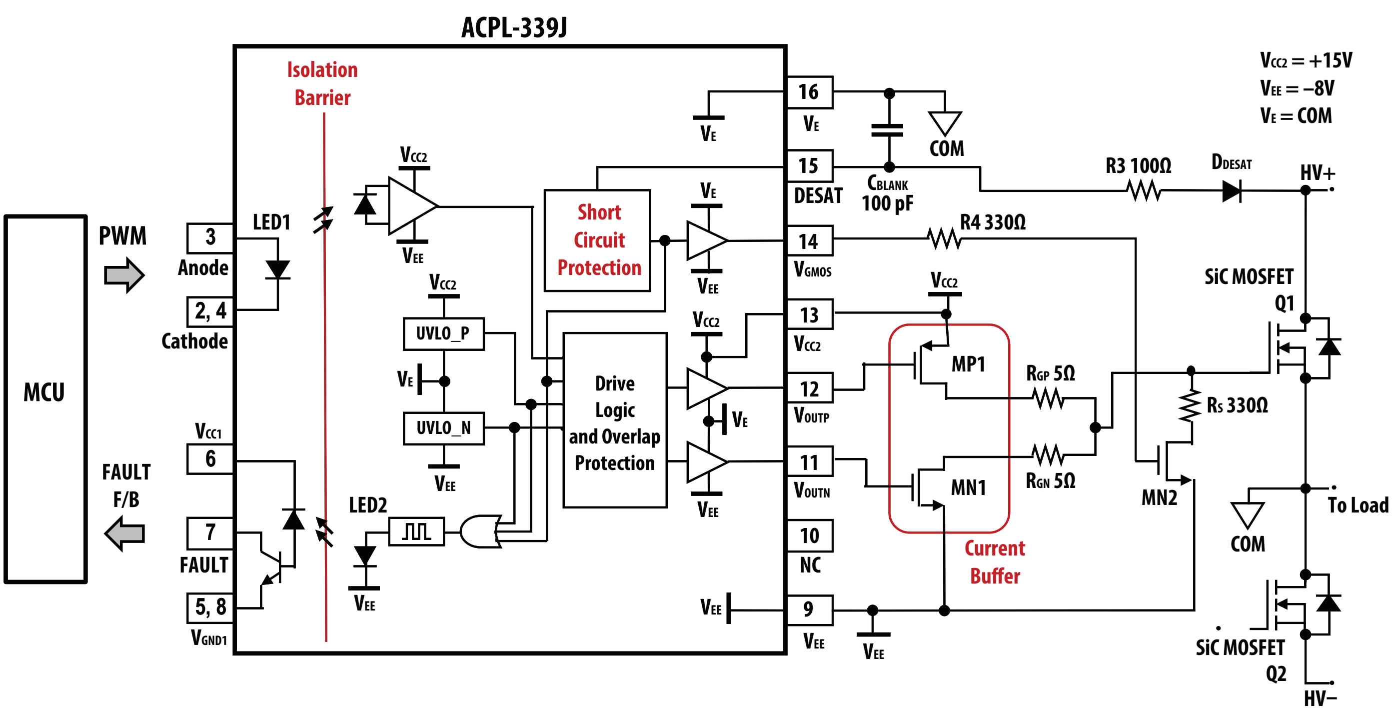


Figure 5 A Smplified Connection Circuit using ACPL-339J with SiC MOSFET [23]



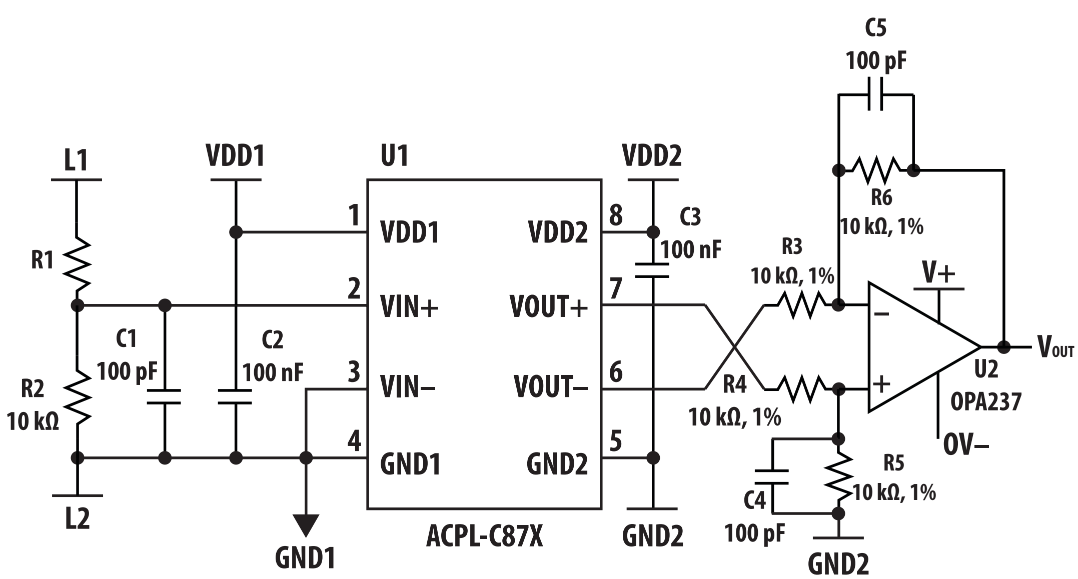
Voltage and Current Sensing

For EV batteries, there are three primary charging methods: (1) constant voltage; (2) constant current; and (3) a combination of the two. Most EV charging systems use a constant voltage for the initial portion of the charging process, followed by a constant current for the finish [24]. To effectively implement these charging methods, voltage at various nodes and current through several branches must be measured and fed back to the MCU for calculations, which will adjust the PWM signals accordingly. For example, with reference to Figure 3, voltages at the DC link and the charger output require continuous monitoring and accurate readings. Besides voltage information, currents in the PFC stage, through the input and output rails are required to be measured. Many studies, such as [7], [19], and [25], on high charging efficiency systems take in voltage and current information as basic parameters in control algorithm and power calculation, where accuracy of the information is a key. Charging voltage, current, and charging time constitute energy consumption during a charge, which translates to a bill of charge. Therefore, certain levels of measurement accuracy are required.

A typical method of measuring high voltage is to use a resistive potential divider to step down the voltage to a suitable level for a linear sensing chip to measure and send to the MCU. A current sensing circuit often uses a precision shunt resistor to convert the current to a small voltage, which is sent to the MCU via some signal-conditioning devices. However, there is always a challenge to transmit the signals accurately from high voltage areas, such as the PFC and DC-DC converter stages, to the low voltage controller side. This is due to high switching noise and ground loop noise across these two areas. These commonly encountered circuit problems can ruin data accuracy, damage the MCU, and threaten user safety. In these situations, isolation amplifiers, such as the ACPL-C87X series and ACPL-C79X series, are handy to carry out voltage and current sensing functions [26], [27].

Using the ACPL-C87X isolated voltage sensor is straightforward. A detailed DC voltage sensing circuit with the ACPL-C87X is shown in Figure 6. Given that the ACPL-C87X's nominal input voltage for V_{IN} is 2 V, a user must choose resistor R1 according to R1 = $(V_{L1} - V_{IN})/V_{IN} \times$ R2. For example, if V_{L1} is 600V and R2 is 10 kΩ, then the value of R1 is 2990 kΩ. Several resistors can be combined to match the target value. For example, 2 MΩ, 430 kΩ and 560 kΩ resistors in series make 2990 kΩ exactly. The down-scaled input voltage is filtered by the anti-aliasing filter formed by R2 and C1 and then sensed by the ACPL-C87X. The isolated differential output voltage ($V_{OUT+} - V_{OUT-}$) is converted to a single-ended signal V_{OUT} via a post amplifier U2. V_{OUT} is linearly proportional to the line voltage on the high voltage side and can be safely connected to the system microcontroller. With the ACPL-C87X typical gain of 1, the overall transfer function is simply V_{OUT} = VL1 / (R1/R2 + 1) [26].

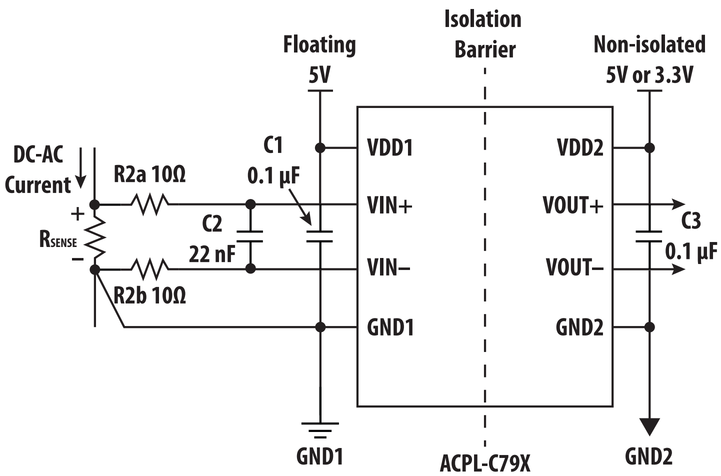
Figure 6 High Voltage Measurement with Conversion to an Isolated Ground Referenced Output



Using an isolation amplifier to sense current can be as simple as connecting a shunt resistor to the input and getting the differential output across the isolation barrier, as shown in Figure 7. By choosing an appropriate shunt resistor, a wide range of current, from less than 1 A to more than 100 A, can be measured. In operation, currents flow through the shunt resistor and the resulting analog voltage drop is sensed by the ACPL-C79X. A differential output voltage is created on the other side of the optical isolation barrier.

This differential output voltage is proportional to current amplitude and can be converted to a single-ended signal using an op-amp such as the post amplifier shown in Figure 6, or sent to the controller's analog-to-digital converter (ADC) directly [27].

Figure 7 Typical Current Sensing Application Circuit



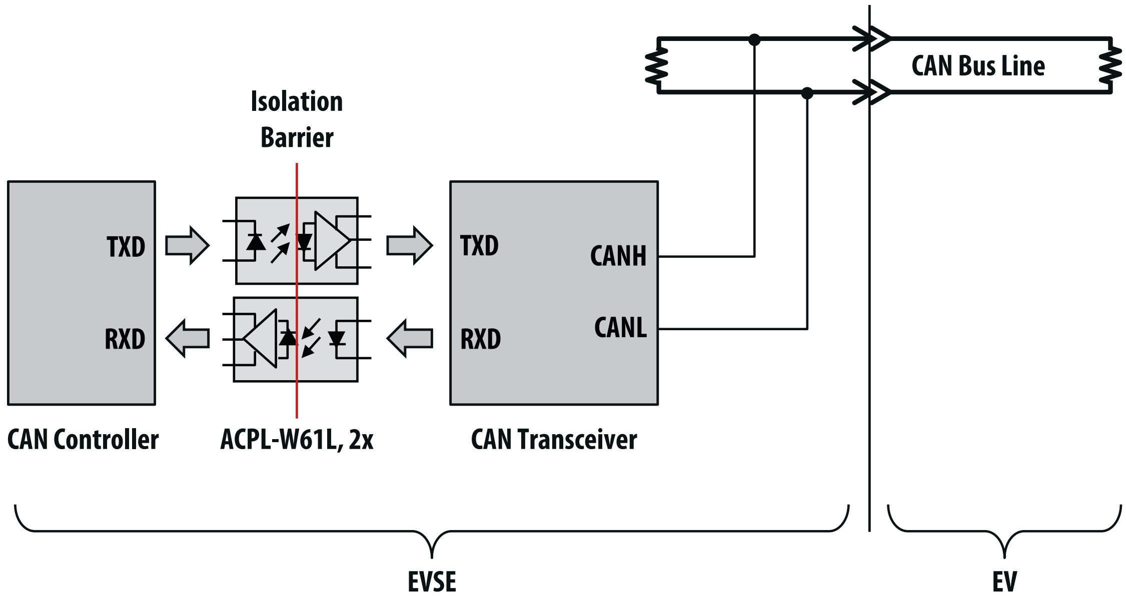
Digital Communication

Advanced control scheme is necessary to implement a charging control protocol between the charging station and the EV. However, this is another area prone to divergent standards. For example, the SAE J1772 specifies the Control Pilot signal communication method using a duty cycle modulation for AC Level 1 and 2 [12]. For digital communication that is required for DC charging, the SAE committee is working on updating the J2931, which proposes power line communication (PLC) schemes on the Control Pilot signal or mains [28]. Tesla apparently participated in the SAE committee process and made the decision that they would use the same control signaling scheme as the SAE J1772 [29].

The most popular plug standard CHAdeMO (based on EV sales with fast charging type) [2] chooses Controller Area Network (CAN) for fast charging. High communication reliability is required because 500 V/100 A output of DC fast charger could lead to a fatal accident if one error occurs, states the Japanese association on its website. The association considers that CAN has a highly reliable record of being used as a standard communication method for automotive electronic control systems. Its higher noise tolerance excels PLC as a communication method for Electronic Control Unit (ECU) to control the charging process [13, p. "FAQs – Technology"].

The CHAdeMO standard provides a pair of CAN bus lines that connect the charger side and the vehicle side at the coupler interface. The coupler pins 8 and 9 are assigned as CAN-H and CAN-L, [13, p. "Technological details"], respectively, to which a CAN transceiver can be connected. Adding optical isolation between the CAN transceiver and the CAN controller significantly improves system safety because optocouplers provide a safety barrier that prevents any damage from cascading to the system MCU. This arrangement also enables more reliable data communication in extremely noisy environments, such as high-voltage battery charging systems. Figure 8 shows how to use optocouplers to implement isolated CAN bus digital communication for fast-charging station designs. A similar circuit is applicable for the vehicle side, where automotive-grade parts are required.

Figure 8 Isolated CAN Bus Digital Communication



In the example circuit shown in Figure 8, a pair of 10-MBd fast optocouplers ACPL-W61L is used for data transmit and receive. This product requires a 1.6 mA very-low LED current to work and is delivered in an SSO-6 package that is less than half of the size of a traditional DIP-8 package. Although in small size, the ACPL-W61L withstands high voltage of 5000 Vrms for 1 minute, per UL1577 rating. Designed to transmit signals in the presence of strong transient noises, this part guarantees common mode transient immunity of 35 kV/µs [30]. In case of different design needs, other optocouplers also can be used in place of the ACPL-W61L. These include the 5-MBd-rated ACPL-W21L [31], and the 25-MBb dual-channel bidirectional ACSL-7210 [32].

Conclusion

EVs help reduce transportation dependence on petroleum and tap into a source of electricity that is often relatively inexpensive. They help reduce emissions of greenhouse gases and other pollutants, which can be further improved as the electricity generation portfolios add more renewable sources. EV-charging infrastructure is key to enabling wide EV adoption. In an EV charging station, especially DC fast-charging, complex power supply systems are used to deliver huge amount of energy to the battery in the vehicle within a short period of time. Safety isolation is imperative as low voltage control systems, high voltage power systems, and the person-accessible user interface coexist in a single charging station. Efficiency in energy conversion is another critical design consideration in EV chargers. Optocouplers, such as the gate drivers, voltage sensors, current sensors, and digital optocouplers, deliver both safety isolation and respective electrical function in a single package, helping realize highly efficient systems.

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