Powering the Next Generation of Transportation

Design Electric Vehicle Charging Stations for Safety, Efficiency, and Reliability

Climate change, government initiatives, and technology have converged to increase the penetration of electric vehicles in the market. As of 2020, an estimated 5.5 million electric vehicles (EVs) were on the road with an expectation that by 2025, over 24 million EVs would be in use. One of the significant limitations to wider adoption of EVs is the public charging infrastructure needed to support long-distance, inter-city travel. In 2019, there were only 7.3 million chargers worldwide and less than a million were for public access.[1] In addition, very few of these chargers can charge an EV battery in a timeframe that is somewhat short enough to rival the filling up of an internal combustion vehicle's gas tank. Fortunately, new, high-power, DC charging technology is permitting battery charging in under 30 minutes. A build-out of fast chargers will accelerate the adoption of EVs.

Design engineers have multiple challenges developing EV charging stations. Safety concerns are paramount as users must interface with kW to over 300 kW of power generated by the charging stations. This necessitates maximizing the design for high efficiency to reduce both power consumption and maximum temperature rise during operation. The public stations must be outdoor devices and are subject to the challenges of ensuring reliable performance under the stress of a wide range of environmental conditions. This article will advise designers on methods to ensure their charging stations comply with safety standards, have high efficiency, and provide protection against environmental electrical hazards for high reliability operation.

Types of EV charging stations

There are three types of charging stations currently on the market as illustrated in Figure 1. In North America, the different stations are classified as "Levels" while the European Union differentiates the charging stations using "Modes." The AC Level 1 charging station, with the in-cable control box (ICCB), is intended for charging at a residential home. The AC level 2 can be either a home or a public installation. The third type is a DC Fast Charging Station used in public and commercial installations. Organizations such as the Society of Automotive Engineers, the European Union automotive standards organization, and Asian counties such as Japan and China are working toward standardizing charging stations for the automotive manufacturers.

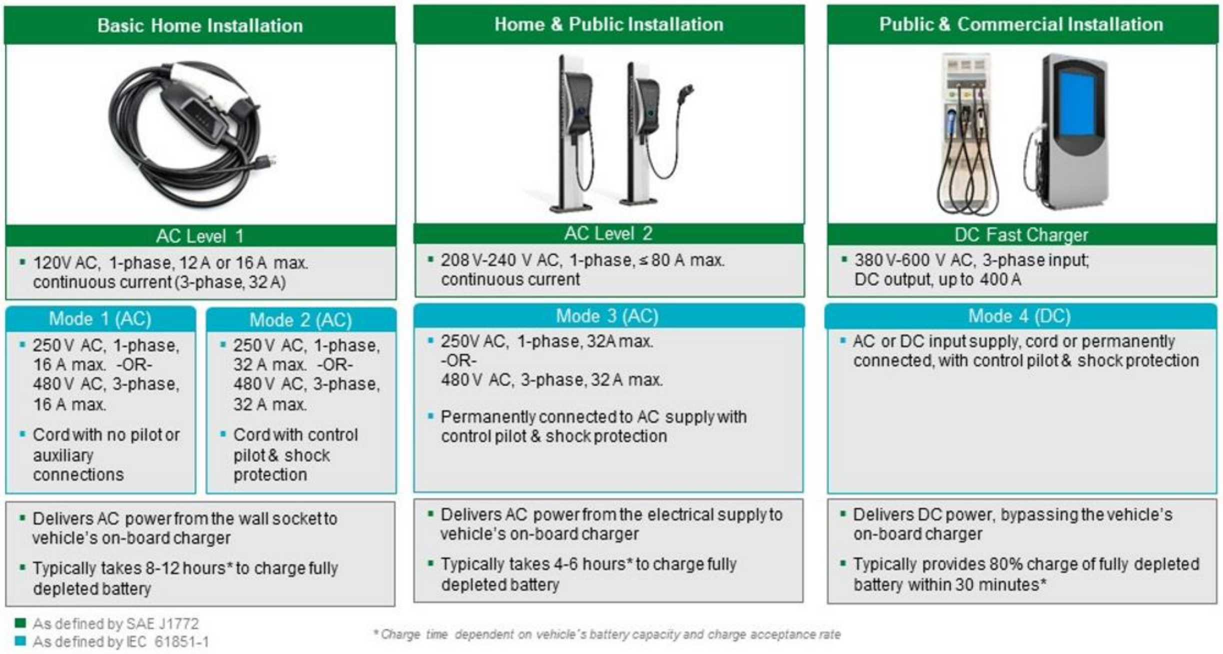


Figure 1. EV charging station types and their power capacity

The DC Fast Charger, the Mode 4 charger, is designed to charge an EV battery to 80% capacity in under 30 minutes. These chargers have power ratings up to 350 kW and can supply up to 400 A to a battery. These high-power chargers have special challenges such as keeping the charger cables cool and preventing ground currents. When designing with tens of hundreds of kilowatts of power, special emphasis on power efficiency conversion, reliability, and user safety is essential.

Recommendations for safe, efficient, and reliable AC charging station designs

We will start with suggestions for incorporating safety, efficiency, and reliability in AC charging station designs. Figure 2 shows an example AC charging station with its elements highlighted. Recommended protection, control, and sensing components are shown for each element of the charger. Figure 3 shows a detailed block diagram of an AC charging station showing the circuits and the protection, control, and sensing components recommended for key circuit blocks.

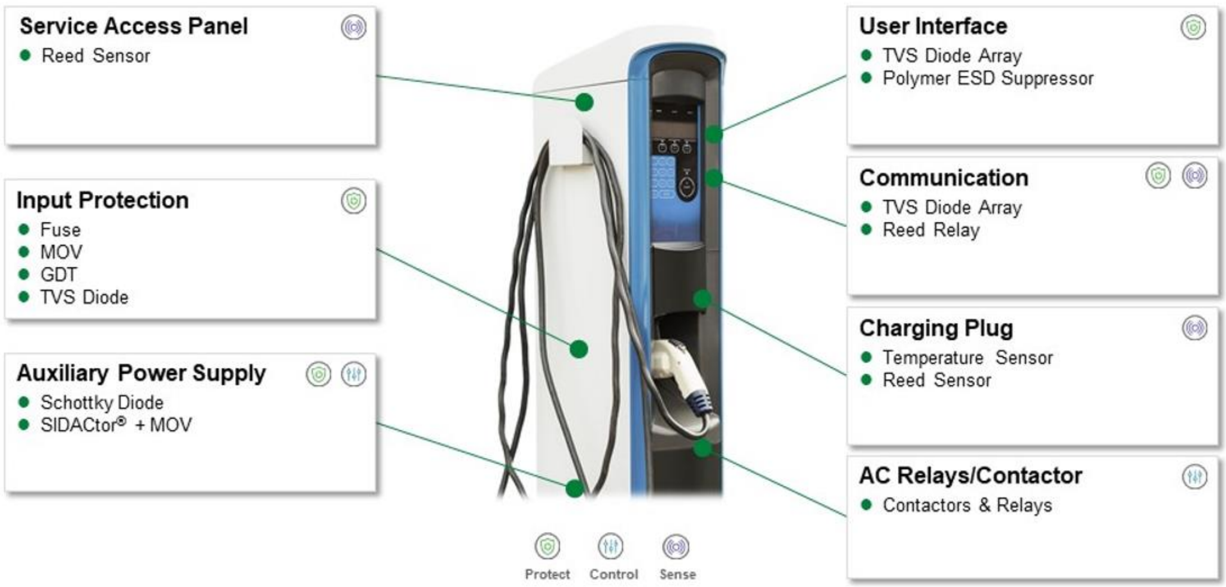
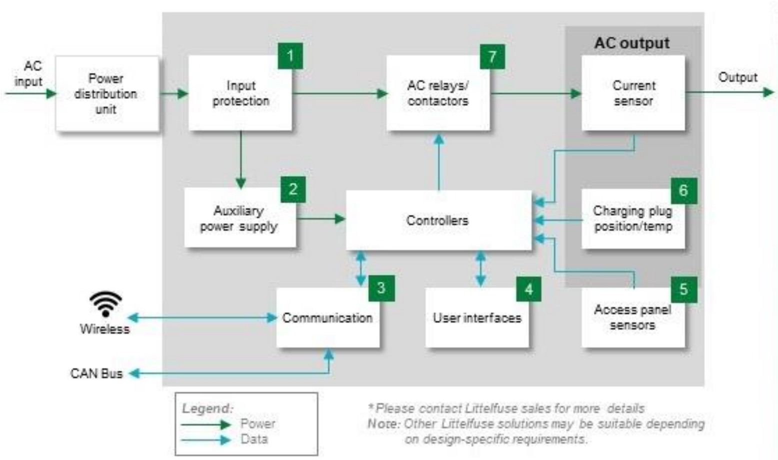


Figure 2. The elements of an AC charging station with the recommended protection, control, and sensing components



	Technology	Product
1	High-current Fuse (Primary protection)	606
	Surge protection (Primary protection)	SPD Type 2
	Fast-acting or Time lag Fuse (Secondary protection)	314, 324, 215
	Metal-Oxide Varistor	TMOV, UltraMOV
	Gas Discharge Tube	CG2, CG3
	TVS Diode	AK6, 1.5SMC
2	Schottky Diode	DST, DSA, DSB
	SIDACtor + MOV	Pxxx0FNL + UltraMOV
3	TVS Diode Array	AQ24CAN, SM712
	Reed Relay	HE3600
4	TVS Diode Array Polymer ESD	SP1026 XGD10402
5	Reed Sensor	59060, 59045
6	Temperature Sensor	PPG, USW, Glass Coated Thermistor
	Reed Sensor	59060, 59045
7	Contactors or Relays	HCC 1 & 2 Pole, HCC 3 & 4 Pole, HCD, or SCO1*, SCO2*

Figure 3. Block diagram of an AC charging station and the components recommended for specific circuit blocks

Input Protection circuit

The Input Protection circuit connects to the AC power line and is subject to overload currents and voltage transients that originate on the AC line. Blocking overload currents and voltage transients protect the downstream circuitry from these damaging conditions. Proper fusing the input against current overloads is recommended, along with surge protection for voltage transients. Use either a metal oxide varistor (MOV) with a gas discharge tube or a transient voltage suppressor (TVS) diode for additional transient protection.

For protection against current overloads, use a high current fuse with a high voltage rating. Ensure that the fuse has a voltage rating higher than the AC line voltage powering the charger. Verify that the fuse has a sufficient interrupting rating that exceeds the maximum potential fault current that the AC line could deliver, and the fuse has a melting point rating (A^2sec) that exceeds power line transient energy due to transients such as motors turning on or off. An adequate melting point rating avoids nuisance tripping. Look for a fuse that complies with UL, CSA, or IEC requirements to minimize agency certification costs and time. Make sure the fuse has the temperature range needed to operate in the outdoor environment. Finally, make sure that the fuse fits into its allotted space.

The most damaging transient is a lightning-induced transient on the power line. The Input Protection circuit should have a surge protection device across the line or across all three lines of a 3-phase power system. A surge protection device can safely absorb a surge current as high as 50 kA and clamp the transient voltage to a safe level. Look for a surge protection device with a fast response time under 30 ns.

Following the surge protection device, consider inserting a fast-acting fuse for a secondary level of protection against portions of a current overload that have propagated through the primary fuse and the surge protection device. Use the criteria described earlier for the fuse selection.

An alternative to the surge protection device is a series combination of a metal oxide varistor and a glass discharge tube (GDT). The combination is needed due to the fact that the GDT is a crowbar device that could become a near-short to the AC line. The MOV is a clamping device that provides a lower clamping voltage than the surge protection device. Consider a thermally-protected MOV which offers a quick thermal response to a transient. The MOV-GDT combination offers lower clamping voltage for the protection of low-voltage downstream components. Look for components that can safely absorb as much as 10 kA transient surges with energy levels up to 500 J.

A third alternative or an extra level of protection would involve the use of a TVS diode across the AC line. TVS diodes provide nanosecond response times and can safely absorb up to a 10 kA direct contact, electrostatic discharge (ESD) strike. The TVS diodes have lower clamping voltages than MOVs and are more suitable for protecting low voltage downstream circuitry. Models of TVS diodes can be uni-directional or bi-directional; a bi-directional TVS diode is suggested for use in an AC line application.

AC/Relays/Contactors

The AC Relays/Contactors circuit applies the AC charging power to the AC output stage for vehicle charging. This circuit also provides a safety cutoff if an abnormal condition is detected. Select high current contactors up to 40 A in either single-pole or two-pole configurations to interrupt the high line output or both high and low output. Look for contactors that guarantee long-life contacts that have excellent resistance to oxidation. An alternative to contactors is a PC board (PCB)-mount relay. Select a relay with low coil power consumption to minimize heat generation. Find either contactors or relays that meet applicable UL or IEC standards.

Charging Plug Position/Temperature circuit

The Charging Plug Position/Temperature circuit monitors the charging plug connection and the temperature of the plug. Monitoring the temperature of the charger's contacts will protect users from the charger handle reaching a dangerously hot temperature and will protect the contacts and the circuitry associated with the contacts from overheating. Consider a thin-film platinum resistance temperature detector (PT RTD). PT RTDs have high measurement accuracy, excellent stability, and high reliability. To ensure that the plug is fully seated in the vehicle receptacle before charge current is supplied, consider employing a reed sensor such as the type recommended for the Access Panel Sensors circuit.

Auxiliary Power Supply

The Auxiliary Power Supply provides the DC power for the charger's control and communication circuits. For this circuit, maximize efficiency of the supply by employing low switching voltage, Schottky rectifiers. They will reduce switching losses and contribute to improved thermal management of the supply circuit.

At the front end of the Auxiliary Power Supply, protection against portions of surges that propagated through the Input Protection circuit is recommended. Since the Auxiliary Power Supply is powering the logic, control, and communication circuitry, protection elements should have very low clamping voltage. The combination of a protection thyristor, a crowbar device with an MOV, a clamping device, can absorb up to 3 kA and provide a clamping voltage as low as a TVS diode's clamping voltage.

Communication circuit

The Communication circuit transmits and receives information via a wireless protocol or a CAN Bus link. To ensure the protection of the CAN bus circuitry from ESD and other transients, consider a dual-line, bi-directional TVS diode array. Look for TVS diode arrays that can absorb over 25 kV from an ESD strike. For switching between the wireless RF circuit and the CAN bus circuit, consider using of a reed relay to galvanically isolate the two circuits. Look for a reed relay that consumes a minimum of power and is small so that it consumes the least amount of PCB real estate.

User Interface circuit

The User Interface allows the user to control the charger. The primary hazard is ESD from users. Consider bi-directional TVS diodes to protect the touchpad from ESD transients as large as 30 kV. Use polymer ESD suppressors on the I/O lines. ESD suppressors have a negligible impact on the circuit with under 1 nA of leakage current and capacitance that can be under 0.1 pF. Thus, the I/O lines are protected without disturbing the transmission and reception signals.

Access Panel Sensors circuit

The Access Panel Sensors circuit protects the user from hazardous voltages inside the charger. Use a reed proximity sensor/actuator to force the shutdown of charger power if the charger enclosure is opened. Ensure the sensor/actuator is rated for the circuit voltage and for the current required to activate the disengagement circuitry. A sensor/actuator that is intended for use in a high-moisture environment is recommended.

Recommendations for safe, efficient, and reliable DC charging station designs

The DC charging station, an example of which is illustrated in Figure 4, has the added complexity of AC-DC power conversion. Along with safety concerns, maximizing efficiency must be a critical design requirement. The following paragraphs offer guidelines for safe, efficient, and reliable DC charger design.

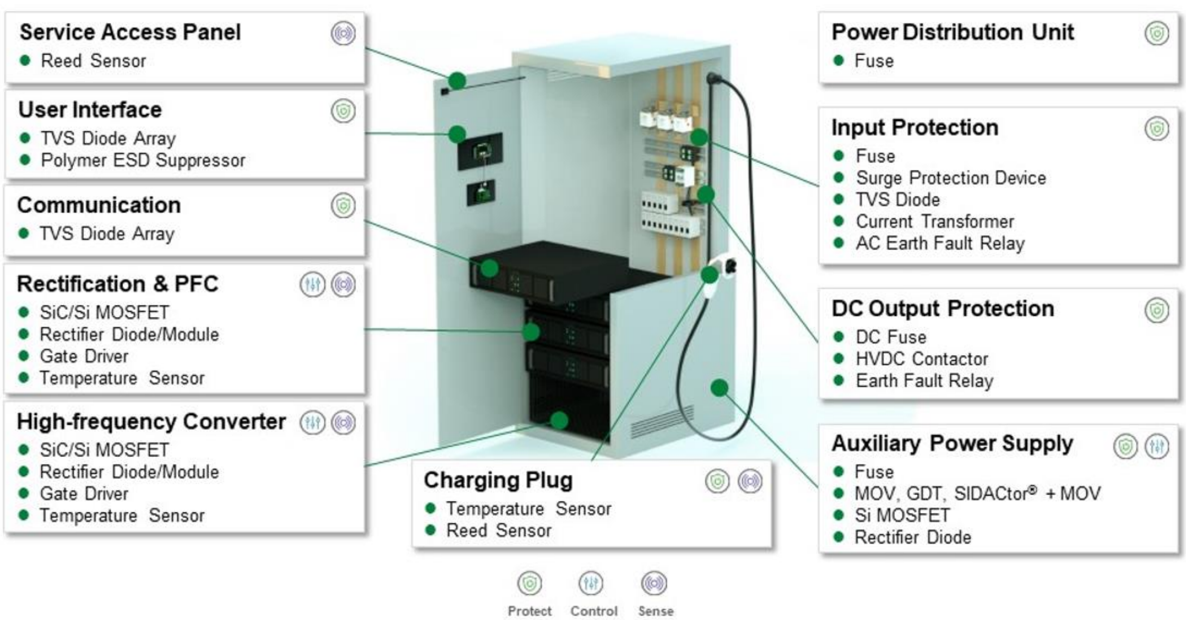
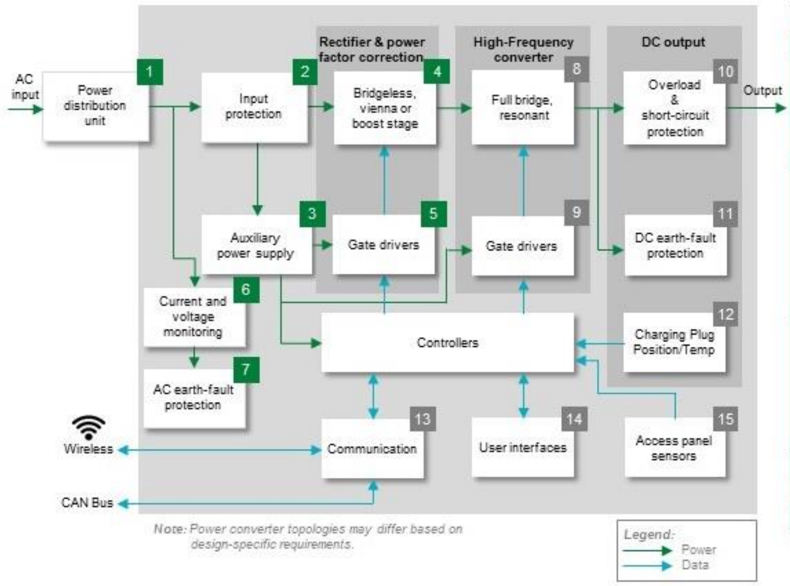


Figure 4. A DC charging station with its main elements and the recommended protection, control, and sensing components needed for each element

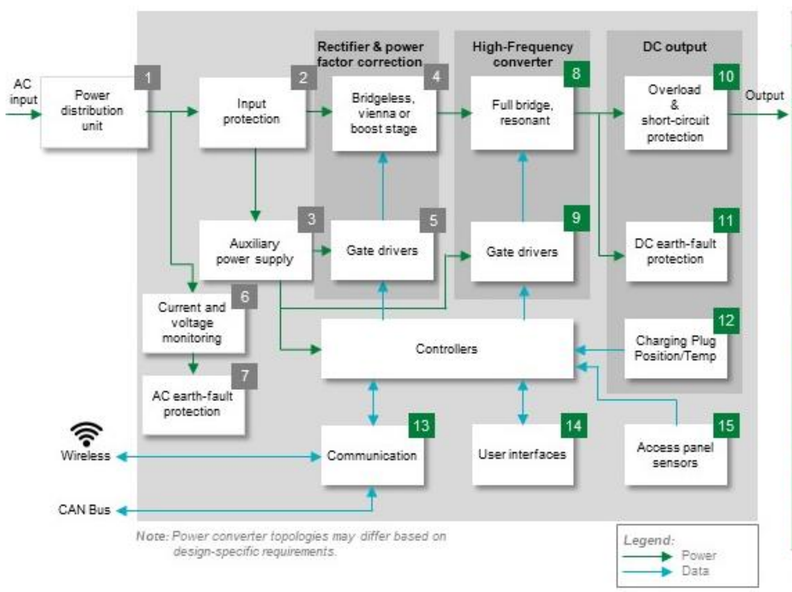
Figures 5a and 5b show a block diagram for a DC charging station. In Figure 5a, the components recommended for circuit blocks 1-7 are highlighted. Figure 5b shows the same block diagram but highlights the recommended components for circuit blocks 8 – 15.



	Technology	Product
1	AC Fuse (PDU level)	JLLS, JLLN
2	Overcurrent protection (Primary protection)	PSR, L60QS, L75QS
	Surge protection (Primary protection)	SPD Type 2
	TVS Diode	AK6, 1.5SMC
3	Si MOSFET	Polar™
	Rectifier and Schottky Diode	DMA, DST, DSA, DSB
	AC Fuse (Secondary protection)	314, 324
	Metal-Oxide Varistor	TMOV, UltraMOV
	Gas Discharge Tube	CG2, CG3
	SIDACtor + MOV	Pxxx0FNL + UltraMOV
4	Rectifier Diode	DMA
	Rectifier Module	MDD, VUO, MDNA
	SiC/Si MOSFET/ Discrete IGBT	LSIC1MO/X2-Class/XPT
	Diode	LSIC2SD, DHG, DSEI
	Temperature Sensor	USUR1000, KC
5	Gate Driver	IXDN609, IX4351NE
6	Current Transformer	SE-CS30
7	AC Earth-Fault Relay	SE-704

Note: Other Littelfuse solutions may be suitable depending on design-specific requirements.

Figure 5a. DC charging station block diagram with components recommended for circuit blocks 1 - 7



	Technology	Product
8	SiC or Si MOSFET	LSIC1MO, X-Class, X2-Class, HiPerFET™
	Diode	LSIC2SD, DHG, DSEI
	Temperature Sensor	USUR1000, KC
9	Gate Driver	IXDN609, IX4351NE
10	DC Fuse	PSR, SFPJ
	Diode	DMA, DHG, DSEI
	HV DC Contactor	DCNxx
11	DC Earth-Fault Relay	SE-601
	Earth Reference Module	SE-GRM
12	Temperature Sensor	PPG, USW, Glass Coated Thermistor,
	Reed Sensor	59060, 59045
13	TVS Diode Array	AQ24CAN, SM712
14	TVS Diode Array Polymer ESD	SP1026 XGD10402
15	Reed Sensor	59060, 59045

Note: Other Littelfuse solutions may be suitable depending on design-specific requirements.

Figure 5b. DC charging station block diagram with components recommended for circuit blocks 8 - 15

Power Distribution Unit

At the connection to the AC line, protect the DC charger from overload currents and short circuit conditions with a fast-acting, high current fuse. Select a fast-acting fuse with a large current interrupting rating to ensure that the rating exceeds the energy available from the AC line. Some fuses can have ratings up to 200 kA.

Input Protection circuit

The main protection from current overloads and voltage transients is provided by the Input Protection circuit. Use a very-fast acting fuse to protect downstream sensitive semiconductor circuitry. As with the AC charging station, a surge protection device is recommended to withstand high-energy transients to prevent degradation and damage to the downstream circuits. Instead of the surge protection device or as a secondary level of protection, consider a power TVS diode for fast response and low voltage clamping.

Current and Voltage Monitoring Circuit and AC Earth-Faut Protection

For 3-phase power sources, monitoring for a fault in the power system ground is an essential requirement for safety certification. A current transformer is recommended to monitor the current in the ground line. Select a current transformer that can detect under 30 mA and has flux conditioning to avoid saturation. Use a ground-fault protection relay to measure the current from the current sensor and disconnect the input power in the event a high ground current is detected.

Rectifier and Power Factor Correction function

The Bridgeless, Vienna, or Boost Stage

Bridgeless power factor correction circuits seek to minimize the number of semiconductor devices in the active current loop at any time to minimize power losses and maximize efficiency. If the AC power source is 3-phase for a high-power DC charger, the topology is known as Vienna or a boost stage topology.

Since the DC charger is a high-power system, every improvement in efficiency is a significant saving in power consumption. Using Schottky rectifier diodes or diode modules reduces turn-on voltage requirements. Along with low forward voltage, look for diodes with low leakage current. Select individual diodes or use diode modules if the component count is a critical concern.

To maximize the efficiency of the rectifier and power factor correction circuit, Si MOSFETs, SiC MOSFETs, or IGBT transistors are recommended. Si and SiC MOSFETs exhibit fast switching rates and enable higher frequency operation. Higher frequency operation allows use of smaller inductors which reduces power loss and improves efficiency. The temperature of the power transistors should be monitored to prevent thermal runaway due to a transistor’s junction temperature reaching an excessively high level.

Gate Drivers

Consider using a gate driver chip to control the power transistors. Gate drivers have the speed to drive the transistors at a high switching frequency and consume very low supply currents to maximize the efficiency of the charger power circuit. Versions offer inverting or non-inverting drivers, and some versions can offer drive currents as high as 30 A. Using a gate driver chip simplifies the task of controlling power MOSFETs and IGBT transistors.

High-frequency Converter function

For the Full Bridge, Resonant, and Gate Drivers circuits, use identical components to those suggested for the Rectifier and Power Factor Correction circuitry, as these components help to minimize power losses in the whole AC-DC conversion block.

DC Output

Overload and Short-Circuit Protection circuit

For the Overload and Short-Circuit Protection circuit, use a fast-responding high current, high voltage rating fuse for protecting the output circuitry from overheating due to the high DC charging current. To follow the CHAdeMO Association standard recommendation for DC charging, add a reverse-flow protection diode for redundant protection against a short condition in the secondary rectifier.[2] Finally, control the output to the vehicle with a high voltage DC contactor. Use an IP-67-rated, gas-filled contactor both to mitigate arcing and to prevent moisture and dust ingress.

DC Earth-Fault Protection

The DC-Earth-Fault Protection circuit monitors for ground faults on ungrounded systems. Consider using a DC ground-fault monitor. Select one with an adjustable alarm threshold limit and an adjustable trip delay to avoid nuisance activation of the relay. Use a ground reference module, a two-element resistor network, which, with the ground-fault monitor, is designed to detect when either the high or low output lines short to earth ground. The contacts of the high voltage DC contactor are opened to prevent damage to the vehicle's battery circuitry and the charger circuitry.

Charging Plug Position/Temperature circuit

The Charging Plug Position/Temp circuit, as with the AC charger, is a significant safety circuit. Use the same temperature and proximity sensors in the DC charger as selected for the AC charger.

Auxiliary Power Supply

In the AC-DC converter for the logic and control circuitry, minimize power loss and maximizing efficiency with Schottky diode rectifiers and high power MOSFETs with high-speed switching. The MOSFETs reduce power loss during transitions and have a low $R_{DS(On)}$ which reduces power consumption when the MOSFET is in the on-state.

We recommend protecting the Auxiliary Power Supply from overcurrent events with a standards-compliant fuse. Standards bodies require a fuse in this circuit. Provide transient protection either with an MOV-GDT combination identical to the AC charging station Input Protection circuit or an MOV-protection thyristor as recommended for the AC charging station Auxiliary Power Unit.

Communication, User Interface, and Access Panel Sensors Circuits

The Communication, User Interface, and Access Panel Sensors circuits perform the same functions in the DC charging station as in the AC charging station. Protect the data lines of the Communication and User Interfaces circuits from ESD using the components recommended for the AC charger. Use the reed proximity sensor recommended for the AC Access Panel Sensors circuit in the DC charger circuit.

Required Safety Standards for Vehicle Charging Stations

Charging stations consume and deliver high power to vehicles. They cannot be sold without safety certifications. Table 1 lists the standards with which your designs will have to comply. IEC 61851, UL 2594, and GB/T 18487 Series are the three primary standards that charging stations will have to meet for obtaining access to the worldwide market.

Standard	Title	General Scope	Region
IEC 61851 Series	Electric Vehicle Conductive Charging System	Various parts of this standard cover general requirements, along with AC chargers and DC chargers specifically.	Global
IEC 62196 Series	Plugs, Socket-Outlets, Vehicle Connectors and Vehicle Inlets - Conductive Charging of Electric Vehicles	Standards for charging plugs, sockets, and connectors.	Global
GB/T 18487 Series	Electric Vehicle Conductive Charging System	Various parts of this standard cover general requirements, along with AC chargers and DC chargers specifically.	China
GB/T 20234 Series	Connection Set for Conductive Charging of Electric Vehicles	Standards for charging plugs in China.	China
SAE J1772*	Electric Vehicle and Plug-in Hybrid Electric Vehicle Conductive Charge Coupler	Physical, electrical, functional and performance standard for charging plugs in North America.	North America
UL 2594	Standard for Electric Vehicle Supply Equipment	Safety standard for supply equipment (charging stations, cord sets, power outlets, etc.) in North America. Tri-national standard for U.S., Canada, and Mexico (known as CAN/CSA C22.2 No. 280 in Canada and NMX-J-677-ANCE in Mexico).	North America
UL 2202	Standard for Electric Vehicle (EV) Charging System Equipment	Safety standard for electric vehicle charging equipment	U.S.

*J1772 is a registered trademark of SAE International

Table 1. Safety standards for EVs

Managing the convergence of high power with safety, efficiency, and reliability

Products such as high-power charging station designs are challenging designs, and ensuring that these circuits are both protected from environmental hazards and safe for user interaction adds further complexity. Furthermore, maximizing power efficiency and ensuring high reliability add additional layers of complexity. Designers need to include these requirements in the initial design definition to reduce development time cost overruns resulting from extra time to modify circuitry. Design revisions could result from failed tests by a certification body, the need to reduce higher than planned power consumption, or failures during accelerated life tests.

It is difficult to be an expert in all areas of design. Consider taking advantage of the expertise of manufacturers of protection, control, and sensing products. Their help in offering design recommendations and in product selection can save a significant amount of development time. The manufacturer's application engineers can advise on the tradeoffs between power/volume, efficiency, and component costs. Some manufacturers can provide assistance with standards compliance and can offer pre-compliance testing services. Use all means possible to overcome the challenges of safety, efficiency, and reliability to ensure your EV charging stations successfully address the market's requirements.

References:

[1]Alternative Propulsion Forecast. June 2021. HIS Markit. Automotive Alternative Propulsion Forecast | IHS Markit and Littelfuse estimate combined.

[2]CHAdeMO Association & Protocol. April 2019. https://www.chademo.com/

About the author

Philippe Di Fulvio is on the eMobility team as a Business Development Manager for Electric Vehicle Infrastructure at Littelfuse. He has more than 25 years of electronics industry experience, having started his career with Zodiac Aerospace, before joining TE Connectivity, and then Littelfuse upon the acquisition of TE's circuit protection division in 2016. Throughout his career, he has held various roles including Power Electronic Design and Application Engineering as well as Technical Marketing. Philippe holds a Masters's degree in engineering from Polytech Clermont-Ferrand University.