WHITE PAPER

Powering the future of global transportation

Electric vehicle charging

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Introduction

The rebirth of the electric vehicle occurred around 2009. Over the last 15 years, the growth of electric mobility has continued to increase on a global scale. Governments around the globe are implementing policies to put more electric vehicles on the road by 2030. Public acceptance and use of electric vehicles are on the rise. Policies around the world are focused on decarbonization of the transportation fleet, and the industry has been highly active in exploring new, greener technologies. All these factors point to a promising and exciting future for electric vehicles.

Today, tens of millions of electric vehicles are on the road, and the number continues to grow rapidly. As seen in Figure 1, China remains the largest market, with Europe and the United States (U.S.) next. Electric vehicles must be charged prior to use, and most electric vehicles accomplish this with external charging. Today, there are millions of charge points located around the globe, and installation of new charging stations has been stimulated by government and private investment. As the use of electric vehicles continues to increase, the need to charge more vehicles faster and more conveniently will also be an important practical consideration.

Over the last 15 years, we have seen many advances in the area of electric vehicles and electric vehicle charging. Up to now, most of these advances have been related to the installation of infrastructure and decreasing overall charge times. There also have been many lessons learned related to how products would be used, what were considered best practices and what types of abuse could be expected in the field. During that time, equipment and safety requirements began to stabilize around this technology. But recently, new technologies and ideas have emerged that push the envelope of existing requirements and create a need to look at electric vehicle charging in a new light.

This white paper will look at the existing standards and equipment in the electric vehicle landscape, as well as the trends forming the electric vehicle landscape of the future. This discussion will focus primarily on standards associated with North America and the European Union (EU), with information about other importing markets as applicable.

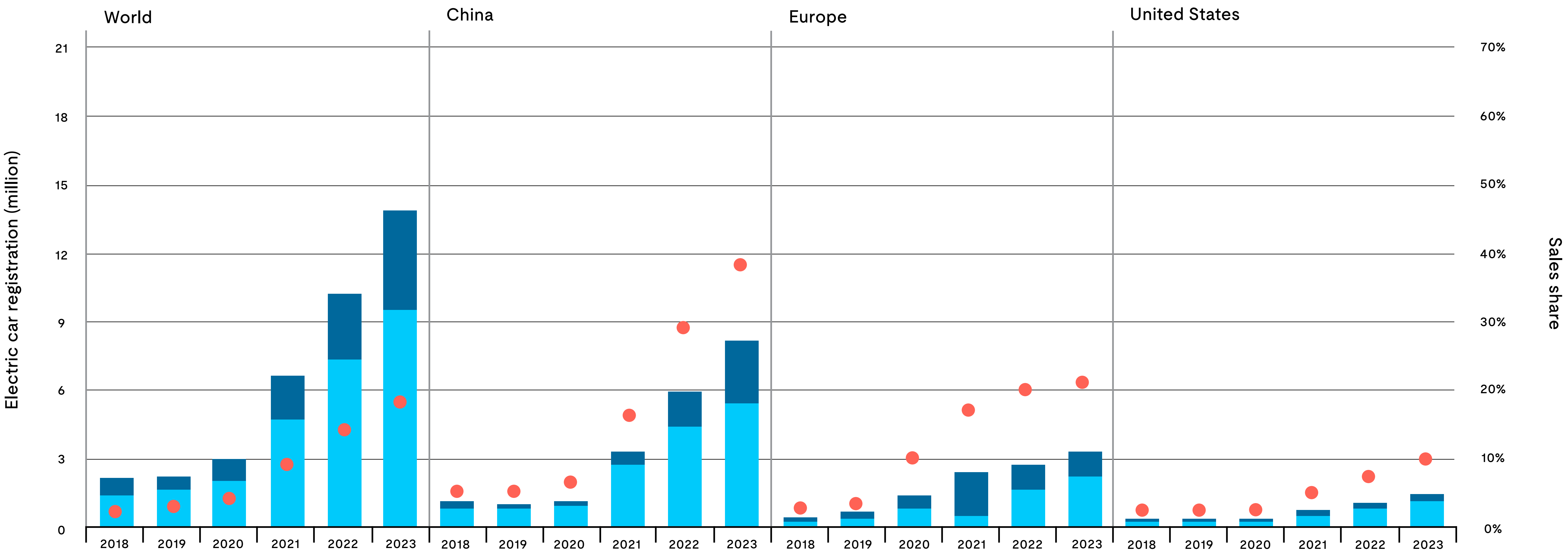

Figure 1 - Global Electric Vehicle Deployments

Notes:
BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle

Source:
International Energy Agency

Conductive charging

In recent years, charging of electrical vehicles has been accomplished mainly through a wired conductive connection to the electric vehicle. Although the types of equipment for accomplishing conductive charging are well established today, a brief discussion of legacy conductive charging methods is included to best contrast the new technologies and innovations that will be implemented in the near future.

In legacy conductive charging equipment, a physical connection is required to be made by the user to transfer power to the vehicle. The connection is made by physically mating a vehicle connector with a vehicle inlet. The connection could be used to deliver alternating current (AC) power that requires an on-board conversion of the voltage to direct current (DC) to charge the vehicle battery. Alternatively, the connection to the vehicle could be used to directly deliver DC power that can be used to charge the vehicle battery without the need for an on-board charger. The off-board equipment with an AC output is generally referred to as electric vehicle supply equipment (EVSE), as it does not charge a battery directly but rather supplies power to the electric vehicle. The off-board equipment with a DC output is referred to as electric vehicle charging equipment or a charger.

Electric vehicle charging is a complex process, with communication protocols, charge event controls, battery management and protection systems that require this type of equipment to be much more sophisticated than traditional general-use battery chargers. Additionally, not all conductive charging equipment is the same. Different physical output configurations at the vehicle connector and vehicle inlet will dictate the corresponding communication and charging protocols that are used with that particular equipment.

Connecting to an electric vehicle and transferring power, whether AC or DC, requires communication between the off-board equipment and the vehicle to manage the power transfer in a safe manner. The communication protocol is complex and involves many messages to determine that the conductive connection is made, that the vehicle and off-board device can agree on a charging power level based on vehicle battery status and infrastructure limitations, concurrence (sometimes referred to as “handshakes”) to start and stop the charging event, and the like.
In North American end-product safety standards, the approach is to show that the off-board device will mitigate risks or fail safe in the event that the communication from the vehicle is in error. The automotive industry is self-regulating in North America, and the adequacy of the automotive communication system — including efficacy, reliability, and the effects over time from abuse, damage, weather, or modification of the vehicle — lies exclusively with them. Because the vehicle is not included or verified as part of the certification evaluation of the off-board charging equipment, it is not possible to rely on the communication from the vehicle, and therefore, the off-board device must mitigate the risks or fail in a safe mode. The International Electrotechnical Commission (IEC) standards use the same general approach: communication to and from the vehicle cannot be relied on for safety, and the system must mitigate risk and/or fail safe regardless of what is being communicated from the vehicle.

Protection systems are required to be provided in all off-board equipment in order to protect the user and general public. The main focus addresses protection for the user having direct physical access to parts operating at hazardous voltage, current and/or energy when touching the vehicle and charging equipment during power transfer. The protection systems in North America involve a system that can monitor the vehicle frame, the vehicle connection and the systems of the off-board device to shut down the charging event if anything occurs outside normal operational parameters. This is administered through the conductive connection to the electric vehicle. As the off-board equipment can physically touch the electric vehicle during power transfer, the off-board equipment can monitor the vehicle. The protection system in IEC standards can be a single component or a more robust system. The protection system in North American standards and the protection system in the IEC standards are not identical, but the overall conceptual approach is similar.

This baseline serves as a useful foundation for the discussion of future technology and provides context for how future technology will affect the standards and the safety approach.

The present electric vehicle charging landscape

In the original wave of electric vehicle deployment, EVSE made up most, if not all, of the electric vehicle charging infrastructure. The first products to be marketed were provided with the vehicle and used as portable convenience chargers. They were intended to be carried in the vehicle and taken out whenever charging was needed. Once charging was complete, the portable EVSE was intended to be returned to its storage area in the vehicle until it was needed again. They were lower power and could be plugged into any available receptacle so the vehicle could be charged wherever and whenever needed. However, based on their power limitations, these devices took longer to charge a vehicle and were generally considered overnight charging equipment.

The next step in charging evolution was to increase power, and wall-mounted, residential charge stations and public infrastructure began to be installed. These devices were still provided with AC outputs, but the power levels were higher and reduced the charge time to a matter of hours rather than overnight.

The demand emerged for DC chargers that would provide DC power at higher power levels and lower charge time compared to AC charge stations. DC charging was a way to decrease range anxiety for drivers by allowing a vehicle to charge in a matter of one hour or less so that a driver would not be fearful of being too far from home or their normal charger. This was commonly called “fast charging.” Over time, other designations were also used for fast charging, such as “lightning” and “turbo” charging.

Today, both technologies exist and infrastructure of both types are installed in public areas for use by all electric vehicle owners.

AC output devices — Electric vehicle supply equipment

EVSE is provided as portable, movable or fixed devices. Portable devices can be moved with the vehicle and are commonly carried in the vehicle so that a means to charge the vehicle is always present. Movable devices are cord-and-plug connected devices that are mounted on the wall in a garage, car port or other residential location. If the driver sells the vehicle or moves to a new location, the charger can move with the vehicle, but it is not intended to be moved on a regular basis. Fixed devices are typically publicly located in parking lots or workplaces and are fixed in place, for example, by bolting them to the pavement or securing them to a post or pedestal. They are also permanently connected to the source of supply. No cord-and-plug connections are used for fixed products. The power levels can be higher in fixed devices compared to cord-and-plug connected devices, as the limitations associated with cord-and-plug connected devices do not apply to permanently connected versions of EVSE.

In all cases, the EVSE is essentially a pass-through device. This means that the EVSE provides control and monitoring functions along with communication, but the input and output electrical ratings are generally identical because AC power modification does not occur within the EVSE.

In order to provide AC power to a vehicle, a means to conductively connect the off-board device to the vehicle is required. These connections are not as simple as plugging a device into the wall, and they require multiple contacts for power, communication, pilot and ground (earth) connections. In order to accomplish this, special connection configurations are used.

There are four main components that provide for an EVSE conductive connection: the EV socket-outlet, EV plug, vehicle connector and vehicle inlet. All four of these devices are designated as accessories. See Figure 2.

Two methods are used to implement the connection between the EVSE and the electric vehicle. In both methods, the cable is permanently connected to the vehicle connector. The difference in the methods occurs at the opposite end of the cable. In one method, the cable is permanently connected to the EVSE, called Case C in the IEC standards. In the other method, the cable ends in an EV plug that can be connected to an EV socket-outlet provided on the EVSE, called Case B in the IEC standards. These methods are not interchangeable and depend on the design of the EVSE. In general, North America uses Case C, the method in which the cable is permanently connected to the EVSE, and the EU uses Case B, the method in which the EVSE is provided with a socket-outlet and the vehicle owner brings the cable with them to connect to the EVSE and the vehicle.

This is not a requirement, as both types of connection are permitted in North America and the EU, but rather a market choice that was implemented by the industry.

Regardless of the connection method, two main AC configurations apply to North America and the EU in order to provide AC power to a vehicle: the SAE J1772/Type 1 configuration and the Type 2 configuration.

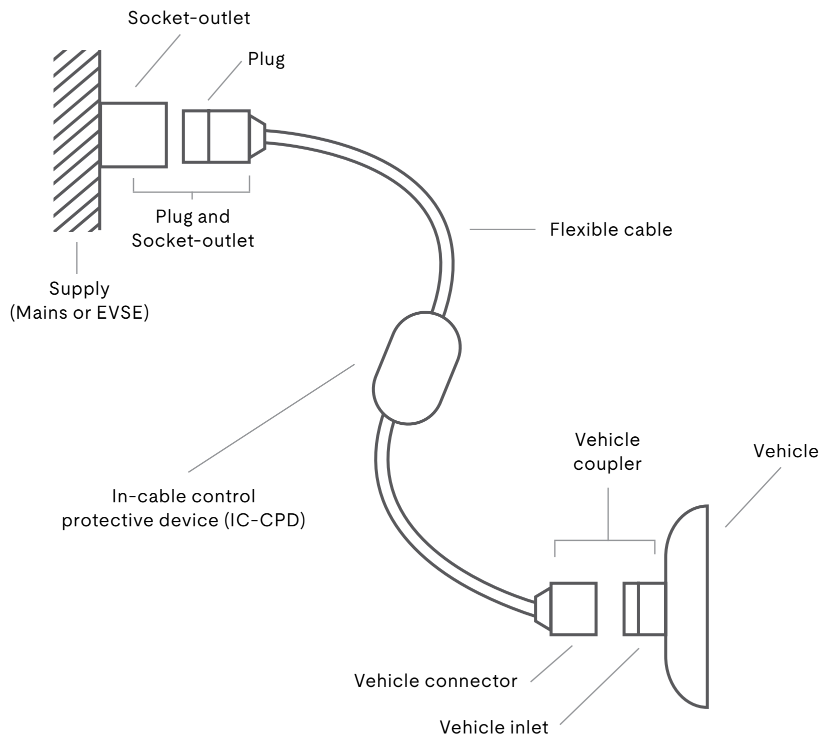

Figure 2 - EVSE Accessories

In North America, a single-phase connection to the vehicle is used for all EVSE. The single-phase version of the configuration is referred to as the J1772 connector in North American standards and as a Type 1 connector in the IEC standards. The J1772 designation comes from SAE J1772™, Electric Vehicle and Plug-In-Hybrid Electric Vehicle Conductive Charge Coupler, which covers the physical and functional requirements for the accessories. The Type 1 designation comes from IEC 62196-2, Plugs, Socket-Outlets, Vehicle Connectors, and Vehicle Inlets — Conductive Charging of Electric Vehicles — Part 2: Dimensional Compatibility Requirements for AC Pin and Contact-Tube Accessories, which includes the same J1772 configuration but designates it as Type 1.

In the EU, a three-phase electrical supply to the vehicle is used for most EVSE, but single-phase electrical supply is also used for some EVSE. The typical configuration in the EU is a Type 2 configuration, which can be used as three-phase or as single-phase electrical supply depending on how it is wired. The Type 2 configuration is covered in IEC 62196-2. Both Type 1 and Type 2 configurations that are used in EVSE make use of a similar communication protocol. This communication protocol requires the use of two communication contacts on the connection. Therefore, the J1772/Type 1 configuration is a five-contact configuration with two power contacts, a ground contact and two communication contacts, as shown in Figure 3. The Type 2 configuration is a seven-contact configuration; it uses three-phase power, and it has three power contacts, a neutral contact, a ground contact and two communication contacts, as shown in Figure 4.

For the North American and EU markets, these are the AC configurations that have been in use to transfer power conductively to an electric vehicle. Note that other AC configurations exist around the globe, including within China, and some of these configurations may be proprietary to a particular automaker, such as the original Tesla connector.

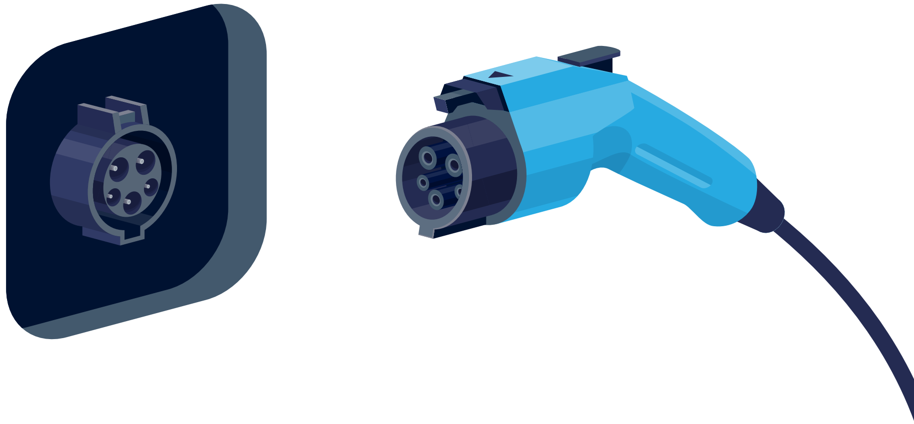

Figure 3 - SAE J1772/Type 1 Configuration

Figure 4 - Type 2 Configuration

Residential equipment — Private access

Residential-type equipment is typically dedicated to charging one vehicle and used by one person or family in a residential setting. There are two main types of residential devices: the portable EVSE and the wall-mounted, movable EVSE.

Today, residential charging is more prominent, and in some locations in the U.S., building codes require new homes to be "residential charging ready" so homeowners can easily have an EVSE installed if they choose to purchase an electric vehicle.

Commercial equipment — Public access

Public-use equipment is typically located in an area that is accessible to any driver in any vehicle. The product is used to charge any vehicle on the market that is provided with a vehicle inlet that matches the configuration of the EVSE output vehicle connector.

DC output devices — Chargers

DC output devices are typically fixed-in-place, permanently connected devices. Although cord connection was always allowed, DC chargers typically have not made use of this construction. Today's chargers are typically publicly located, such as in parking lots of commercial locations, workplaces or car dealerships, and are used to charge a vehicle in the shortest time to help decrease range anxiety and make the use of electric vehicles more attractive. The power levels can be quite high, and the industry is continually pushing to increase those levels.

DC chargers take many forms. Some chargers are housed within a single cabinet, and others consist of multiple, interconnected cabinets housing different parts of the charger system.

In theory, the output rating of the charger can be any power level, but this is typically controlled by the charging protocol, which in turn is tied to what electric vehicles are capable of using. For example, having a 1,500 V output at 600 A is not useful if vehicles are not capable of using that power level. Today, the maximum voltage contemplated is 1,000 VDC, and the maximum current is 400 A when not provided with active cooling. When provided with active cooling, the rating can increase up to 1,000 VDC and 800 A respectively.

Another form of output control is dynamic current control, referred to as boost current in the IEC standards. Under dynamic current control, the DC charger is allowed to output a current level that is higher than its rating, but only for a short period of time. Active cooling and dynamic current control are discussed in later paragraphs.

Similar to AC connections, in order to provide DC power to a vehicle, a means to conductively connect the off-board device to the vehicle is required. These connections also require multiple contacts for power, communication, pilot and ground (earth) connections. Three main DC configurations apply to North America and the EU in order to provide DC power to a vehicle. These include the combo coupler versions of the AC configurations described previously and the CHAdeMO configuration. The CHAdeMO configuration originated in Japan but has limited use in North America, the EU and elsewhere as an alternative to the combo coupler configurations, although mainly for electric vehicles produced by Japanese and Korean automakers.

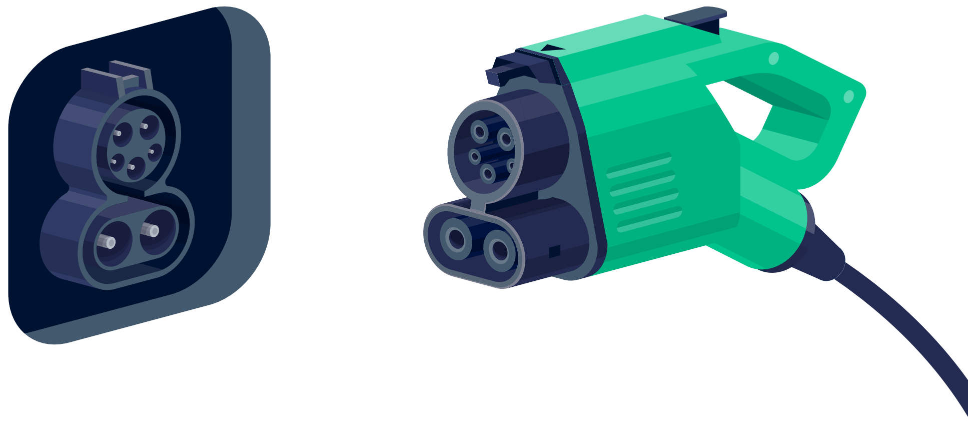

Figure 5 - CCS1 Configuration

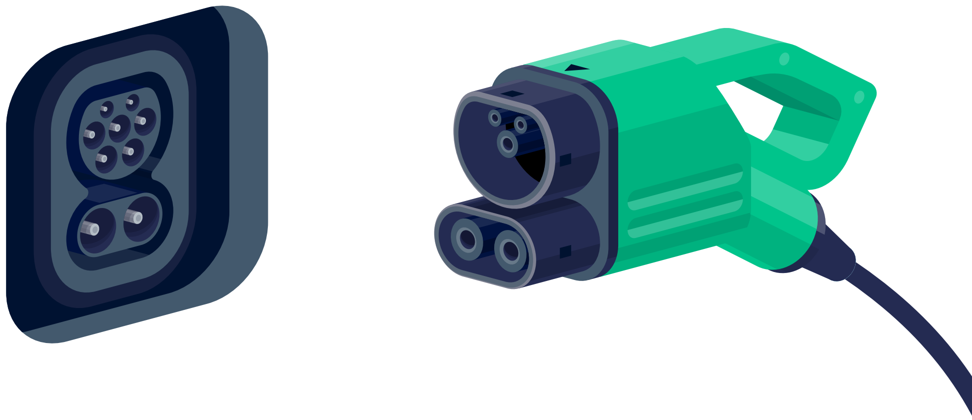

Figure 6 - CCS2 Configuration

In North America, a combo connection based on SAE J1772 is used and expanded to include DC. In the EU, the Type 2 configuration is expanded into a combo connector. These are then designated as CCS1 (Type 1 based) or CCS2 (Type 2 based). The concept of this configuration is to have one inlet with the smallest-possible footprint on the vehicle that can be charged with an AC connector or a DC connector. These two options make use of the same charging protocol, communication scheme and ground connection as the AC charging connectors described previously. Therefore, the only addition is the DC+ and DC- contacts, shown in Figures 5 and 6.

The CHAdeMO configuration uses a more complex communication protocol compared to the combo couplers. This results in a total of six communication contacts, a functional earth contact (for monitoring purposes) and two DC contacts. It is a DC-only configuration, requiring vehicles that utilize CHAdeMO inlets to be provided with an additional AC inlet to allow for AC charging. See Figure 7 for the CHAdeMO connector and an example of the inlet.

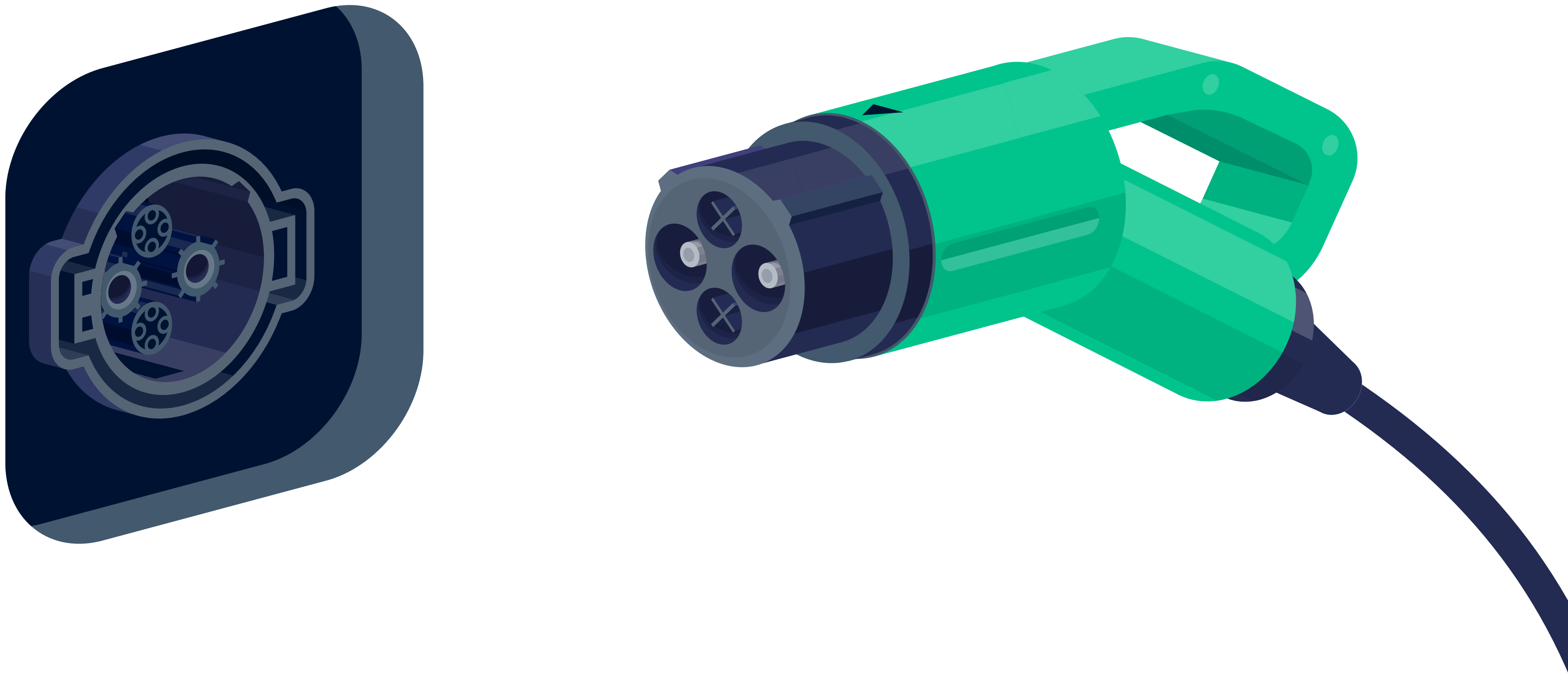

Figure 7 - CHAdeMO Vehicle Connector

Figure 8 - DC fast charger

Residential equipment — Private access

For DC chargers, there is not much residential equipment. This is not necessarily prohibited by standards, but the initial push for infrastructure was AC output with an on-board charger, with the use of DC reserved for fast charging. The thought of DC in a residential setting was not specifically considered in the early adoption of electric vehicles. As time goes on, there is some interest in pursuing a residential application with lower DC power to eliminate the need for an on-board charger. However, this has not come to full fruition yet.

Commercial equipment — Public access

This equipment is typically located in an area that is accessible to any driver and is used to charge any vehicle on the market that matches the configuration of the charger. These devices are typically fixed in place and are larger in physical size. See Figure 8 for an example of a DC charger with multiple outputs.

Active cooling

Active cooling is one type of output control that is provided for DC chargers. Without active cooling, the output cable to the vehicle must be sized appropriately for the maximum rated current that can be delivered to the vehicle. The higher the current, the larger the cross-sectional area of the conductors. The larger the conductors, the larger the cable. This leads to heavier cables that have less flexibility during use, especially in cold weather, when copper wires stiffen. To reduce the overall size of the output cable while still being able to conduct higher current levels, the concept of active cooling was developed.

Active cooling results in a complex, engineered approach to charging electric vehicles. The concept is to allow components to handle higher power than they would normally be able to handle by providing a means to cool the components while the current is being conducted. This involves cooling the electric vehicle connector and cable on the output of DC chargers. In this way, a smaller cable can be used, but a higher current could be passed through the cable. This can enable the higher current to flow through the cable without damaging the conductors or insulation.

In order to accomplish this, coolant lines must be passed from the charger through the cable and the connector. The coolant is circulated in order to cool the contacts in the connector and the conductors in the cable. The coolant generally will also need to be cooled through a radiator system to continue its function, so the coolant needs to be brought back to the charger where these radiator systems are located. However, if the active cooling fails, the results could be catastrophic. Therefore, continual monitoring of the active cooling system is needed to prevent the development of hazards. This involves monitoring temperatures at the connector contacts as a minimum and monitoring of various parameters associated with the cooling function. The parameters that are monitored are at the discretion of the charger manufacturer. However, a risk assessment is used to determine if the monitored parameters are sufficient to mitigate risks associated with the cooling system. The charger itself needs to demonstrate its ability to monitor the entire system to reliably maintain operational parameters below specified limits.

If any parameter exceeds those operational limits, the charger will shut down or reduce output power. The operating limits when not actively cooled are based on the current rating that could be passed through the output cable without any outside controls required to comply with the standard's requirements.

The overall operation and functionality is based on the individual manufacturer's design. The requirements for each engineered system need to address the overall outcomes for compliance with safety standards. The coordinated use of hardware and software systems to effectively and reliably achieve required safety outcomes is the key aspect of functional safety. The overall compliance evaluation would require a risk assessment and functional safety review to demonstrate the reliability of the monitoring means and the components used in the particular system.

In North America, UL 2202, the Standard for DC Charging Equipment for Electric Vehicles, contains system-level requirements for active cooling. Additionally, the liquid-cooled connector is covered by the requirements of UL 2251, the Standard for Plugs, Receptacles, and Couplers for Electric Vehicles.

There are also two separate IEC standards that address these topics. IEC 61851-23, second edition, covers the requirements for liquid-cooled charging systems. Additionally, IEC TS 62196-3-1 covers the actively cooled connector. It is anticipated that this document will be combined with IEC 62196-3 during that document's next revision phase.

Dynamic current control

Similar to active cooling, dynamic current control is another method for charging at higher current while controlling the output to maintain temperatures of the DC charging system within operational limits. However, rather than relying on a cooling means to cool the cable and connector, dynamic current control monitors the temperatures on the system during use. When the system approaches a specific temperature limit, the output current is reduced to a lower level based on the overall size of the cable and the components involved to allow the system to maintain temperatures within the operational limit. Overall operation commences by passing a current at a maximum level specified by the manufacturer. During this period, temperatures are monitored at the connector contacts, at a minimum, and the system reacts based on the temperature indications. Higher current is delivered for a short duration, and as temperatures on the contacts approach a preset limit, the current is reduced to a base rating so the charger can continue operation. The base rating is the current that can be passed through the systems without any outside controls in compliance with the requirements in the standard. If temperature limits are exceeded, the charger shuts down.

In North America, UL 2202 contains requirements outlining how to address dynamic current control from a system level. Additionally, connectors used in systems with dynamic current control are covered by requirements in UL 2251.

There are two IEC standards in development that will address direct current control; they are part of the same standards in development addressing active cooling. IEC 61851-23 will cover the system level, and IEC 62196-3 will cover the accessories.

Summary of existing standards

In this section, we will provide a high-level summary of the current standards covering the products noted previously. We will present the standards that exist in North America and the EU based on product type. These documents are similar but not identical, due to the type of certification scheme used in each region, the installation codes and practices used in each region, and specific country differences for how products are certified.

Standards in general

In North America, several standards cover safety requirements for EVSE and chargers described earlier. In all cases, these documents are harmonized between Canada, the U.S. and Mexico. This means the requirements for the three countries are essentially identical.

These standards are used for safety certification in North America. They address the safety of these devices for risk of fire, shock and injury associated with the use and reasonably foreseeable misuse of the product. They do not necessarily cover the design of the product and are design agnostic overall.

Internationally, several standards also cover safety requirements for EVSE and chargers. This paper will discuss the IEC version of the document with the understanding that European Norm (EN) standards may exist that are based on these IEC standards and that individual country differences may also exist within these EN standards.

However, this paper will focus on the IEC-level standards without having to consider whether an EN standard exists or to contemplate all the differences between countries. Although this is a simplification of the actual applicability of the IEC standards, it gives us a baseline for discussion.

The CB scheme applies for all off-board equipment discussed in this paper. The CB scheme is based on evaluation to the IEC base document along with the group and national differences for each destination country within the EU. The standards cover the fire and shock safety aspects and some design aspects and performance requirements.

Standards based on product type

EVSE

The North American end-product standard for EVSE is a trinationally harmonized document for the U.S., Canada and Mexico. The designation is UL 2594/CSA C22.2 No. 280/NMX-J-677-ANCE, with the number designations applying to the U.S., Canada and Mexico respectively. This is the Standard for Electric Vehicle Supply Equipment, and it covers portable, movable and fixed EVSE for residential and public access EVSE. See Figure 9 for an example.

In the IEC documents, two standards currently address these product types. IEC 61851-1, Electric Vehicle Conductive Charging System — Part 1: General Requirements, covers portable, movable and fixed EVSE and provides the general requirements for DC chargers. IEC 62752, In-Cable Control and Protection Device (IC-CPD) for Mode 2 Charging of Electric Road Vehicles, covers portable and movable, cord-and-plug connected EVSE. The term Mode 2 refers to cord-and-plug connection with AC output in accordance with IEC 61851-1. Both standards include the products in Figures 10 and 11 within their scope.

Currently, the use of both standards is allowed, and the customer drives the decision of which standard to use. However, future revisions of these documents will move all Mode 2 (cord-and-plug-connected) charging equipment to IEC 62752 and all Mode 3 (permanently connected) charging equipment to IEC 61851-1.

These documents have been published. As of the time of this writing, both UL 2594/CSA C22.2 No. 280/NMX-J-677-ANCE and IEC 61851-1 are in a revision phase. A new edition of IEC 62752 was published in March 2024.

Figure 9 - Public Access EVSE

Figure 10 - Portable EVSE

Figure 11 - Wall Mounted, Residential EVSE

DC chargers

The North American end-product standard for chargers is also a trinationally harmonized standard for the U.S., Canada and Mexico. The designation is UL 2202/CSA C22.2 No. 346/ NMX-J-817-ANCE with the number designations applying to the U.S., Canada and Mexico respectively. This is the Standard for Electric Vehicle (EV) Charging System Equipment and covers all forms of off-board chargers with a DC output.

The main IEC standard is IEC 61851-23, Electric Vehicle Conductive Charging System — Part 23: DC Electric Vehicle Charging Stations. This is used in conjunction with IEC 61851-1 to cover all aspects of the DC charger. Additionally, IEC 61851-24, Electric Vehicle Conductive Charging System — Part 24: Digital Communication Between a DC EV Charging Station and an Electric Road Vehicle for Control of DC Charging, defines use cases and messaging for the control of the charging event.

These documents have been published. The North America document is beginning a revision phase as of the date of this paper. The latest edition of both IEC standards was published in December 2023.

Accessories

In North America, UL 2251/CSA C22.2 No. 282/NMX-J-678-ANCE, the Standard for Plugs, Receptacles, and Couplers for Electric Vehicles, is a trinationally harmonized standard with the number designations applying to the U.S., Canada and Mexico respectively. This document covers vehicle connectors, vehicle inlets, EV plugs and EV receptacles. This standard is agnostic to the type of configuration and is capable of covering what is available in the market.

A series of IEC standards cover these accessories. IEC 62196-1, Plugs, Socket-Outlets, Vehicle Connectors and Vehicle Inlets — Conductive Charging of Electric Vehicles — Part 1: General Requirements, provides general requirements for all these accessories, which apply unless they are modified by specific requirements in the other parts. IEC 62196-2, Plugs, Socket-Outlets, Vehicle Connectors and Vehicle Inlets — Conductive Charging of Electric Vehicles — Part 2: Dimensional Compatibility Requirements for AC Pin and Contact Tube Accessories, covers AC-rated accessories for specific configurations, including Type 1 and Type 2, described in earlier in this white paper. IEC 62196-3, Plugs, Socket-Outlets, Vehicle Connectors and Vehicle Inlets — Conductive Charging of Electric Vehicles — Part 3: Dimensional Compatibility Requirements for DC and AC/ DC Pin and Contact Tube Vehicle Couplers, covers DC-rated accessories for specific configurations, including CCS1, CCS2 and CHAdeMO, described in this white paper.

IEC 62196-2 and IEC 62196-3 contain standards sheets to determine compliance of AC configurations and DC configurations respectively. Therefore, only the configurations shown in Parts 2 and 3 are suitable for use in accordance with the IEC standards. The North American standard and the IEC series of standards are currently in a revision cycle, with anticipated publication dates in mid-2026 for the North American standards and early 2025 for the IEC standards.

Protection systems

In North America, there are two trinationally harmonized standards that together cover protection systems used in electric vehicle charging: UL 2231-1/CSA C22.2 No.281.1/NMX-J-668-1-ANCE, the Standard for Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits, Part 1: General Requirements, and UL 2231-2/CSA C22.2 No. 281.2/NMX-J-668-2-ANCE, the Standard for Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits, Part 2: Particular Requirements for Protection Devices for Use in Charging Systems. These standards allow for a grounded protection system or an isolated protection system, and both systems are made up of devices and insulation in a manner that can protect the user. These systems are typically embedded into the overall system design and are rarely standalone systems.

In IEC documents, this is handled in a slightly different manner. Most protection is based on a residual current device (RCD), which is required to be installed in the building wiring or in the product. For EVSE, the RCD is the main protection component, and additional devices are not necessarily required. The EVSE standards will call out a specific type of RCD in accordance with IEC 61008-1, IEC 61009-1, IEC 60947-2 or IEC 62423. For electric vehicle chargers, an RCD based on the same requirements as those given in IEC 61851-1 may be included, but this is not required, as the RCD would most likely be in the installation.

The need for an RCD is required by both the IEC 61851 series and IEC 60364-7-722 for the installation of EVSE. In fact, IEC 60364-7-722 requires an RCD to be provided in the panel of the building installation. However, for older installations, receptacles may not provide an RCD, so portable and wall-mounted, cord-and-plug connected EVSE may not provide the protection in the installation. Therefore, IEC 62752, In-Cable Control and Protection Device (ICC-PD) for Mode 2 Charging of Electric Road Vehicles, was created to address the portable RCD and protection system. As mentioned in the EVSE section, this standard also duplicates coverage of the overall EVSE, which is also covered in IEC 61851-1. However, the protection system requirements only exist in IEC 62752 and are different than what is required for an RCD in IEC 61851-1.

These documents have been published. UL 2231-1/CSA C22.2 No.281.1/NMX-J-668-1-ANCE and UL 2231-2/CSA C22.2 No. 281.2/NMX-J-668-2-ANCE are in a revision phase as of the writing of this white paper. A new edition of IEC 62752 was published in March 2024.

New technology

Now that we have set a baseline understanding for existing technology, we can look to the future. This involves conductive technologies such as increasing the power limitations for equipment output, using automatic connection means to handle high-power connections, incorporating energy storage systems into the overall charging system, using the vehicle as a source, and incorporating the use of adapters to expand the use of infrastructure to more vehicles. Each of these advances moves a step beyond the existing technology but uses the same basis for conductive connection to the vehicle.

Additionally, we will look to another technology that is used for charging electric vehicles but is significantly different in overall functionality compared to what exists today. This technology is a method of charging that includes no conductive connection to the vehicle and is designated as wireless power transfer.

These new technologies are new in that standardization is not yet complete. In all cases, some progress has been made in standardization, pilot programs may be in process, the technology may be used successfully in a given market or region, but widespread commercial application is not yet available. We will discuss the technology from a high level to support an understanding of what is coming in the near future and provide an overview of the standards being developed to cover these technologies.

Adapters

Recently, the formerly proprietary Tesla connector configuration was opened up to other manufacturers. This configuration was also identified as the North American Charging Standard (NACS) to be used consistently for future electric vehicle charging deployments in North America. The main goal for NACS is to use NACS inlets on vehicles other than Teslas and then allow those vehicles to use all existing and future charging infrastructure with that same configuration. A number of vehicle manufacturers have announced their intentions to switch, and in future model years, the vehicles will have NACS inlets for use with NACS infrastructure.[1] There are vehicles on the road today that still have a J1772 combo inlet, but the intent is to optimize their ability to use NACS infrastructure. As the NACS connector will not physically mate with the J1772 inlet, and these legacy vehicles will be on the road for years, there is a need for a product that will convert from NACS to J1772.

Enter the adapter.

Although NACS implementation is the main driver of the need for adapters, other configurations not associated with NACS could also be used with adapters. To support safe charging with these adapters, a new standard is needed to evaluate the safety of the adapter and the user, as well as safety impacts on installed infrastructure designed and built before adapters were a consideration.

UL Solutions developed UL 2252, the Outline of Investigation for Adapters for use with Electric Vehicle Couplers. UL 2252 is currently available to be used for certification, and it is progressing through the consensus cycle to become the binational standard for the U.S. and Canada. The standard addresses fire, shock and injury hazards associated with the use and abuse of the adapter and includes requirements that address safe use of the adapter with existing infrastructure.

Megawatt charging systems

Another innovation in conductive charging centers around the charging of trucks, buses and other heavy-duty vehicles. This DC charging innovation is referred to "megawatt charging" due to the megawatt power levels involved in the power transfer. The maximum ratings associated with this technology are 1,500 VDC (with actual operation at 1,250 VDC) and 3,000 A.

Megawatt charging requires new charging systems, protocols and couplers. At the time of this paper's publication, this is being standardized at various levels.

In North America, UL 2278, the Outline of Investigation for Megawatt Charging Configured Electric Vehicle Couplers, covers electric vehicle connectors and inlets that are of standardized configurations intended for use at megawatt charging levels. This document is currently in the consensus process and, when complete, will also serve as the binational standard for the U.S. and Canada.

Additional work is occurring for electric vehicle cables suitable for 1,500 VDC and charger systems that operate at these increased ratings. As stated previously, these systems require components that are different from what is currently available in the market. Some of the diverging aspects can be absorbed into legacy requirements with minimal changes, whereas other differences necessitate significant changes to the safety approach.

In the EU, there is work in progress that mirrors the work in North America. IEC 63379 is currently in development to cover the megawatt configured charge couplers. It is anticipated that this document will first be published as a technical specification with subsequent, continued work to move it to a standard. Additionally, IEC 61851-23-3 is in development to cover the megawatt charging systems.

Electric vehicle charging integrated with energy storage systems

In order to expand the range of electric vehicles and enable their use over long distances, infrastructure equipment that can be used for charging these vehicles along the travel route is critical. The concept of having fast charging along main traffic routes requires that sufficient power be delivered to these sites in order to use the infrastructure.

However, some of these charging locations may be located where there is no readily available power. Furthermore, some of the applications, such as large megawatt charging stations, can present a significant demand on the existing grid. One way to provide for practical charging in these locations is to use energy storage systems to provide power to the charging systems. The energy storage system could be supplied from any source, including photovoltaics, wind and hydropower. The chargers are interconnected with the energy storage device, and that power is used to charge the electric vehicles.

This technology could also be used for public or private infrastructure in remote locations, rural areas or anywhere else energy storage is considered an option to accomplish strategic geographical support for electric vehicle charging.

Although the system may not have a connection to the grid, it is still an electrical installation. Regional codes and safety requirements for the battery, the energy storage system and the charger would apply. In the U.S. and internationally, the same standards would apply for any charger or charge station product described in previous sections. Regardless of where the input comes from, the charger and charge station standards cover the infrastructure. In North America, the energy storage portion of the system is covered by UL 9540, the Standard for Energy Storage Systems and Equipment, and further supplemented by UL 9540A, the Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems, as applicable. Internationally, IEC 62933-5-1, Electric Energy Storage (ESS) Systems — Part 5-2: Safety Requirements for Grid Interconnected Energy Storage Systems — Electro-Chemical Based Systems, was developed to address these systems. However, it will not include the thermal runaway fire propagation aspect. The technology around these system types is increasingly becoming an important discussion topic and systems are nearing commercialization at scale. These charging systems will go a long way to enabling long-distance travel of electrical vehicles, and the systems can be installed where they may be needed. This innovation, along with the increasing prevalence of charging stations, can offer the driver peace of mind.

Automatic connections means

An overall trend in vehicle charging, especially for larger, heavy-duty vehicles, is the increase to higher voltage and higher current, which yields higher power to the vehicle. This higher power can reduce overall charge times, especially for larger vehicles, leading to more manageable and attractive charge times. However, as those power levels increase, the means for connection can become larger, more complex or potentially hazardous for the general public to handle. This is where automatic connection means come into play.

Initially, automatic connection means were used with what is referred to as heavy-duty charging and is typically associated with trucks and buses. (Over time, the concept has slowly moved into the area of electric vehicle charging in general, meaning that passenger vehicle options for automatic connections are now in the process of being standardized.) Trucks and buses make use of larger, more energy-dense batteries to gain the range needed to move the large vehicle throughout the day. The increase in battery size means it takes longer or more power is needed to charge the battery. The use of automatic connection means eliminates the concerns around large cables that must be manipulated by a person and helps mitigate risks associated with people handling such high-power connections.

Automatic connection also creates a secondary opportunity. A delivery vehicle, public bus or the like will stop at various locations during its daily routine, and charging can occur each time the vehicle is stopped. However, it is not beneficial to have the driver plug in at each stop, so the automatic connection means are an ideal way to address this scenario. Quick charging sessions each time the vehicle is stopped are referred to as opportunity charging, and this is possible because the vehicle is intended to stop at the same location each time. We can look at an electric bus used for public transportation as an example. If an electric bus must complete its entire route multiple times per day on one charge, very large batteries would be necessary to store all the energy required. If the bus could be charged every time it stops to load and unload passengers, the batteries could be smaller but accomplish the same task. Automatic connection means could be installed at bus stops so that the bus can be charged for a few minutes while the bus is stopped at that location. This will extend the range of the bus during the day and allow smaller, less expensive batteries to be used.

Standards development began to address automatic connection means, and many concepts were included. One of the concepts was to have a bus pull into a charge bay and link up with a connection means that was mounted on an overhead rack. This connection means could move a little to each side to compensate for misalignment when the bus pulled in.

A second concept involved a pantograph construction that would lower and contact charging rails on the roof of the bus, shown in Figure 12. A third concept resulted in connection means extending from the ground under the bus to contact charge rails on the bottom side of the bus. A fourth involved a robotic arm extending and inserting a connector into the inlet on the bus. Any of these or similar means would help alleviate the concerns around flexibility of cables, access to high power and ease of use.

Depending on the design, other concerns that do not exist for manual connections must be considered. Does the connection mate properly and only attempt to mate when the vehicle is ready to accept charge? Does the system disconnect correctly so the vehicle can drive away without damaging the vehicle or the charging equipment? Under conditions of power loss, can the vehicle disconnect from the charging equipment and drive away? Will the connection make and break under load? Can the connection means become live when no vehicle is present? What effect will environmental stressors have on the connection means, both on board the vehicle and within the infrastructure? All these issues and many other issues associated with a given design must be addressed through electrical safety requirements, but the standards development process would be able to address those concerns.

Some automatic connection means for buses are already in use in Europe and in the U.S., either as installed systems or pilot programs to test the technology. See Figure 13 for an example of an overhead pantograph system installed in Europe. Although not all of the systems are the same, the standardization efforts are reacting to those installed systems, and the lessons learned are based on these installations.

The standards in North America are preparing to address automatic connection means. The SAE J3105 series, Electric Vehicle Power Transfer System Using Conductive Automated Connection Device, is published and covers the physical connector specification, communication and vehicle interface. The charging equipment connected to the connection means would not be all that different from existing technology, with the exception of the communication protocol. However, electrical safety will need to be addressed for this connection means as well. A UL Standard for the electrical safety of this technology is in the process of development at the time this paper is being written. The development of an IEC standard, IEC 61851-23-1 is also underway. Lastly, there are two additional development efforts underway for IEC 61851-26 and IEC 61851-27, which cover automatic connection means for general-use vehicles.

Figure 12 - Automatic connection means

Vehicle as a source

Another conductive technology that is under development involves using the vehicle as a mobile distributed energy resource. This requires some thought behind how it will work and be maintained in a safe manner and the impacts on the products connected to the vehicle.

There are potentially different levels of requirements based on the intended use case for the system. This includes vehicle-to-load (V2L), vehicle-to-premise (V2P) and vehicle-to-grid (V2G) applications. In each use case, either the off-board equipment or the vehicle can contain the inverter. Depending on where the inverter is located, different standards may come into play. Stakeholders include the vehicle manufacturer, the utility and everyone in between.

V2G applications involve connecting the vehicle to the grid through an inverter so that the utility can pull power from a vehicle during high demand or the vehicle owner can sell power back to the utility. Vehicles exporting power to the grid at any location and at any time introduce safety concerns for line workers, for example, in cases where they believe a particular circuit is deenergized, but it is, in reality, energized by a vehicle. Power quality is also a safety concern for V2G. Power exported to the grid must not be detrimental to the grid's stability or functionality. This use case is under discussion and will require additional work so that it performs as required and intended to perform while addressing safety considerations.

V2P involves connecting the vehicle to a home or other premise so that power can be transferred to the premise during emergency situations. In this use case, the vehicle acts as a generator and to power a home during power outages or other emergency situations.

V2L connects the vehicle to an off-board load that is not tied to the grid or the premise. This could include a device that is powered from the vehicle and provided with receptacles to plug in off-board loads, devices that plug into the vehicle inlet and convert the inlet to a receptacle (referred to as V2L adapters within the industry), or receptacles located on board the vehicle. In each case, the loads that are plugged in could be anything provided with a cord-and-plug connection that could be used at any time.

Some of the issues associated with the development of this technology center on the vehicle acting as a branch circuit in the vehicle-to-load case. Concerns about protection of the loads when the vehicle is acting as a source (i.e., feeder or branch circuit) are important from a safety perspective. However, there is no standardized construction or regulation that controls how that vehicle-based premises wiring system functions, including how it protects the appliances and products that are plugged into the vehicle source. Product certification can rely on the circuit breaker in the building installation to protect the product when it is plugged into a traditional branch circuit. If it is plugged into a vehicle, there is no way to guarantee that the equivalent protection is provided or in place because the vehicle is acting as a source and must comply with requirements for premises wiring systems as outlined in the National Electrical Code. This may pose problems for the equipment that is plugging into the vehicle source. Due to this unknown factor, products that are certified to published standards and requirements, regardless of which region, may no longer have adequate protection when plugged into a vehicle. Therefore, further effort has been applied in this area to address the safety of the installation when a vehicle is used as a source.

In North America, UL Solutions led the work to develop safety requirements for this application. That led to the subsequent publication of UL 9741, the Standard for Bi-Directional Electric Vehicle (EV) Charging System Equipment. After its initial publication, this document was then harmonized for use in Canada. The scope of this document covers all of the use cases described above.

Utilities have strict rules for what can be connected to their grids, and in some cases, UL 1741, the Standard for Inverters, Converters, Controllers and Interconnection Systems Equipment for Use with Distributed Energy Resources, is written in law, requiring compliance before a device is allowed to connect to the grid. An on-board inverter can be certified to UL 1741. Further, as advanced technology inverters propagate, there is development underway for UL 1741, Supplement SC, which provides requirements for equipment that will be placed between the utility grid and the vehicle to establish that all proper communication, protocols and safety measures are followed on both sides in order to allow an appropriate and safer interconnection.

In the IEC development community, committees associated with IEC 61851-1, Electric Vehicle Conductive Charging System — Part 1: General Requirements (covering AC output devices), and IEC 61851-23, Electric Vehicle Conductive Charging System — Part 23: DC Electric Vehicle Supply Equipment, are currently discussing this topic for inclusion in future editions.

Wireless power transfer

Work has also been done on the development of wireless power transfer as an alternative to conductive charging. This is a method of transferring power to an electric vehicle through an inductive connection that does not require physical contact or wires connected to the vehicle. The driver simply needs to park in the proper location for the wireless system and walk away. There are no potentially dirty, wet or broken connectors to handle.

Additionally, this technology can be used for opportunistic charging, which would enable a vehicle to charge whenever it is stopped. This could potentially involve opportunity charging at stop lights, drive throughs or toll booths. For service vehicles, such as buses and delivery trucks, this opportunity charging could take the form of specialized parking or stopping locations that allow the vehicle to charge while it is stopped at bus stops, delivery locations and the like. The concept of dynamic wireless power transfer can be taken a step further to allow the vehicle to travel over a specialized path that will recharge the vehicle as it drives along the road.

The overall technology works through an inductive connection between two coils, one located on the ground and one located on the vehicle. The off-board system energizes the ground coil from a high-frequency source, and the vehicle coil induces current from the inductive coupling between coils.

Many standards centered around this technology are in development. In North America, requirements are being developed for the U.S. in UL 2750, the Standard for Wireless Power Transfer Equipment. For Canada, harmonization with the IEC 61980 series is expected. SAE International has published SAE J2954, Wireless Power Transfer (WPT) for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology, which covers design, functionality, charging protocol and interoperability requirements. Efforts have been made by SAE, UL Solutions, and UL Standards & Engagement to coordinate the requirements. Internationally, IEC 61980-1, Electric Vehicle Wireless Power Transfer (WPT) Systems — Part 1: General Requirements; IEC 61980-2, Electric Vehicle Wireless Power Transfer (WPT) Systems — Part 2: Specific Requirements for MF-WPT System Communication and Activities; and IEC TS 61980-3, Electric Vehicle Wireless Power Transfer (WPT) Systems — Part 3: Specific Requirements for the Magnetic Field Wireless Power Transfer Systems, have all been published.

UL 2750 covers the electrical and system safety of the off-board equipment up to and including the coil on the vehicle. SAE J2954 covers the system on board the vehicle and addresses alignment when parking and interoperability of the overall system. UL and SAE International have agreed to work together to develop these two documents in conjunction with one another in order to avoid gaps and contradictions and foster a harmonized set of requirements.

The design aspects relate to safety, interoperability and functionality. Safety of the overall system involves traditional electrical safety, but in the case of wireless power transfer, the consideration of protection from exposure to the hazardous magnetic field under the vehicle must also be considered. Exposure to this field must be prevented. Systems that are part of the vehicle and/or the off-board system are used to detect metallic and organic material in the field and cause the power transfer to shut down. These systems are referred to as foreign object detection for metallic objects and living object detection for organic objects.

Design aspects related to interoperability involve enabling all vehicles to charge at any charge station. Since there is no physical connection, the driver assumes the charge event has begun, and user acceptance of the technology might suffer if it does not work reliably every time. A lot of attention has been paid to this design aspect in order to get the technology right the first time.

For design aspects around functionality, communication between the vehicle and the off-board equipment needs to be addressed. Unlike conductive charging in which the off-board equipment can monitor the vehicle during the charging event, for wireless power transfer, there is no method to monitor the vehicle except through communication from the vehicle. The vehicle must monitor itself and communicate correctly and reliably to the off-board system to control the charge event parameters.

[1]Motor Trend, " The Great NACS Migration: Who Is Switching to Tesla's Charging Port?, https://www.motortrend.com/features/tesla-nacs-charging-port-automaker-compatibility/

Conclusion

Many significant developments have taken place in the area of electric vehicle charging since the inception of the current generation of technology in 2009. As we move forward from a complex present into an even more dynamic future, demands from the user community and new technological innovations are pushing the infrastructure to do more and do it faster than before. This evolution leads to new developments and the need for innovative thinking, especially for standards and safety requirements. Safety is a foundational element of any successful and sustainable technological deployment and must continue to be actively addressed to support the emerging needs. Standards and requirements comprise a critical element of codifying which risks we agree to mitigate and which will be accepted. This establishes a solid threshold for consistent approaches to issues such as safety and morphologies and responsible innovation to differentiate in the market with technological advancements. These factors will support the expanded use of electric vehicles, powering the future of our global transportation systems.

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