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Toward Extreme Fast Charging

Challenges and opportunities in directly connecting to a medium-voltage line.

With an increasing awareness of the detrimental effects of the fossil fuel–based transportation sector, which accounts for 14% of human-made greenhouse-gas emissions globally, individuals, companies, and government entities have made a concerted push to develop solutions to provide modes of transportation that are less carbon intensive. Importantly, several countries, including Norway, India,

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France, and Britain, have decided to end the sale of internal combustion engine cars in the near future, further accelerating the shift to electric transportation. Many progressive strides have been taken in recent years to make electric vehicles (EVs) cost competitive while delivering a driving range of more than 200 mi (see Figure 1). At the same time, recent advances in lithium-ion battery technology promise to deliver vehicles with an even longer range while reducing battery costs and weight. These new batteries also exhibit ever-improving charge acceptance, allowing significantly faster charging rates.

To serve this growing fleet of new vehicles, an adequate charging infrastructure is needed. The simplest recharge method uses a vehicle's onboard charger, which connects to the residential single-phase ac supply. The so-called Level 1 and Level 2 ac chargers (defined in SAE J1772) serve as interfaces between the 120-V (Level 1) and 240-V (Level 2) supply lines and the onboard charger and can deliver up to 1.92 kW (Level 1) or 19.2 kW (Level 2) to the vehicle. The International Electrotechnical Commission (IEC) classification (IEC 61851) allows up to 26.6 kW for Mode 2 home ac chargers. Due to their limited power rating, the onboard chargers are not capable of replenishing the battery charge quickly enough to provide a refueling experience comparable to that of gasoline cars. As seen in Figure 1, it takes more than 8 h to add 200 mi of range to the battery of an EV when using the standard 208-V or 240-V plug available within U.S. homes. While this is acceptable for overnight charging, it is not suitable for longer trips, and it can create range anxiety (the fear that a vehicle has insufficient range to reach its destination).

The limited capability of onboard chargers has led to the development of dc fast chargers, typically rated at 50 kW and, more recently, at power levels up to 350 kW. These chargers deliver dc power to the vehicle battery via an isolated power converter located outside the vehicle, and they have the potential to provide the user with an experience similar to that of refueling a gasoline car. A fast charger rated at 50 kW requires more than 1 h to deliver enough charge for a 200-mi trip, while a 350-kW extreme fast charger would only take roughly 10 min to deliver the same amount of energy, as illustrated in Figure 1. Clearly, designing and building a system that can deliver this much power is quite challenging.

In this article, we present the current state-of-the-art fast-charging technologies. We discuss the state-of-the-art-fast chargers, their design, and their main characteristics. Additionally, we detail how these chargers can be combined to form fast-charging stations that mimic the functionality of a gasoline refueling station. Various power delivery concepts for these charging stations are described, and we discuss the benefits and shortcomings of the current and proposed approaches. Finally, we present a novel approach in which the charging station directly connects to the medium-voltage (MV) line, thus eliminating a number of power electronics conversion stages and the low-frequency step-down transformer. We outline significant benefits of this technology when considering extreme fast-charging rates, and we identify the key technology gaps in making this technology more widely accepted.

State-of-the-Art EV dc Fast Chargers

State-of-the-art dc fast chargers are installed either as single-stall units or multistall charging stations. Single-stall units are typically rated at 50 kW and powered by a dedicated service transformer. These chargers are capable of adding up to 100 mi (161 km) of range in approximately 30 min. Higher-power multistall charging stations, such as Tesla's supercharger stations, include multiple chargers and need additional switchgear and low-voltage (LV) metering circuits, as illustrated in Figure 2. In the case of Tesla's stations, each supercharger unit serves two charging stalls and can add up to 170 mi (273 km) of range in 30 min. When these systems are deployed, all of the system components are commonly installed on relatively

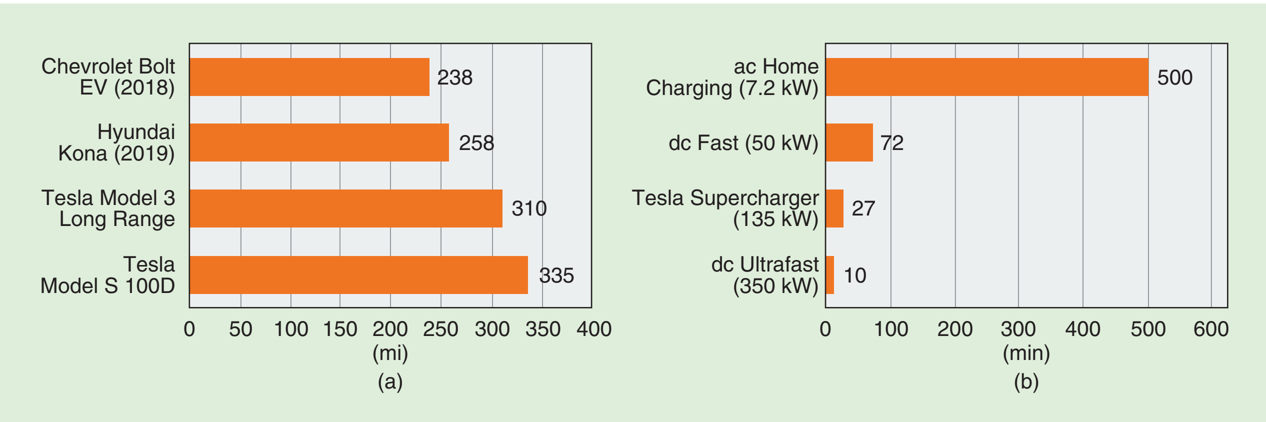

Figure 1. EVs with more than 200 mi of range and time to add 200 mi of range to the vehicle if it is charged at a constant power equal to a charger's rated power. The (a) range of EVs in miles and (b) the minutes to add 200 mi.

large concrete foundations, which adds to the installation costs. According to a study by the Idaho National Lab, the main cost drivers for charging station infrastructure installations include electrical service upgrades, the condition of the ground surface under which the electrical conduits were installed, the length of the conduits from the power source to the service transformer and from the transformer to the fast charger, material costs, permits, and administration.

Typical state-of-the-art dc fast chargers have two power conversion stages: a three-phase ac/dc rectification stage that includes power factor correction (PFC) and a dc/dc stage that provides galvanic isolation. The simplified block diagram of a state-of-the-art dc fast-charger power stage is illustrated in Figure 3. The ac/dc rectification and PFC stage converts three-phase input ac voltage to an intermediate dc voltage and ensures acceptable power quality on the grid side. The dc/dc stage converts the intermediate dc voltage into the regulated dc voltage required by the vehicle and provides galvanic isolation. The galvanic isolation separates the vehicle from the grid and also allows for the charger output stages to be easily connected in parallel.

A conventional dc fast charger typically uses an active pulsewidth-modulated (PWM) rectifier to implement the conversion and PFC functions. This single-stage converter is preferred at higher power levels because of its high reliability and simplicity. Strict harmonic standards are met by introducing an input filter. The active PWM rectifier is often based on converter modules used in motor drives that are typically based on reverse-conducting insulated-gate bipolar transistors and operate at switching frequencies not higher than 10 kHz. The more compact and efficient converter can be achieved with silicon carbide (SiC) power MOSFETs, which have substantially lower total power losses and operate at switching frequencies of several tens of kilohertz. The second stage is an isolated dc/dc converter, which provides dc regulation and galvanic isolation between the grid and the EV. Since the vehicle battery is not grounded, the isolated dc/dc converter stage maintains the isolation of the vehicle battery and the secondary side of the dc/dc converter. By maintaining system isolation, the charging system leaves the protection scheme designed for the vehicle battery intact.

Table 1 lists the technical specifications of some of the commercially available fast chargers. The vast majority of the commercially available units are rated at 50 kW and powered from a three-phase LV distribution grid. The chargers are typically built out of identical building blocks whose power output is combined to meet the required power needs. For example, Tesla's 135-kW supercharger

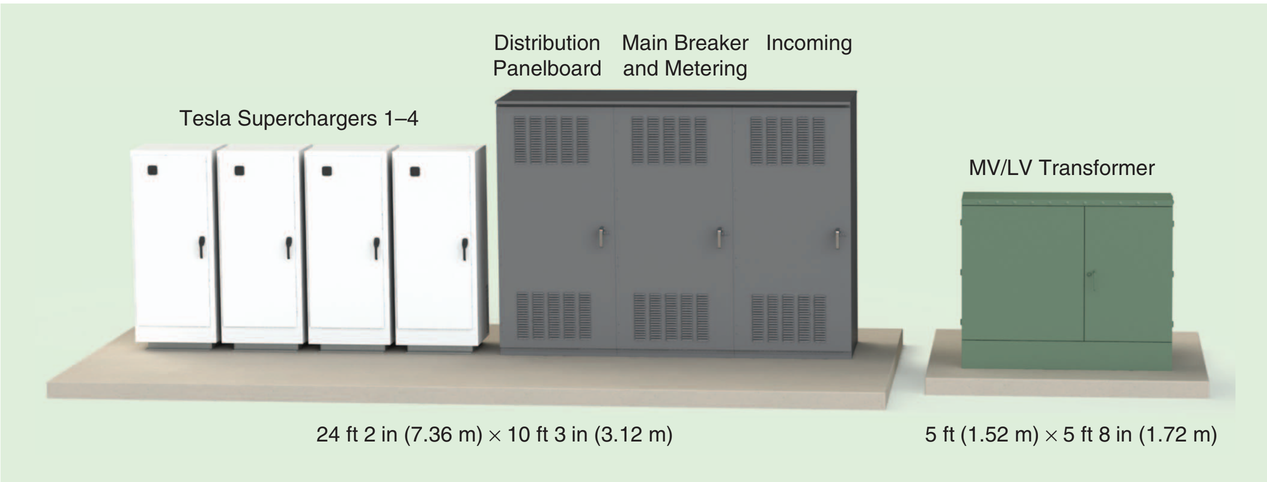

Figure 2. The layout of Tesla's supercharger station in Madison, Wisconsin (charging stalls and the seclusion composite fence surrounding the superchargers and switchgear are not shown). The transformer is located approximately 24 ft (7.3 m) from the superchargers.

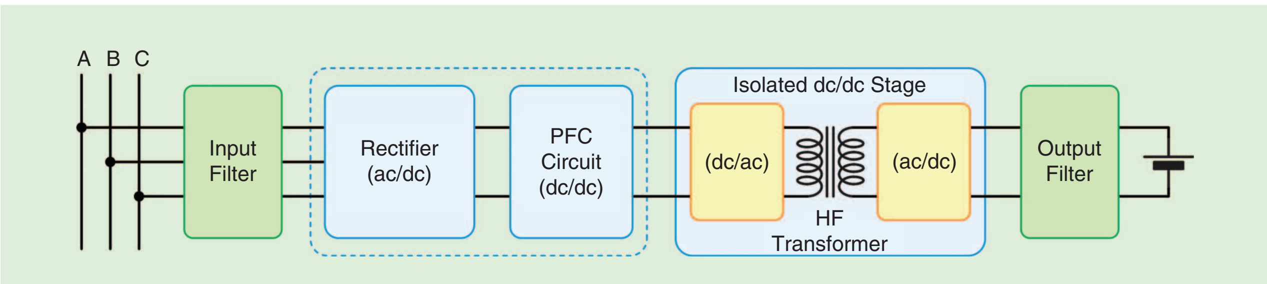

Figure 3. A simplified block diagram of a state-of-the-art dc fast charger power stage. HF: high frequency.

was made by combining and packaging 12 converters into a single system.

Commercial dc fast chargers support one or more of the five existing dc fast-charging systems: CHAdeMO (used globally), CCS Type 1 (in the United States), CCS Type 2 (in the European Union), GB/T (in China), and the Tesla supercharger (used globally). In all cases, the charging process follows a sequence of events defined by the charging protocol. The charging sequence typically starts with signal handshaking, insulation testing, and exchanging maximum charging parameters between the vehicle and the charger. If all of the required criteria are met, the vehicle closes its dc contactor, and charging begins. During the charging process, the vehicle and the charger exchange information on the desired current and voltage reference; in addition, the vehicle battery management system updates the charger on the battery state of charge (SOC) and other system parameters that may be displayed on the human–machine interface. When the battery reaches a certain preset SOC, the vehicle signals the charger to terminate charging by reducing the charging current to zero. The vehicle then disconnects itself from the charger by opening its dc contactor.

Typically, the charging profile follows the well-known constant current, constant voltage (CC/CV) profile, which is commonly used in charging most lithium-ion battery variants. As the battery charges in the CC region, the battery voltage increases with the SOC. As a result, the power acceptance by the battery pack slowly increases in the CC region. Once the charge profile transitions to the CV phase, the power delivered to the battery reduces since the charge current reduces to maintain the CV at the battery terminals. As a result, the battery's rate of charge rapidly reduces during the

TABLE 1. Technical specifications of commercially available dc fast chargers.

Manufacturer and Model	ABB Terra 53	Tritium Veefil-RT	Tesla Supercharger	EVTEC espresso&charge	ABB Terra HP
Rated power	50 kW	50 kW	135 kW	150 kW	350 kW
Supported standards	CCS Type 1 CHAdeMO 1.0	CCS Types 1 and 2 CHAdeMO 1.0	Supercharger	SAE Combo 1 CHAdeMO 1.0	SAE Combo 1 CHAdeMO 1.2
Input voltage	480 Vac	380–480 Vac 600–900 Vdc	200–480 Vac	400 Vac ± 10%	400 Vac ± 10%
Output dc voltage	200–500 V 50–500 V	200–500 V 50–500 V	50–410 V	170–500 V	150–920 V
Output dc current	120 A	125 A	330 A	300 A	375A
Peak efficiency (charger only)	94%	>92%	92%	93%	95%
Volume	758 L	495 L	1,047 L	1,581 L	1,894 L
Weight	880 lb (400 kg)	364 lb (165 kg)	1,320 lb (600 kg)	880 lb (400 kg)	2,954 lb (1,340 kg)

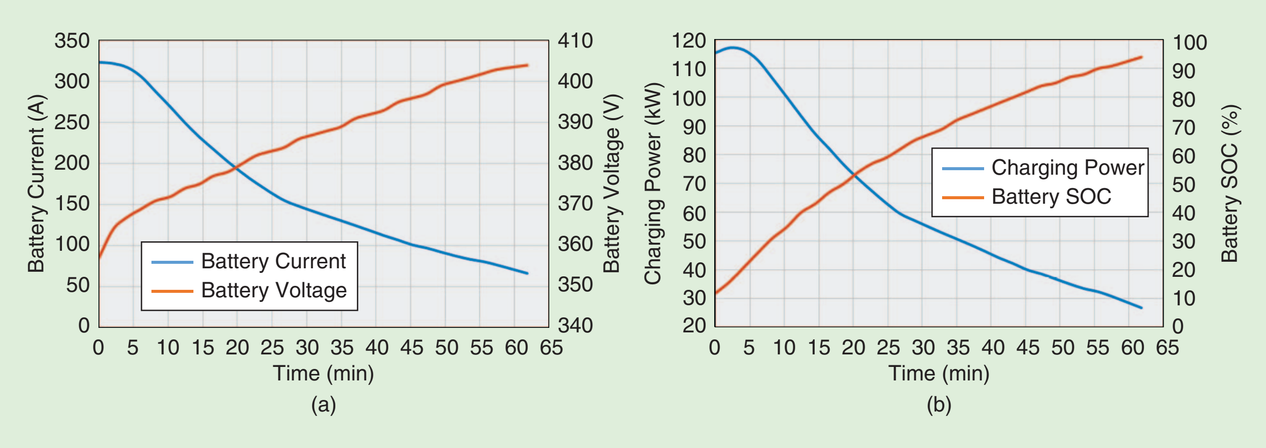

Figure 4. The Tesla Model S85 (a) charging profile and (b) battery SOC and charging power.

CV charging period, as illustrated in Figure 4. In Figure 4, the battery was charged from 12 to 94% SOC, with a peak power of 117.2 kW occurring at 16% SOC (2 min after the charging was started). The CC mode lasted for approximately 2 min.

Fast-Charging Station Designs: dc and ac Distribution Concepts

Since EV fast chargers are meant to operate similarly to gas stations, the design of a system with multiple charging nodes is necessary. Such a system would attempt to mimic the design of a conventional gasoline refueling station, with the same infrastructure supplying multiple vehicles from the same reservoir by using multiple pumps. Figure 5 shows conceptual designs of EV fast-charger stations with ac and dc coupling. In the case of an ac-coupled system, shown in Figure 5(a), the entire system connects to the MV utility supply via a three-phase step-down transformer that delivers power at LV (up to 480 V line to line) to all of its subsystems. The subsystems are connected to the transformer via switchgear cabinets that contain breakers and disconnects. The system may include local storage and generation capabilities to help mitigate demand charges that are incurred during peak power consumption requirements at the station. An example of an ac-coupled system is a supercharger station in Mountain View, California, which includes six superchargers and 200 kW (400 kWh) of battery-energy storage, as illustrated by the simplified one-line diagram in Figure 6.

The ac-connected system is typically used in today's multiport charging stations. The advantages of the ac-coupled approach include availability and maturity of the converter technology, switchgear, and protection devices and

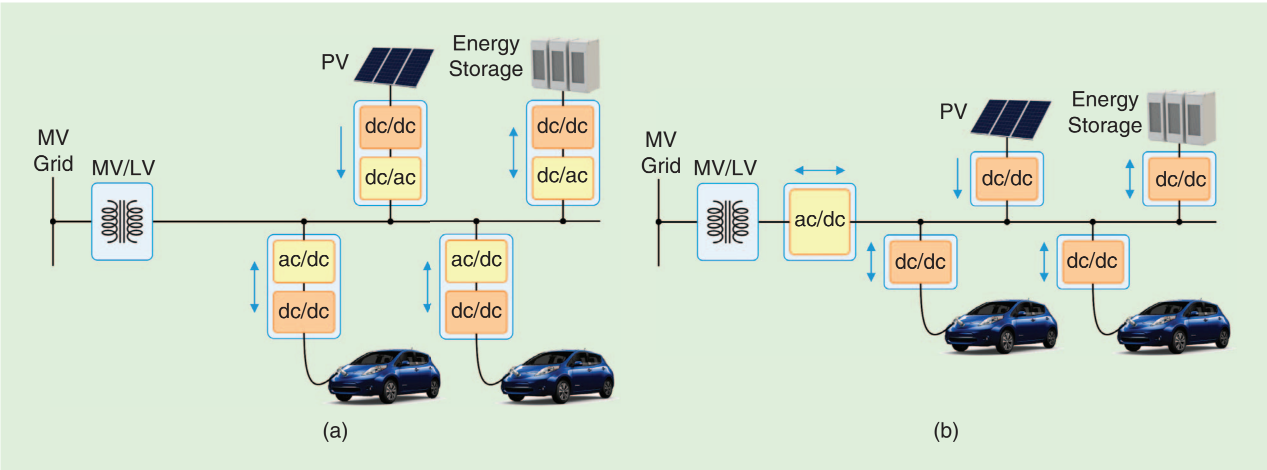

Figure 5. Charging station concepts: (a) an ac-coupled station and (b) a dc-coupled station. PV: photovoltaic.

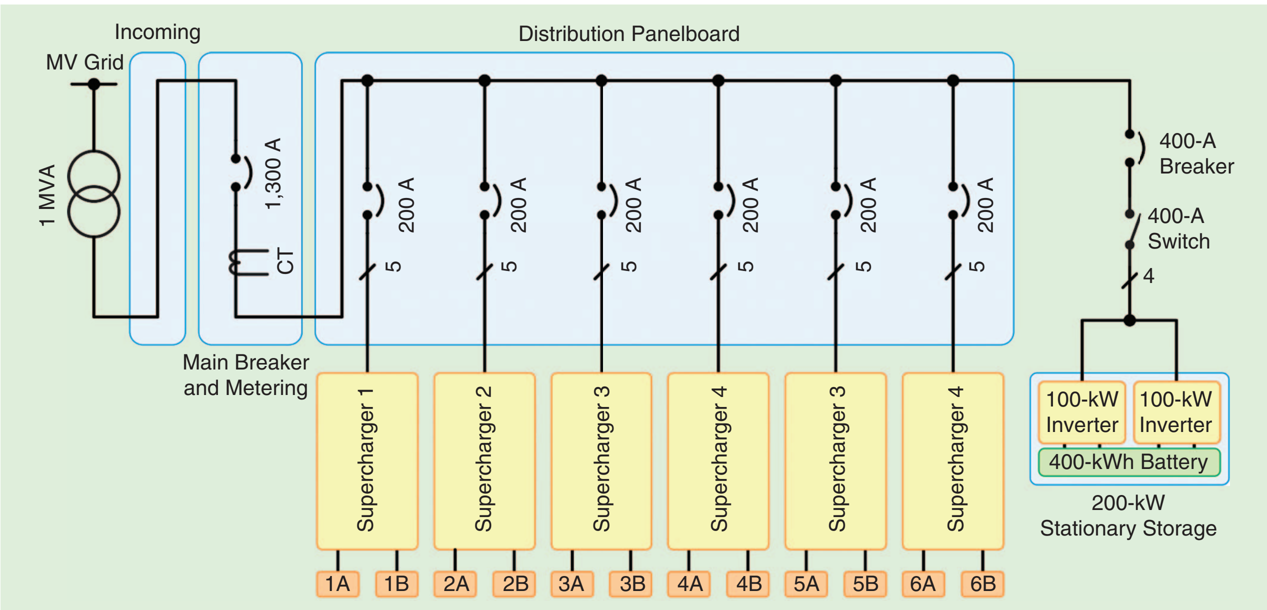

Figure 6. A simplified one-line circuit diagram of Tesla's supercharger station in Mountain View, California. CT: current transformer.

well-established standards and practices for the ac distribution systems. Having more conversion stages (to interface dc loads, dc generation, and battery-energy storage to the ac system) is the main disadvantage of the ac-coupled system. These conversion stages decrease the system efficiency and increase its complexity. Additionally, ac-connected systems are more complicated to control than dc-connected systems since they need to deal with reactive power control, inverter synchronization, and voltage and frequency control during islanded operation of the system.

In a dc distribution concept, shown in Figure 5(b), the charging station connects to the distribution system via a service transformer and an LV rectifier. The three-phase transformer delivers power at LV to a single rectifier stage, which then distributes the dc power to individual station subsystems. The main advantages of distributing dc power are as follows: it eliminates ac/dc and dc/ac conversion stages, it minimizes the number of conversion stages when delivering power from local storage to a charger, and it simplifies the integration of renewable resources and battery-energy storage, which outputs dc power.

Due to the variations in power demand for battery charging as a function of battery size and SOC, there will be a large variation in the power demand when multiple EVs charge simultaneously. Including a local storage capability within the charging station provides significant system-level benefits, as it allows the station owner to profile the power demand from the station while still delivering the desired power to individual customers. By profiling the power demand of the station, the station owner can be responsive to the needs of the local utility and avoid high-demand charges, which can account for more than 90% of the electricity costs for the charging station. In both presented concepts, the system could benefit from load diversification by sharing a large common power supply. A number of studies have shown that when exploiting the load diversification, which results from varying EV battery capacities and changing charge acceptance of the battery as a function of the SOC, the actual system power demand is substantially lower than the rated value.

In our recent work, we showed that for a bank of 50 Level 2 chargers, the power required is only 60% of the sum of the chargers' rated power when accounting for diversity. Similarly, in the case of a dc-coupled system with 10 fast chargers rated at 240 kW each, we found that the power requirement is closer to the average value than the peak power rating and the grid tie can be sized for the average power demand rather than for the peak demand. If a relatively small storage system is connected to the station, more than 98% of the power demand can be satisfied with an average charging delay time of less than 10 s.

Grid Impacts of Extreme Fast Chargers

Today, fast chargers are designed to absorb power from the grid at a unity power factor. That is a realistic approach, given that the power demand from fast chargers is a relatively small fraction of the power consumption even in areas with very high EV adoption. However, a station with multiple extreme fast chargers (XFCs) would require an order of magnitude more power compared to systems deployed today, with the total power rating of the system in the multimegavolt amperes (multi-MVA) range (individual XFCs are rated up to 400 kW). A multi-MVA charging station may severely influence the power quality on the feeder that supplies it. Recent studies show that the additional load at a single point can lead to feeder overload and voltage variations along the feeder that are beyond the allowable limits.

One way to mitigate the negative effects of XFCs on the distribution grid is to allow the utility to control the station's demand during hours of peak consumption. Additionally, if the front end of the charging station is capable of power factor control and bidirectional power flow, the station will be able to provide ancillary services to the grid to help mitigate power quality issues on its feeder. The capability to inject reactive power from power-electronics-interfaced loads is becoming more important, as evidenced by the updated IEEE 1547-2018 standard. Allowing the multi-MVA charging station to inject reactive power would substantially simplify the utility's voltage control problem, and a charger station's abilities to control the power factor and provide for bidirectional power flow are becoming increasingly important from the utility's perspective.

MV Solid-State Transformers: An Enabling Technology for Extreme Fast-Charging Stations

Modern EV fast chargers are designed to connect to a three-phase power supply with line-to-line voltage of up to 480 V, which is usually not readily available in public installations. Therefore, a dedicated service transformer is used to reduce the distribution system MV and provide three-phase supply to a single dc fast charger or to a dc fast-charging station. The service transformer adds cost to the system and generally complicates installation. Furthermore, distributing high power to a charger or a charging station at LV implies the need for large conductors and bulky LV distribution and switchgear equipment, as illustrated in Figure 2.

An alternative approach is to use a solid-state transformer (SST) to connect directly to an MV line, thus eliminating the need for a grid-frequency step-down transformer, as illustrated in Figure 7. The SST would replace both the step-down transformer and the charger unit in a conventional single-stall transformer-and-charger system, or it would replace the step-down transformer and the ac/dc stage in a dc-coupled station. In a SST, galvanic isolation is achieved by using a high-frequency transformer (HF TR). The SST-based converter provides either unidirectional or bidirectional power flow, regulates active and reactive power, performs PFC function, and provides isolation and protection features. The system uses a common dc bus to interface renewable energy generation systems and battery-energy storage to EVs via dc/dc converters only, ensuring a reduced number of conversion stages and high conversion efficiency. Several studies evaluating the benefits of SST-based EV fast chargers have been reported in the literature, and several prototypes demonstrating these benefits are currently in development.

Key Benefits of the SST-Based EV Fast Charger

The SST-based approach to EV fast charging is beneficial to both EV users and charging station owners, as illustrated in Figure 8. The key benefits of the SST-based EV charger that uses wide-bandgap power semiconductor devices are reduced system size and higher power conversion efficiency. The reduced system size means lower installation costs and more available power in the same system footprint. In a conventional system, both the fast charger and the transformer have substantial size and weight, which adds cost and complexity to the installation of the system, as both the charger and the transformer are commonly installed on a concrete foundation. Additionally, fast-charger installation in seismically active areas of the United States requires seismically restrained concrete foundations for both the transformer and the fast charger, further increasing installation and permitting costs. The result can be an expensive system that requires significant infrastructure. By eliminating the service transformer and connecting directly to an MV line, the system installation costs can be reduced by at least 40% compared to the conventional solution, as reported in a study done for 50-kW systems.

Reducing the system size can be particularly beneficial if the fast charger is installed in densely populated areas because it enables better site utilization—that is, more power in the same system footprint. The higher available power from the station leads to faster charging and lower waiting time since more higher-power charging nodes can be served simultaneously. The higher energy efficiency of the system can lead to potentially cheaper charging due to the energy savings. For example, increasing the system efficiency by 5% (from 92.5% to more than 97.5%) at a 1-MW power level would mean the reduction of power losses from 75 to 25 kW. Assuming a 20% utilization of the station at full power, this efficiency improvement will result in 87.6-MWh savings over one year. Of course, the savings would be higher with a higher utilization rate. Connecting directly to an MV line can further reduce the electricity costs since many utilities offer time-of-use rates with up to 20% lower demand charges when the electricity is purchased on the MV side (primary service). These savings can be substantial considering that demand charges account for most of the electricity costs.

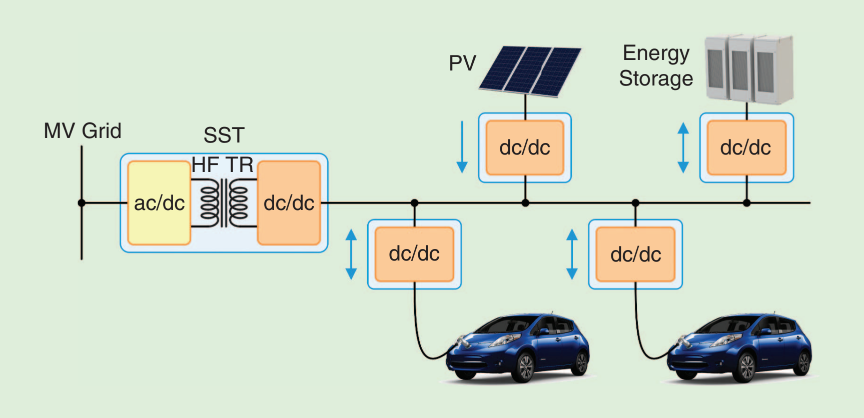

Figure 7. An EV charging station concept based on SST technology.

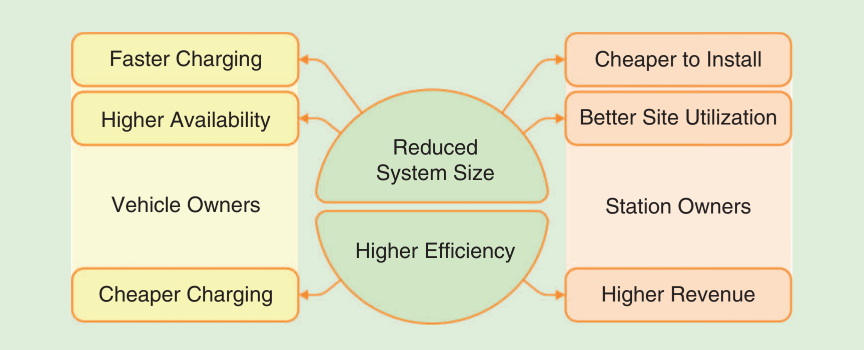

Figure 8. The key benefits of the SST-based dc fast charger.

Case Study: A 50-kW MV Fast Charger

A team at North Carolina State University developed a 50-kW MV fast charger (MVFC) that connects directly to a 2.4-kV single-phase distribution line and outputs 200–500 Vdc to charge the vehicle. The developed system is based on SST technology, and it uses fewer relatively expensive SiC devices compared to other single-phase modular converter topologies. It features a simple input rectifier stage with high-voltage Si diodes, which improves the system efficiency but also makes the system unidirectional. The system is designed to be modular, using three identical 16.7-kW dc/dc modules (shown in Figure 9) as building blocks to reach the desired output power and input voltage levels. The modules' inputs are connected in a series to accommodate the high input voltage coming from the diode rectifier connected to the MV grid, and their outputs are connected in parallel to increase the output power. The series connection of the modules' inputs allows the 1.2-kV off-the-shelf SiC devices to serve the MV application. As such, the existing module design and the control approach can be reused and scaled up to a three-phase system operating at higher voltage and power levels by simply increasing the number of modules in the system.

Due to the lower switching and conduction losses in the SiC devices, the system efficiency is significantly increased compared to the Si-based solution. Additionally, the ability of SiC devices to operate at higher switching frequencies (a few tens of kilohertz as opposed to fewer than 10 kHz for Si devices) enables a significant reduction in size of the inductors and the transformers used to provide the required galvanic isolation, thus reducing the overall system size and weight. The selected topology enables independent control of the input three-level boost stage and the output dc/dc stage. It also enables relatively simple dc bus capacitor voltage balancing and small input and output inductors due to the interleaving of the input three-level boost converters and the NPC-based dc/dc converters at the output.

At a 50-kW level, which represents most of the existing dc fast chargers, the efficiency of the existing systems is approximately 93% when accounting for the 98.5% transformer efficiency. The developed MVFC prototype has a significantly smaller size than the existing system, and it improves the system efficiency from 93% to more than 97.5%, a reduction in losses by more than 60%, as illustrated in Figure 10. Despite the higher cost of SiC devices, the estimated total cost of the system (bill of material and installation) is still acceptable due to the substantial cost savings at the system level.

SST-Enabled MV Extreme Fast Charging

The SST-based MVFC approach can be expanded to an extreme fast-charging station with a dc distribution bus, as conceptually illustrated in Figure 7. In this case, a multi-megawatt three-phase SST can be designed to supply the entire charging station. Figure 11 compares a state-of-the-art 675-kW Tesla supercharger station (with an estimated grid-to-vehicle efficiency of 92%) with an SST-based 2,700-kW MV charging solution (with a grid-to-vehicle efficiency of 97%). As shown in Figure 11, using the MV solution can increase the power delivery capability from the same station footprint by fourfold. At the same time, the energy efficiency savings are even more significant at these high-power levels. Similar to the corridor charging stations, the SST-based MV technology can also be applied in high-power community charging stations, where it can enable a more efficient integration of local renewables and battery-energy storage systems, as illustrated in Figure 12. Moreover, the utility-owned battery-energy storage system can be used in the system to reduce demand charges and provide ancillary services for improved grid stability.

Adoption Challenges for the SST-Based EV Fast Chargers

Despite the many advantages of the SST-based solution for EV charging, some challenges still stand in the way of its complete adoption by the electric utilities today. The key barriers include reliability concerns of replacing the passive transformer with a power electronic equivalent; relatively low penetration of EVs in power systems, which is perceived as not enough to provide economic justification for using higher-efficiency but costlier power conversion equipment; the large inertia still present in the distribution system, supplied by the legacy generators; and the limited ability to monetize the perfect power quality supplied by

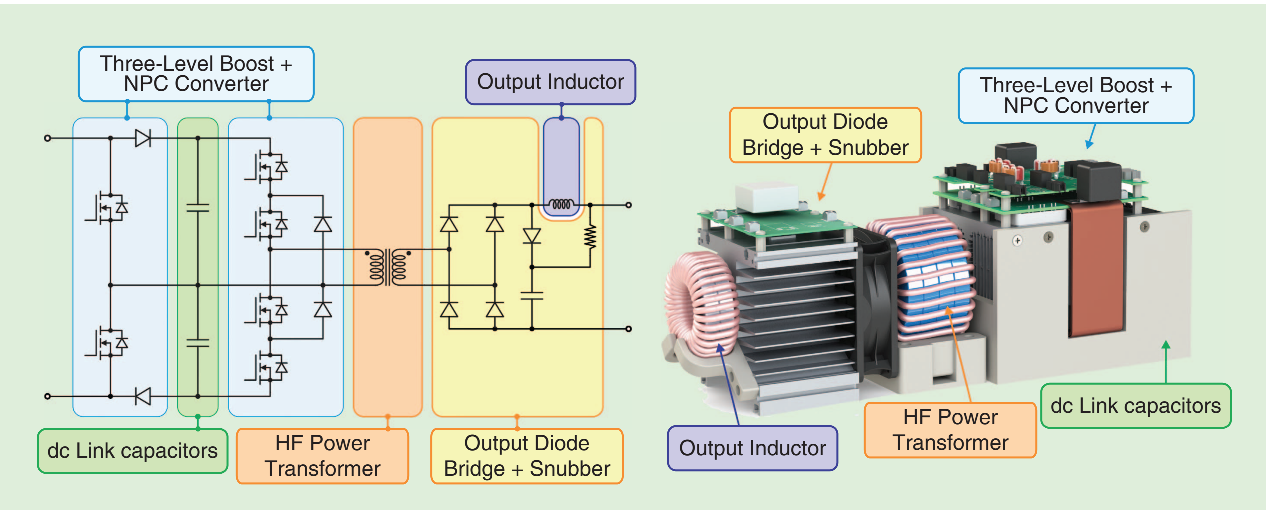

Figure 9. The MVFC's 16.7-kW dc/dc module with PFC functionality. NPC: neutral point clamped.

the SST. Another challenge is the integration of the SSTs in the existing power systems, which could require the implementation of additional layers of communication and control in the system and additional customer education.

There are also some technical challenges that need to be resolved before the wider adoption of SST-based technology can take place. Some of the biggest technical difficulties are the lack of a comprehensive and fast-acting protection against overvoltages, short circuits, and circuit overloads and, especially, the lack of fast-acting circuit breakers that can be used in these protection systems. The conventional mechanical MV circuit breakers can interrupt a fault current in several tens of milliseconds, which is too slow to prevent damage to MV power electronics equipment in the case of a fault. To protect the MV power electronics systems, the breaker would need to interrupt the fault current in several hundred microseconds (depending on the system that is being protected). These speeds could only be achieved with solid-state circuit breakers and hybrid breakers, which are currently under development by several research groups.

Another significant challenge that needs to be overcome is standardization and certification of the EV charging equipment that connects directly to the MV line. Currently, the Underwriters Laboratories (UL) category FFTG, which covers dc fast chargers (with basic requirements used for this category given in the ANSI/UL 2202 standard), does not cover systems supplied from branch circuits of more than 600 V. Instead, MV power conversion equipment is listed under the NJIC category, with the basic

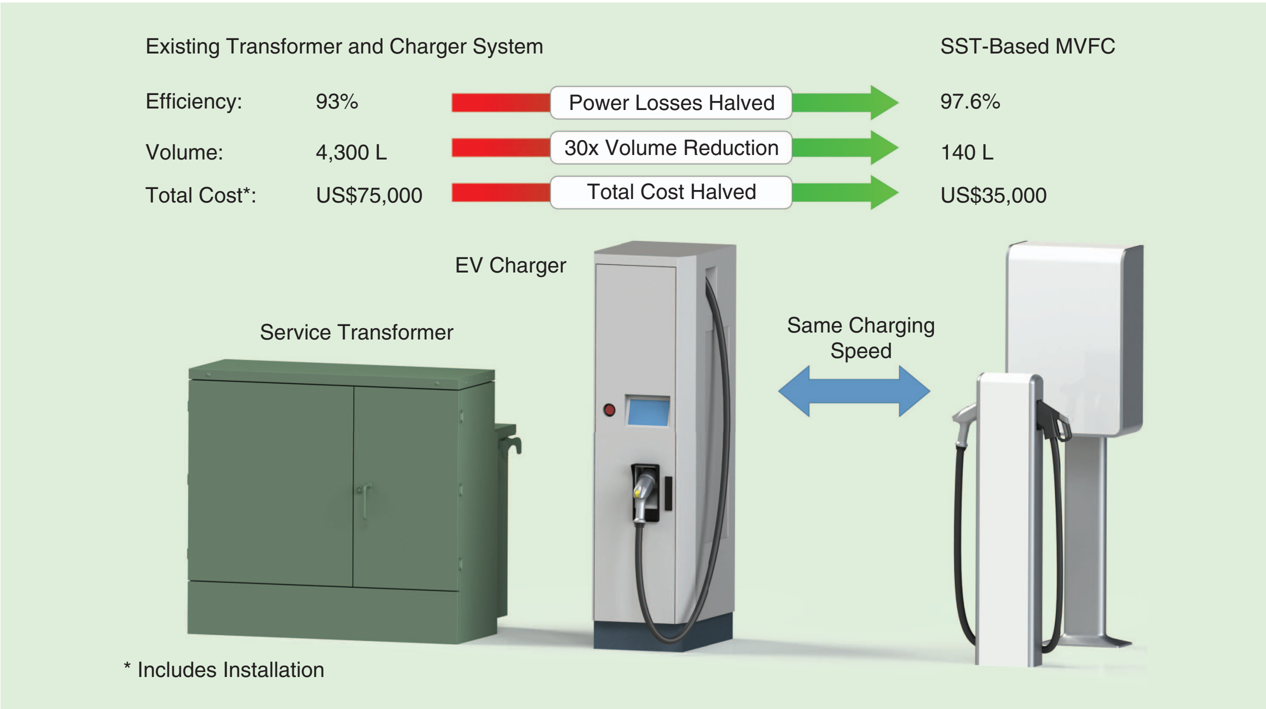

Figure 10. A comparison of the SST-based MVFC to the existing solution.

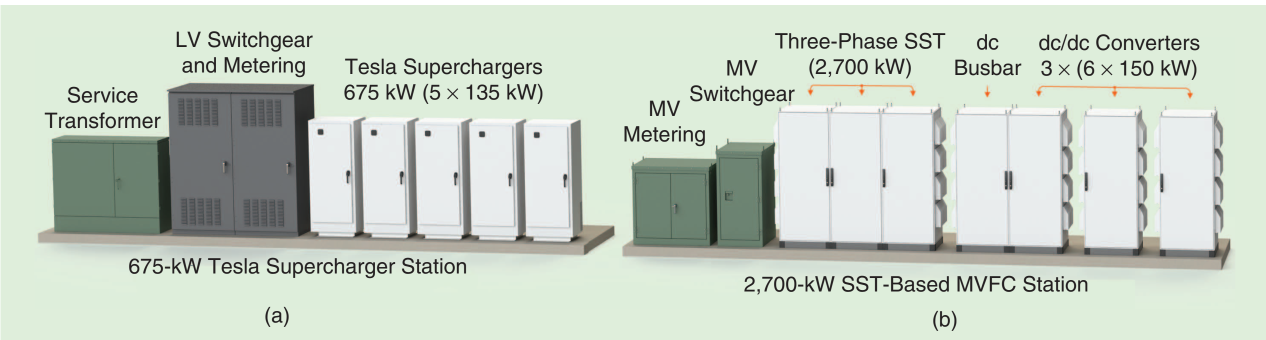

Figure 11. A comparison of (a) a state-of-the-art 675-kW Tesla supercharger station (with an estimated efficiency of 92%) and (b) an SST-based 2,700-kW MVFC solution (97% efficiency) with the same footprint.

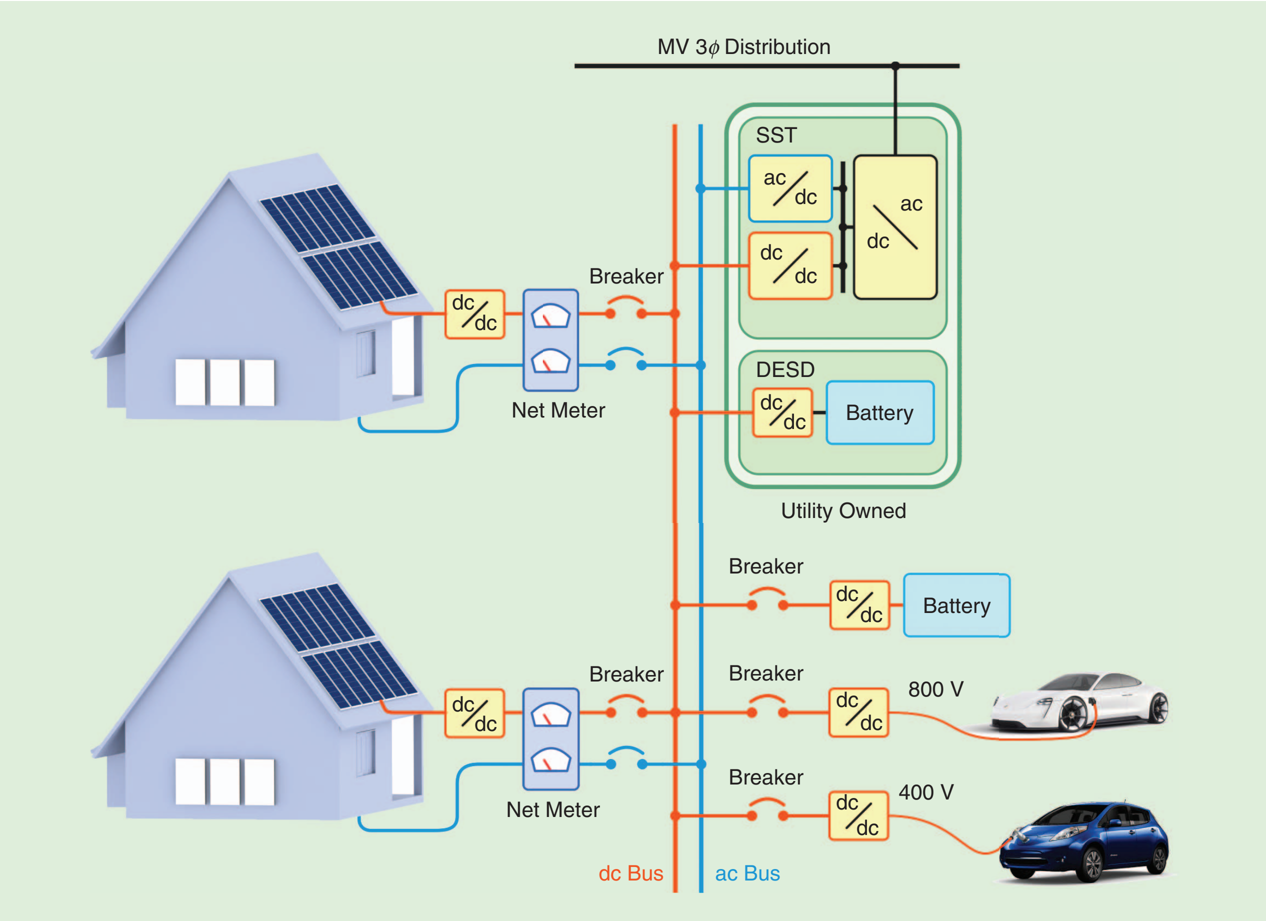

Figure 12. An SST-based intelligent energy router in a high-power community charging station. DESD: distributed energy storage device.

requirements used for this category given in the UL 347 A standard. Despite the substantial market potential and many technical benefits of the SST-based EV fast chargers, a significant pushback from the industry is expected before fully adopting this new approach with power electronic converters directly connecting to an MV distribution line. However, there is a wide consensus that a logical first step toward full adoption is to successfully deploy several pilot charging stations that will demonstrate all of the potential utility and industry benefits that the technology has to offer.

For Further Reading

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