Toward Extreme Fast Charging: Challenges and Opportunities in Directly Connecting to Medium-Voltage Line

Introduction

With increasing awareness of detrimental effects of fossil fuel-based transportation sector, which accounts for 14% of the man-made greenhouse-gas emissions globally, there has been a concerted push by individuals, companies and government entities to develop solutions to provide less carbon-intensive modes of transportation. Importantly, several countries, including Norway, India, France and Britain, have decided to end the sales of internal combustion engine cars in the near future, further accelerating the shift to electric transportation. Many strides forward have been made in recent years in making electric vehicles (EV) cost-competitive while delivering a driving range of over 200 miles (see Fig. 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 vehicle's on-board 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 an interface between the 120 V (Level 1 chargers) and 240 V (Level 2 chargers) supply line and the on-board charger, and can deliver up to 1.92 kW (Level 1) or 19.2 kW (Level 2) to the vehicle. The IEC classification (IEC 61851) allows up to 26.6 kW for Mode 2 home ac chargers. Due to their limited power rating, the on-board chargers are not capable of replenishing the battery charge quickly enough to provide the refueling experience comparable to that of gasoline cars. Referring to Fig. 1, it takes over 8 hours to add 200 miles of range to the battery of an EV, when using the standard 208 V or 240 V plug available within the homes in the US. While this is acceptable for overnight charging, is not suitable for longer trips and can create a so-called range anxiety (a fear that a vehicle has insufficient range to reach its destination).

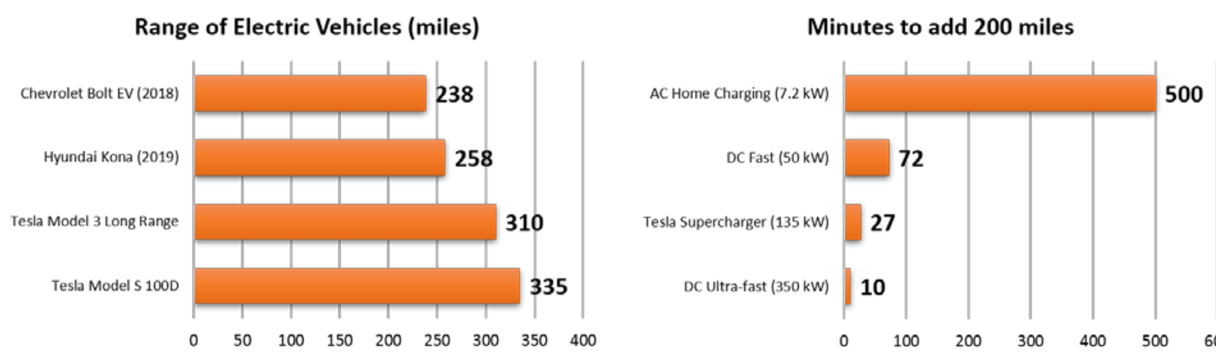

Figure 1. Electric vehicles with over 200 miles of range and time to add 200 miles of range to the vehicle if charged at constant power equal to charger's rated power.

The limited capability of on-board 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 have the potential to provide the user with an experience similar to refueling a gasoline car. A fast charger rated at 50 kW requires over one hour to deliver enough charge for a 200-mile trip, while a 350-kW extreme fast charger would only take about 10 minutes to deliver the same amount of energy, as illustrated in Fig. 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 in fast charging technologies. We discuss the state-of-the-art-fast chargers, their design and main characteristics. We discuss how these chargers can be combined to form fast charging stations that mimic the functionality of a gasoline refueling station. We discuss various power delivery concepts for these charging stations, and discuss the benefits and shortcoming of the current and proposed approaches. Finally, we present a novel approach where the charging station connects directly to the medium voltage line, thus eliminating a number of power electronics conversion stages, as well as the low-frequency step down transformer. We discuss significant benefits of this technology when considering extreme fast charging rates, and identify the key technology gaps in making this technology more widely accepted.

State-of-the-art EV DC Fast Chargers

The state-of-the-art dc fast chargers are installed either as single-stall units or as multi-stall charging stations. The 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 miles (161 km) of range in about 30 minutes. The higher-power multi-stall charging stations, such as Tesla's Supercharger stations, include multiple chargers and need additional switchgear and low-voltage metering circuit, as illustrated in Fig. 2. In case of Tesla's stations, each Supercharger unit serves two charging stalls and can add up to 170 miles (273 km) of range in 30 minutes. When deploying these systems, all the system components are commonly installed on relatively large concrete foundations, which adds to the installation costs. According to the study done by the Idaho National Lab, the main cost drivers for charging station infrastructure installations include: electrical service upgrade, condition of the ground surface under which the electrical conduits were installed, length of the conduits from the power source to the service transformer and from the transformer to the fast charger, material costs, permitting and administrative costs.

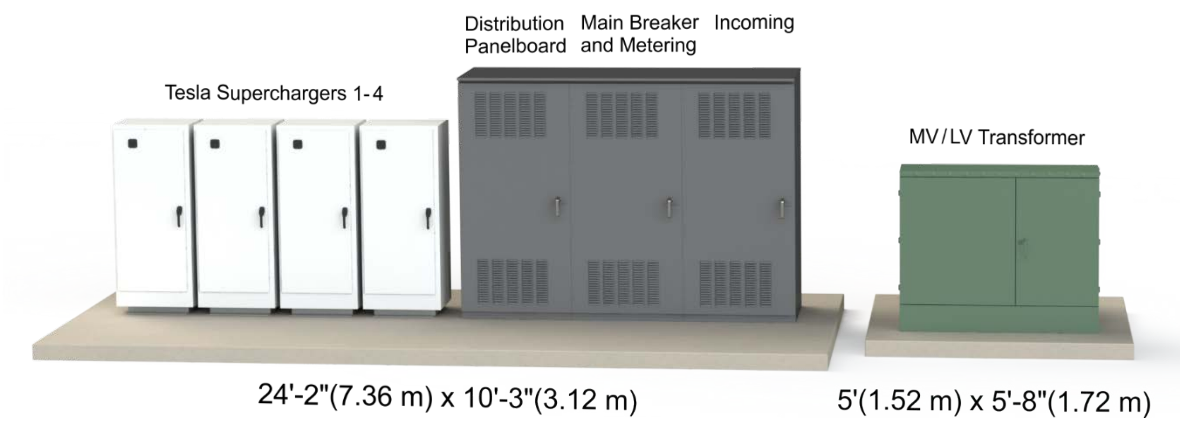

Figure 2. Layout of Tesla's Supercharger station in Madison, WI (charging stalls and seclusion composite fence surrounding Superchargers and switchgear are not shown). Transformer is located approximately 24 ft. (7.3 m) from the Superchargers.

Typical state-of-the-art dc fast chargers have two power conversion stages: a 3-phase ac/dc rectification stage which 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 Fig. 3. The ac/dc rectification and PFC stage convert three-phase input ac voltage to an intermediate dc voltage, and ensure acceptable power quality on the grid side. The dc/dc stage converts the intermediate dc voltage into regulated dc voltage required by the vehicle and provides galvanic isolation. The galvanic isolation isolates 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 rectification 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 which are typically based on reverse conducting IGBTs, and operate at switching frequencies not higher than 10 kHz. The more compact and more efficient converter can be achieved with silicon carbide (SiC) power MOSFETs, which have substantially lower total power losses and can operate at switching frequencies of several tens of kHz.

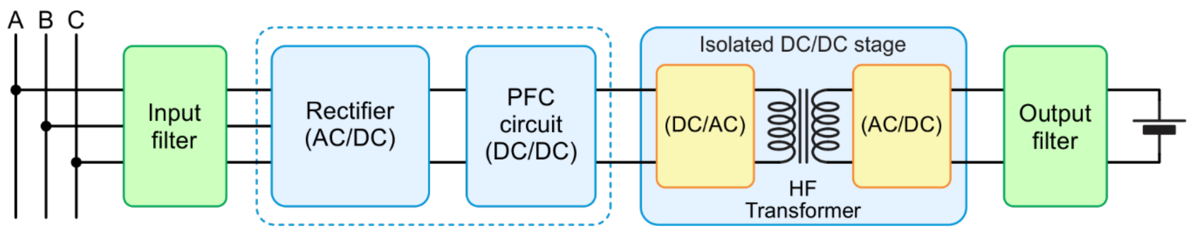

Figure 3. Simplified block diagram of a state-ot-the-art dc fast charger power stage

The second stage is an isolated dc/dc converter, which provides dc regulation and galvanic isolation between the grid and the electric vehicle. 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 intact the protection scheme designed for the vehicle battery.

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

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
Maximum power	50 kW	50 kW	135 kW	150 kW	350 kW
Supported standards	CCS Type 1 CHAdeMO 1.0	CCS Type 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	1047 L	1581 L	1894 L
Weight	880 lb (400 kg)	364 lb (165 kg)	1320 lb (600 kg)	880 lb (400 kg)	2954 lb (1340 kg)

Commercial dc fast chargers support one or more of the five existing dc fast charging systems: CHAdeMO (available globally), CCS Type 1 (USA), CCS Type 2 (EU), GB/T (China) and Tesla Supercharger (available 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 exchange of maximum charging parameters between the vehicle and the charger. If all 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 pre-set SOC, the vehicle signals the charger to terminate the 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, commonly used in charging most lithium ion battery variants. As the battery charges in the constant current region, the battery voltage increases with the state of the charge. As a result, the power acceptance by the battery pack slowly increases in the constant current region. Once the charge profile transitions to the constant voltage phase, the power delivered to the battery reduces, since the charge current reduces to maintain the constant voltage at the battery terminals. As a result, the rate of charge of the battery reduces rapidly during the constant voltage charging period, as illustrated in Fig. 4. In the case from Fig. 4, the battery was charged from 12% SOC to 94% SOC, with peak power of 117.2 kW occurring at 16% SOC (2 minutes after the charging was started). The Constant Current mode lasted for approximately 2 minutes.

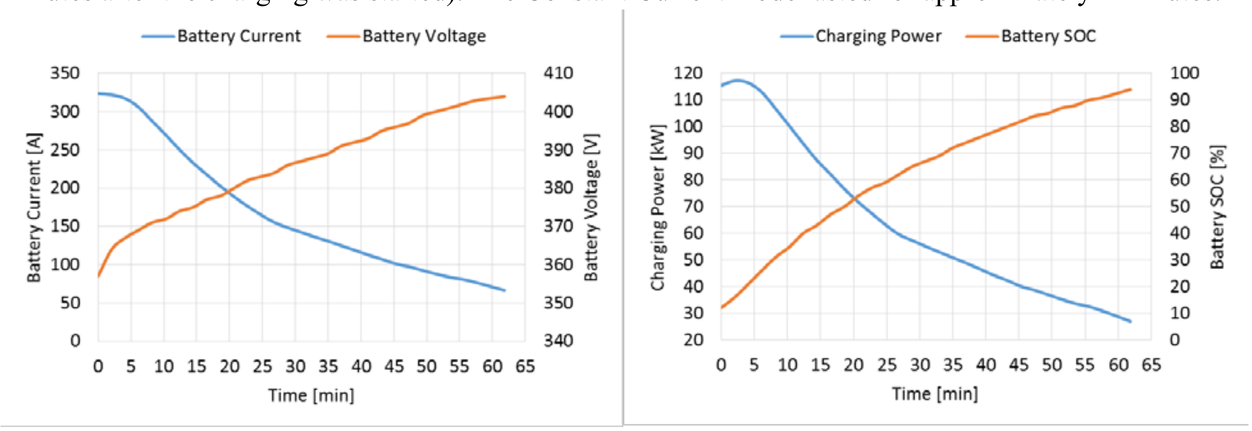

Figure 4. Tesla model S85 charging profile, battery state-of-charge and charging power.

Fast charging station designs: DC and AC distribution concepts

Since EV fast chargers are meant to serve a purpose similar to that of a gas station, the design of a system with multiple charging nodes is of interest. Such a system would try to mimic the design of a conventional gasoline refueling station, with same infrastructure supplying multiple vehicles from the same reservoir, using multiple pumps.

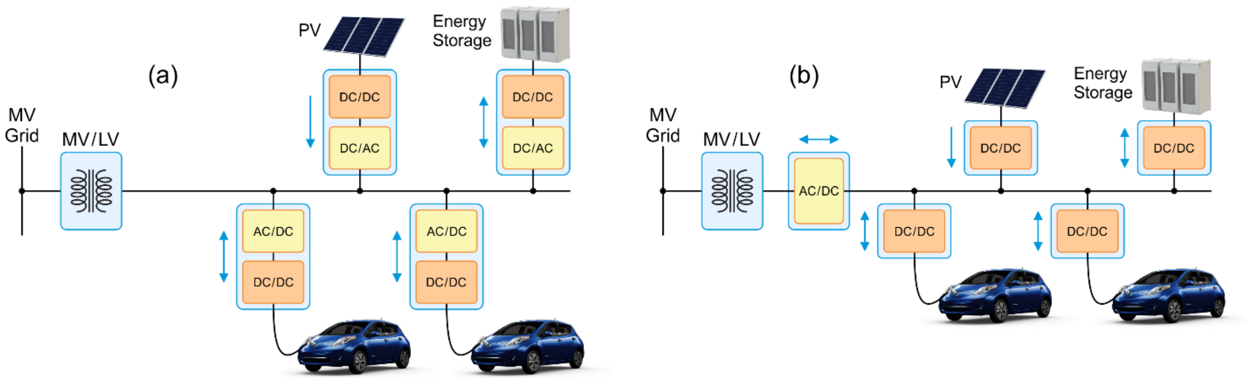

Figure 5. Charging station concepts: (a) ac-coupled station, (b) dc-coupled station.

Figure 5 shows conceptual designs of EV fast charger stations with ac and dc coupling. In the case of ac-coupled system, shown in Fig. 5(a), the entire system connects to the medium-voltage (MV) utility supply via a 3-phase step-down transformer that delivers power at low-voltage (up to 480 V line-to-line) to all 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, CA, which includes 6 Superchargers and a 200 kW (400 kWh) of battery energy storage, as illustrated by simplified one-line diagram in Fig. 6.

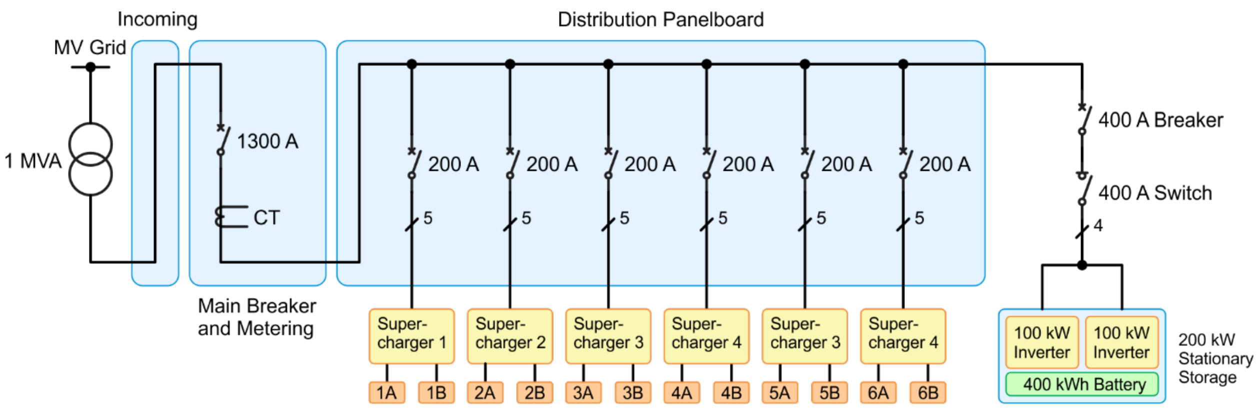

Figure 6. Simplified one-line circuit diagram of the Tesla's Supercharger station in Mountain View, CA.

The ac-connected system is typically used in today's multi-port charging stations. The advantages of the ac-coupled approach include availability and maturity of the converter technology, switchgear and protection devices, and 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 are decreasing the system efficiency and increasing the system 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 case of a dc distribution concept, shown in Fig. 5(b), the charging station connects to the distribution system via a service transformer and a low-voltage rectifier. The 3-phase transformer delivers power at low-voltage to a single rectifier stage, which then distributes the dc power to individual station subsystems. The main advantages of distributing dc power are: 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 integration of renewable resources and battery energy storage, which output dc power.

Due to the variations in power demand for battery charging as a function of battery size and battery state-of-charge, 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 can 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 exploiting the load diversification, which results from varying EV battery capacities and changing charge acceptance of the battery as a function of the state-of-charge, 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 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 that the grid tie can be sized for the average power demand, rather than the peak demand. If a relatively small storage system is connected to the station, over 98% of power demand could be satisfied with an average charging delay time would of less than 10 seconds.

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 relatively small fraction of the power consumption, even in areas with very high electric vehicle adoption. However, a station with multiple extreme fast chargers (XFC) would require an order of magnitude more power compared to systems deployed today, with the total power rating of the system in the multi-MVA range (individual XFCs are rated up to 400 kW). A multi-MVA charging stations 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 extreme fast chargers 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 would 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 charger station's abilities to control the power factor and provide for bidirectional power flow are becoming increasingly important from the utility's perspective.

Medium-voltage solid-state transformers: an enabling technology for extreme fast charging stations

The 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 step down the distribution system medium voltage 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 the system installation. Furthermore, distributing high power to a charger or a charging station at low voltage implies the need for large conductors and bulky low-voltage distribution and switchgear equipment, as illustrated in Fig. 2.

An alternative approach is to use a solid-state transformer (SST) to connect directly to a MV line, thus eliminating the need for a grid-frequency step-down transformer, as illustrated in Fig. 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 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 power factor correction 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 electric vehicles via dc/dc converters only, ensuring 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.

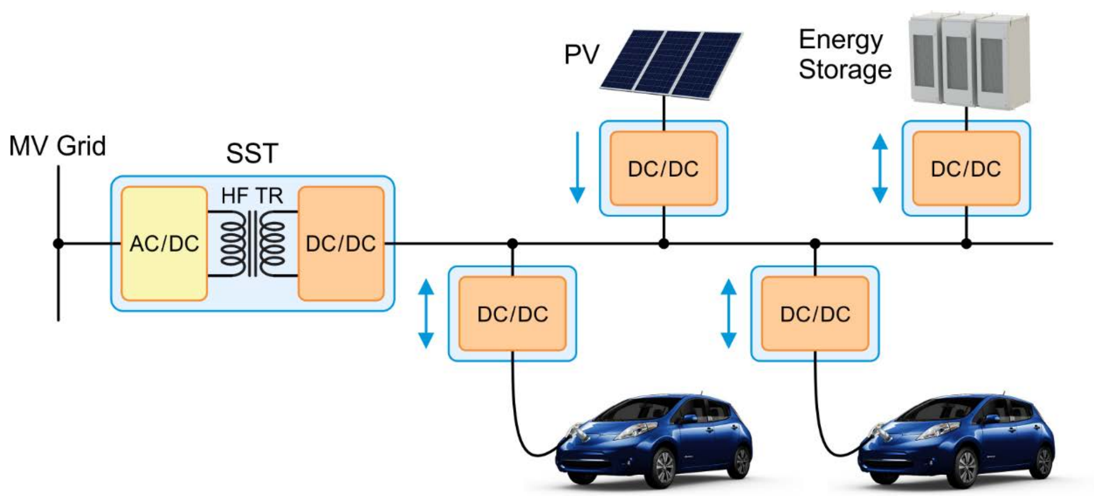

Figure 7. EV charging station concept based on solid-state transformer technology.

Key benefits of the SST-based EV fast charger

The SST-based approach to EV fast charging is beneficial to both the EV users and the charging station owners, as illustrated in Fig. 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.

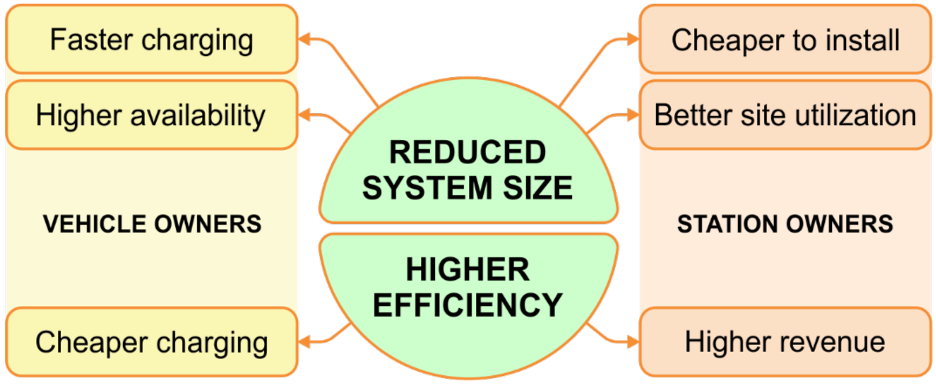

Figure 8. The key benefits of the SST-based dc fast charger.

The reduced system size means reduced 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, installation of fast chargers in seismically active areas of the US require seismically restrained concrete foundations for both the transformer and the fast charger, further increasing the installation and permitting costs. The result can be an expensive system that requires significant infrastructure. By eliminating the service transformer and connecting directly to 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, since it enables better site utilization, i.e. 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 over 97.5%) at 1 MW power level would mean the reduction of power losses from 75 kW to 25 kW. Assuming 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 the higher utilization rate. Connecting directly to medium-voltage line can further help reduce the electricity costs, since many utilities offer time-of-use rates with up to 20% lower demand charges when the electricity is purchased at the medium-voltage side (primary service). These savings can be substantial considering that demand charges account for most of the electricity costs.

Case Study: a 50-kW medium voltage fast charger

A team at NC State University has developed a 50-kW medium voltage fast charger (MVFC) that connects directly to a 2.4 kV single-phase distribution line and outputs 200-500 V dc to charge the vehicle. The developed system is based on SST technology and uses fewer relatively expensive SiC devices, compared to other single-phase modular converter topologies. It features a simple input rectifier stage with high-voltage silicon diodes, which improves the system efficiency but also makes the system unidirectional. The system is designed to be modular, using 3 identical 16.7 kW dc/dc modules (shown in Fig. 9) as building blocks to reach the desired output power and input voltage levels. The modules' inputs are connected in series to accommodate the high input voltage that is 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 relatively low-voltage off-the-shelf SiC devices to serve the medium-voltage 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.

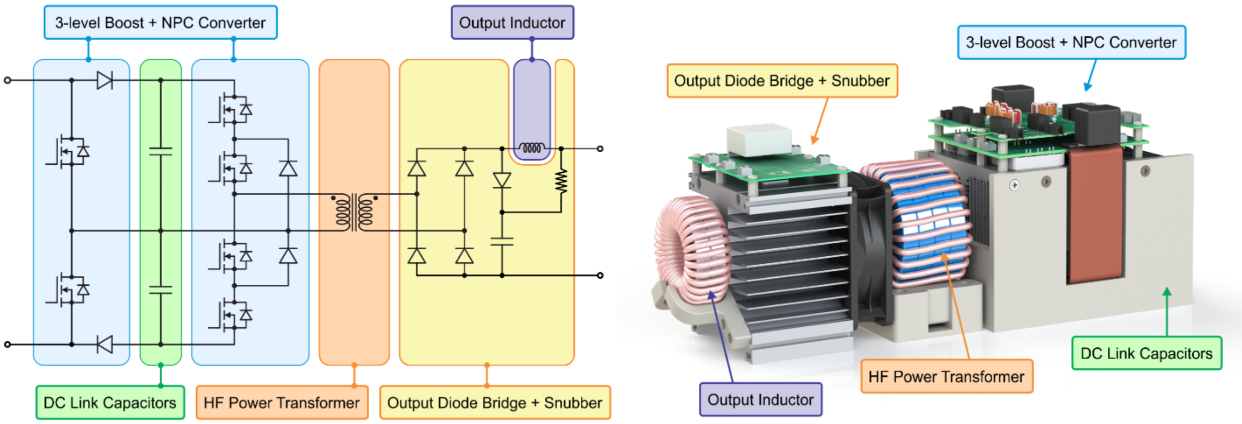

Figure 9. The medium-voltage fast charger's 16.7 kW dc/dc module with PFC functionality.

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 kHz, as opposed to less than 10 kHz for Si devices) enables 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 3-level boost stage and the output dc/dc stage. It also enables relatively simple dc bus capacitor voltage balancing, and uses relatively small input and output inductors due to the interleaving of the input 3-level boost converters and the NPC-based dc/dc converters at the output.

At 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 significantly smaller size than the existing system and improves the system efficiency from 93% to over 97.5% - a reduction in losses by more than 60%, as illustrated in Fig. 10. Despite using the more expensive SiC devices, the estimated total cost of the system (bill of material + installation) is still acceptable, due to the substantial cost savings at the system level.

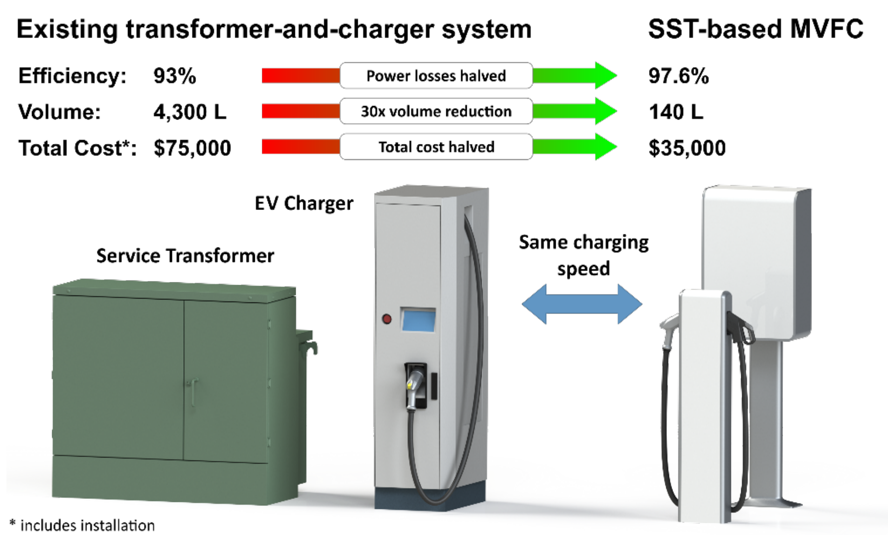

Figure 10. A comparison of the SST-based medium-voltage fast charger to the existing solution.

SST-enabled MV extreme fast charging

The SST-based medium-voltage fast charger approach can be expanded to extreme fast charging (XFC) station with dc distribution bus, as conceptually illustrated in Fig. 7. In this case, a multi-MW three-phase SST can be designed to supply the entire charging station. Figure 11 compares state-of-the-art 675 kW Tesla Supercharger station (with estimated grid-to-vehicle efficiency of 92%) with an SST-based 2700 kW medium-voltage charging solution (with grid-to-vehicle efficiency of 97%). As shown in Fig. 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 medium-voltage technology can also be applied in high-power community charging stations, where it can enable more efficient integration of local renewables and battery energy storage systems, as illustrated in Fig. 12. Moreover, the utility-owned battery energy storage system can be employed in the system to reduce demand charges and provide ancillary services for improved grid stability.

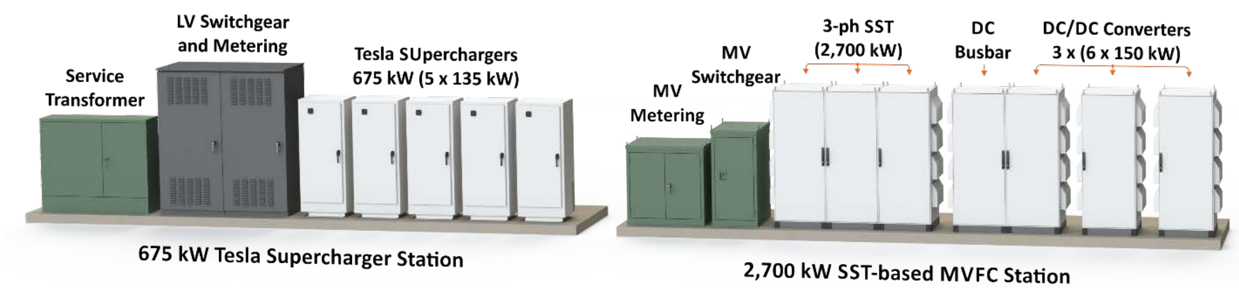

Figure 11. Comparison of a state-of-the-art 675 kW Tesla Supercharger station (with estimated efficiency of 92%) and an SST-based 2700 kW medium-voltage fast charger solution (97% efficiency) with the same footprint.

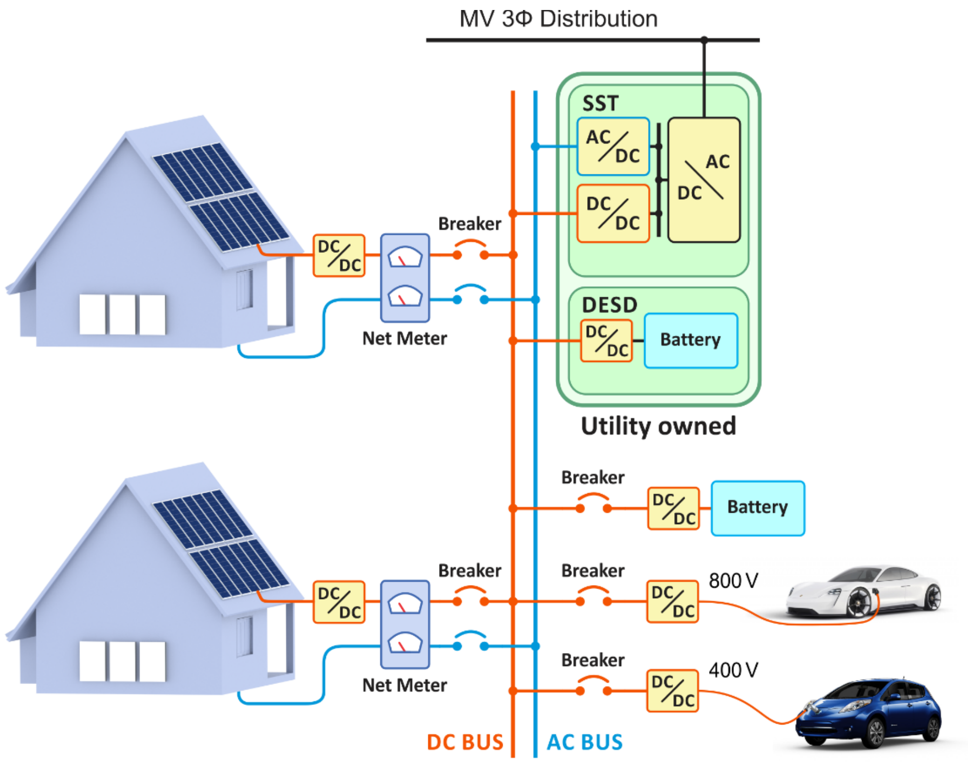

Figure 12. SST-based intelligent energy router in a high-power community charging station.

Adoption challenges for the SST-based EV fast chargers

Despite its many advantages, there are still some challenges that stand in the way of the complete adoption of the SST-based solution for EV charging 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 electric vehicles in power systems, which is perceived 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 limited ability to monetize the perfect power quality supplied by the SST. Another challenge is the integration of the SSTs in the existing power systems, which could require 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. One of the biggest technical difficulties is lack of a comprehensive and fast-acting protection against overvoltages, short-circuits and circuit overloads, and especially lack of fast-acting circuit breakers that can be used in these protection systems. The conventional mechanical medium-voltage circuit breakers can interrupt a fault current in several tens of milliseconds, which is too slow to prevent damage to medium-voltage power electronics equipment in case of a fault. In order to protect the MV power electronics systems, the breaker would have to be able 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 MV line. Currently, the 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 over 600 V. Instead, medium-voltage power conversion equipment is listed under NJIC category, with the basic requirements used for this category given in the UL 347A 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 a medium-voltage distribution line. However, there is a wide consensus in the industry that a logical first step towards full adoption of this technology is successful deployment of several pilot charging stations, demonstrating all the benefits of this new technology to the utilities and the industry.

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