A PROJECT REPORT ON

REQUIREMENTS TO DEVELOP EXTREME FAST CHARGING SYSTEMS

SUBMITTED IN PARTIAL FULFILLMENT FOR THE REQUIREMENT OF THE AWARD OF ***PROJECT BASED INTERNSHIP*** IN ***HYBRID ELECTRIC VEHICLES***

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17 JUNE 2024 – 01 AUGUST 2024

<u>ACKNOWLEDGEMENT</u>

First of all, I thank the supreme power God Almighty for his blessings.

With utmost sincerity, I articulate my profound gratitude sincere thanks to **MR ASHISH JHA**, *for his adroit guidance, inexplicable assistance and unrelaxed support help to carry out this project successfully*.

My heartful thanks and gratitude to family members and friends for their affectionate blessings and inexplicable enthusiasm to finish this project successfully.

SHASHANK CHANDRAVANSHI

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1 Overview

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, 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 miles (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.

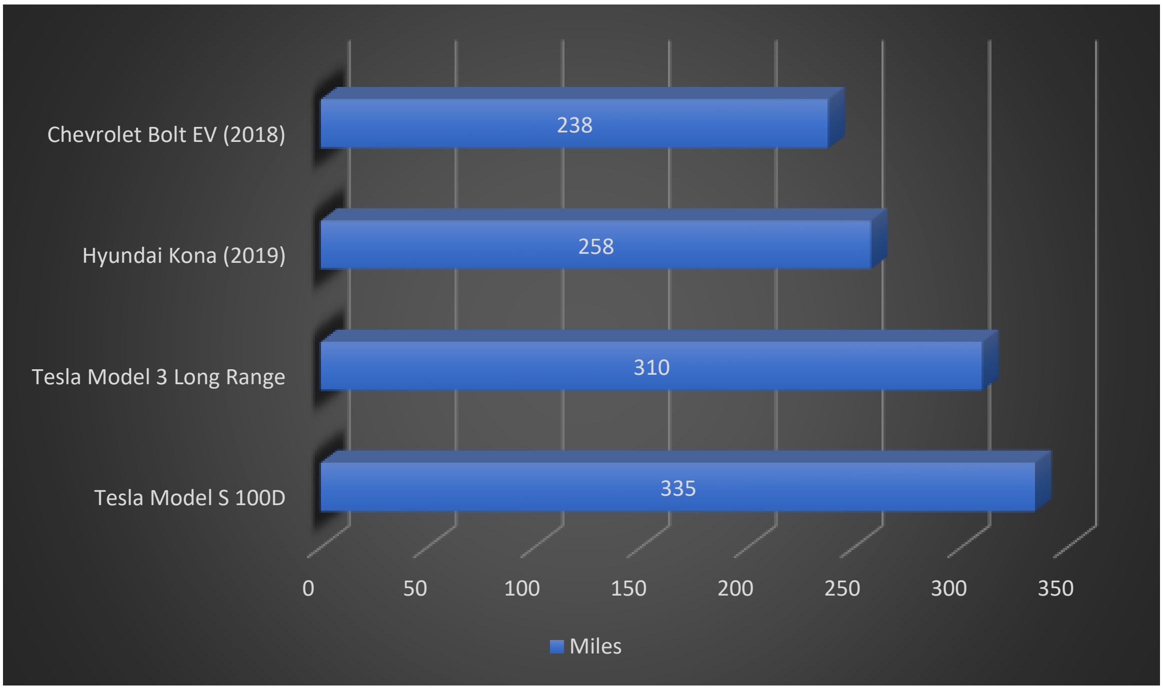

Figure 1. (a) Range of EVs in miles

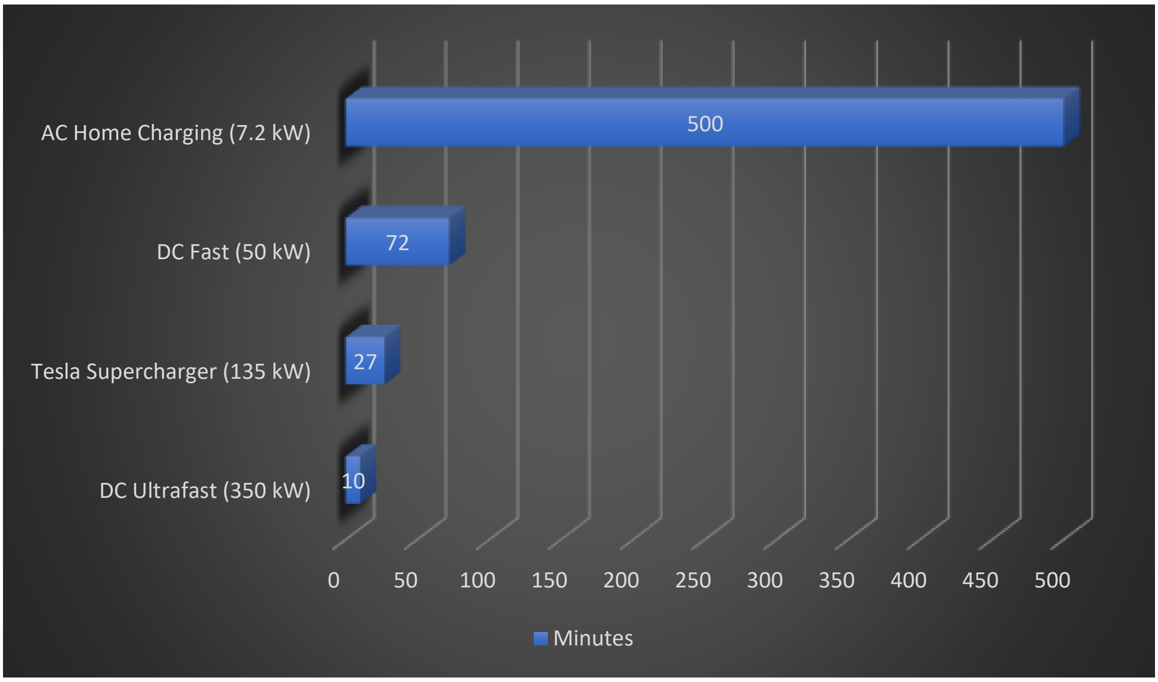

Figure 1. (b) Minutes to add 200 miles

To serve this growing fleet of a new generation electric vehicles (EVs), it is essential to develop an adequate high power charging infrastructure that can mimic conventional gasoline fuel stations. Therefore, much research attention must be focused on the development of off-board DC fast chargers which can quickly replenish the charge in an EV battery. This project aims to review the requirements to develop extreme fast charging systems.

2 Introduction

As battery costs have declined and battery performance has improved, the applicability of vehicle electrification has expanded beyond passenger cars to the commercial vehicle sector. However, due to the larger batteries that would be needed for the medium-duty and heavy-duty (MDHD) sector, the electric charging capabilities to serve these larger commercial vehicles will need to be substantially more powerful than light-duty chargers. More specifically, such “extreme fast charging” (XFC) will likely need to reach the megawatt scale to provide a full charge in less than 30 minutes in some applications. In addition, the combined cost of electrified vehicles and charging must be competitive with the costs of petroleum-based technologies and other alternatives to encourage widespread adoption of battery electric vehicles among MDHD fleets. Most of these fleets have a commercial mission and demand low total cost of ownership (which motivates minimal refueling times) and high performance from their vehicles.

Research and development (R&D) on safe, efficient, and cost-effective XFC is needed now to mitigate technical barriers in time to coincide with the anticipated large-scale adoption of MDHD electrified vehicles across numerous commercial applications. Technological areas of interest include connectors, contactors, solid-state transformers, grid interface devices, power transfer mechanisms, charging control systems, XFC-capable energy storage, and automated charging. Methods to analyze costs and performance from both the vehicle and infrastructure perspectives must be developed. Logistical systems for optimization of commercial vehicle charging and operation need to be created. A viable XFC system must be capable of integrating with the electric grid, renewable energy generators like solar and wind, and stationary energy storage without any adverse impacts. The collaboration among stakeholders—such as MDHD original equipment manufacturers (OEMs), component manufacturers, fleets, truck stop owners, and utilities—will also be essential.

Recharging the battery while parking at work place could be one of the prominent solutions. However, consumers are bound to charge their EVs via residential mains due to the lack of charging infrastructure. These residential chargers are referred to as level-1 (120 V) and level-2 (240 V) chargers as per SAEJ1772 standards and their typical configuration is shown in Figure 2.

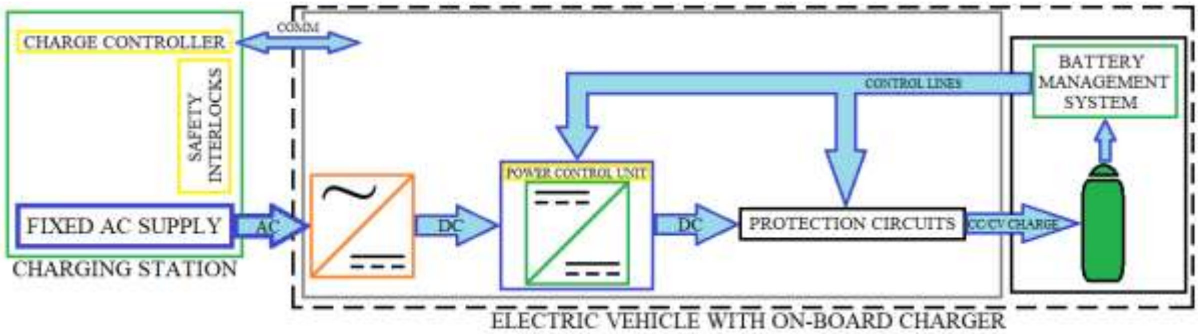

Figure 2. Conventional AC on-board charger configuration

In such cases, the vehicles should be equipped with dedicated on-board chargers that are capable of drawing a power of 1.92 kW (level-1) and 19.2 kW (level-2) from the mains. Typically, these chargers take more than 8 h to add 200 miles of driving range on the EV, which is undesirable for highway driving and long trips. Therefore, there is a significant need to enhance the power capability of on-board battery chargers, which can quickly replenish the charge in an EV battery. However, it is difficult to develop high power on-board chargers due to the size, cost, weight and safety constraints of the EVs.

An alternative is the development of off-board chargers and the corresponding infrastructure that can mimic the functionality of a gasoline refueling station. The off-board chargers are located outside the EV that can deliver the DC power to the EV battery through a power conditioning unit (PCU) as shown in Figure 3.

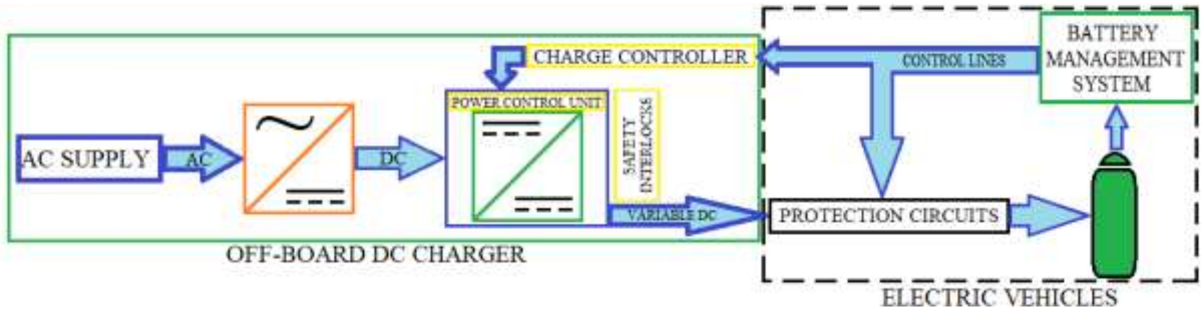

Figure 3. Conventional DC off-board charger configuration

Conventional DC off-board fast chargers are also inbuilt with certain disadvantages. In the upcoming chapter, we will be discussing about these challenges and a prominent solution to overcome it.

3 Solid-State Transformer Technology Based Extreme Fast Charging Infrastructure

A typical 50 kW DC fast charger provides enough charge in 60 min to provide an additional 200 km of driving range, while 350 kW requires only 10 min to deliver 200 km range. These chargers can be installed either as single-stall units or multiple stall units. Each stall is typically rated at 50 kW, which is composed of three-phase AC/DC rectification stages with power factor correction (PFC) and is powered by a dedicated low frequency (LF) transformer. However, the LF transformer adds to the system cost and complicates the installation when directly connected to the MV line.

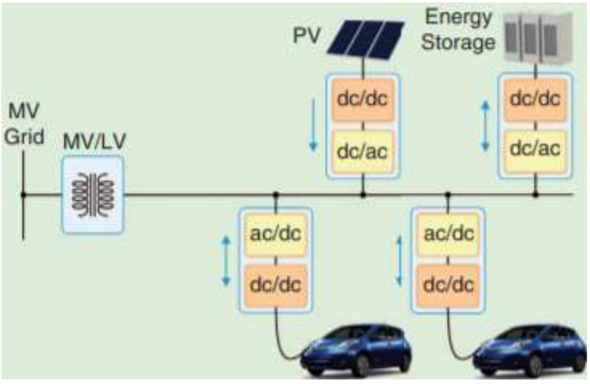

Figure 4. An AC coupled charging station

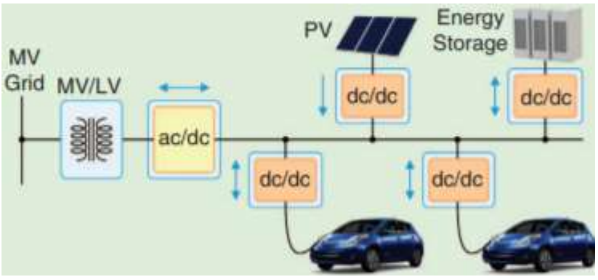

Figure 5. A DC coupled charging station

DC fast chargers are designed to connect three-phase system upto 480 V, which are not available in public areas. Moreover, the high power charger requires larger conductor size and protective equipment at such a low voltage grid. The existing 50 kW chargers deliver with approximately 93% efficiency with a LF transformer efficiency of 98.5%.

A promising approach to overcome the above issues is the utilization of solid state transformer (SST) technology, which is already popular for railway traction and DC distribution grids. This approach enables the direct connection to the MV line with the elimination of a LF transformer. It essentially covers the functionality of LF transformer and AC/DC conversion stage with enhanced power density, its architecture is shown in Figure 6. Furthermore, additional functionality such as bi-directional power flow, fault current limitation and fault isolation. This architecture adopts the common DC bus configuration and the flexibility to integrate the renewable energy sources and energy storage with reduced conversion stages.

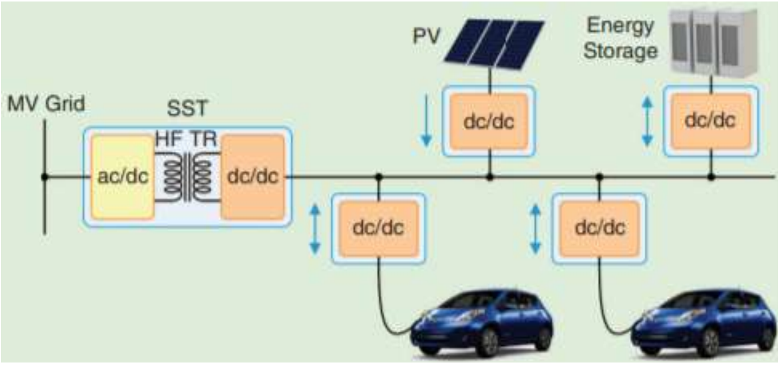

Figure 6. An EV XFC station concept based on SST technology

A list of key characteristics for comparison between LFT and SST-based XFCs is shown in Figure 7. As the power converters are connected to the MV line, series connection at the input and parallel connection of the out stages are recommended. Various AFE power converter topologies have been studied, among them cascaded H-bridge and modular multilevel converters are becoming popular. The SST-based XFCs are beneficial to both EV users and charging station owners with increased efficiency and smaller foot print. It provides faster charging, high availability and cheaper charging to EV users whereas it reduces installation cost and enhances the utilization of resources. For instance, fast charger installation demands concentrate foundation for both LF transformer and charger in seismically active areas. The presented SST-based XFC able to reduced cost to 40% of the conventional 50 kW charging systems.

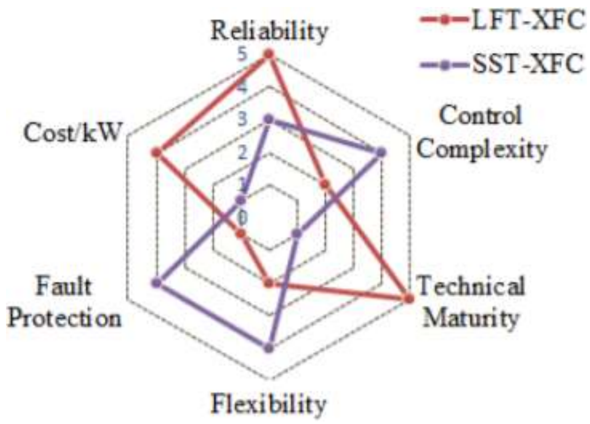

Figure 7. Comparison between LFT and SST based EV charging stations

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 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.

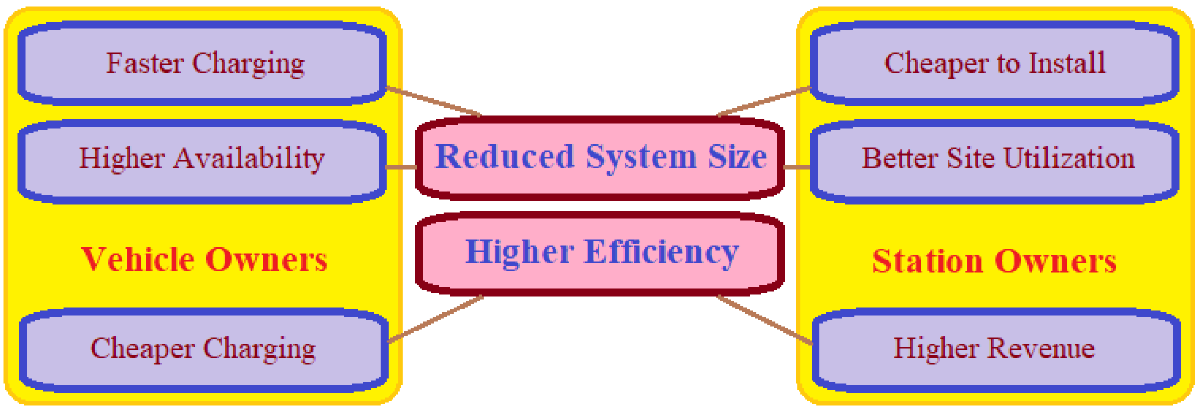

Figure 8. The key benefits of the SST-based DC fast charger

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 10. An SST-based 2700 kW MVFC solution (97% efficiency)

4 Infrastructure and Utilities

The Voltage Source Converter (VSC) regulates the MV DC link voltage. The PCC voltages, V_{abc} are used in a conventional SRF-PLL for synchronization with the three-phase grid and the grid currents, I_{abc} are used for implementing current control in a rotating *dq* reference frame. The VSC can be controlled appropriately to exchange active or reactive power with the grid.

The main function of the solid-state DC transformer (DAB converter) is to regulate the LV DC link voltage. The phase-shift between the bridge voltages, duty ratio of the bridge voltages or frequency of operation can be controlled to regulate the LV DC link voltage. In addition, a dead beat predictive current control is needed in a DAB to minimize any transient DC currents in the high frequency AC link.

The partial power DC-DC converters are used to charge the EV batteries. The input current of the partial rated series element is controlled to inject a desired current into the EV battery. For the full bridge resonant boost converter, a variable frequency control must be implemented to ensure ZCS operation of all the active switches.

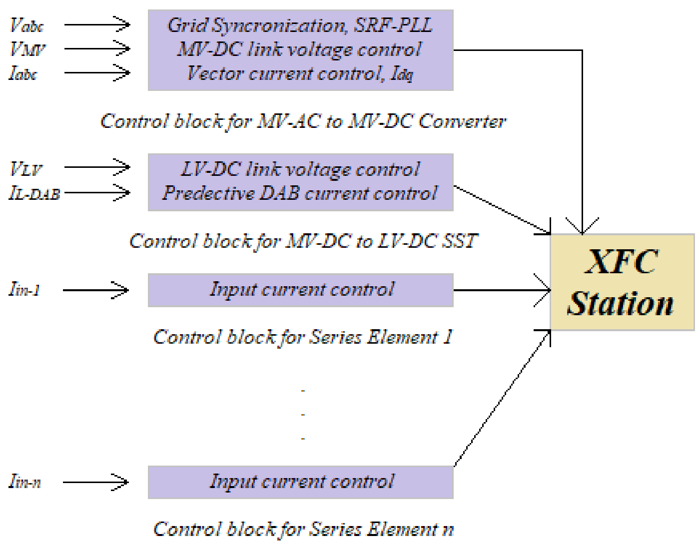

Figure 11. Global control strategy for the XFC station

Connection point on vehicle - The electric vehicle supply equipment (EVSE) connector port location on the vehicle and the EVSE location relative to the parking space would determine the vehicle's parking orientation and/or cord set requirements during charging within a facility. Locating the EVSE in the front of a vehicle parking space would require a charge port in the front of the vehicle and possibly require front pull-in parking, which may contradict current industry practices. If EVSE was at the front of the stall and vehicles were backed in, this would require longer cables (about 18–24 ft) to reach the front port. Coordination and specification of the EVSE location and charge port location will be required for commercial vehicle deployments and could vary by customer/location.

Direct-current (DC) fast charging equipment (typically 208/480 V AC three-phase input) enables rapid charging along heavy traffic corridors at installed stations. There are three types of DC fast charging systems, depending on the type of charge port on the vehicle: SAE Combined Charging System (CCS), CHAdeMO, and Tesla.

The Charging Interface Initiative e. V. (CharIN e. V.) is a registered organization founded by Audi, BMW, Daimler, Mennekes, Opel, Phoenix Contact, Porsche, TÜV SÜD and Volkswagen. CharIN is the coverning body behind the Combo type connectors. The CCS connector (also known as J1772 combo) is unique because a driver can use the same charge port when charging with Level 1, Level 2, or DC fast equipment. The only difference is that the DC fast charging connector has two additional bottom pins. The main attraction of the Combined Charging System connector is that it is compatible with both AC as well as DC charging. These connectors are a part of the IEC 62196-1, IEC 62196-2 and IEC 62196-3 standards. These connectors are capable of handling up to 350 A at voltage ranging from 200 V to 1 kV having a maximum power handling capability of 350 kW.

The CHAdeMO connector is the most common of the three connector types. The "CHAdeMO Association" was established in 2010 by companies like Toyota Motor Corporation, Nissan Motor Co. Ltd., Mitsubishi Motors Corporation, Fuji Heavy Industries Ltd. and Tokyo Electric Power Company, Inc. The CHAdeMO has been a part of the IEC standard (IEC 61851-23, -24, as well as 62196-3) and IEEE standard (IEEE Standard 2030.1.1TM-2015). With power handling capability of up to 200 kW to 400 kW, CHAdeMO is the first DC standard to facilitate V2X (vehicle to x, 'x' might be grid, vehicle, infrastructure etc.) via the 1.1 version of the protocol.

Tesla vehicles have a unique connector that works for all their charging levels including their fast charging option, called a supercharger. Tesla superchargers in the US use their own proprietary charging connector. A unique feature of the Tesla connector is that it uses the same connector and pins for both AC as well as DC charging. They also offer an option for an adapter that makes the connector compatible with CHAdeMO charging stations as well. These connectors offer power levels up to 120 kW.

5 Challenges

As appealing as XFC may sound, the technology is brand new and some challenges still exist. When an EV battery receives higher power, it dissipates a large amount of heat, which leads to battery degradation. Finding a way to keep the battery cool is key to determining exactly how fast one will be able to charge. In addition, the existing power electronics in today's EVs are built for overnight slow charging, and may not be able to handle the high wattage needed to facilitate 350-kW charge rates.

Connector durability – As connector and cable sizes increase due to higher power levels, forces on the connector may cause damage over time. If a connector fails, there is a possibility that the entire connector (and sometimes cord set) must be replaced, which could be costly. Current EVSE connectors are not necessarily designed for repair, and there are a limited number of manufacturers. Currently, the force required for EVSE connector insertion makes it a one-person operation, but large connectors may require mechanical support/assistance in the future. The example of airline fueling connections (which already provide mechanical support for large fuel lines) could be a valuable model for a similar EVSE solution. Alternate connection options include pantographs and wireless power transfer systems, but both have cost, packaging, and efficiency challenges. Fleets should consider what is best for them, but additional cost and installation information would be valuable.

Issues of scale – Some rural locations do not even have three-phase power. Cost recovery could take 30–40 years. On the fleet and facility level, the easiest applications are the first to be electrified, but scaling up quickly becomes nonlinear. Capital costs are high, and total operational costs are not transparent. There are issues related to land use, real estate costs, parking, and existing building infrastructure. Cost models built on press releases and grant awards do not include actual or final costs and create unrealistic expectations. Maintenance costs for mature BEVs are unknown. Existing TCO tools may be inadequate for future projections.

Thermal challenges – Thermal challenges for cables, traction drive systems (including power electronics and batteries), and cabins require further investigation and standardization. Cooling will likely be needed to enable XFC cables with manageable weight, sufficient flexibility, and reasonable cost. The charging heat and close proximity of traction-drive components—vehicle-side cables, connectors, power electronics, and battery—make thermal management challenging and call for R&D on design and technologies such as high-temperature components, thermal storage, and advanced cooling strategies. Cabin heating and cooling are important, particularly for transit buses, where high cabin loads and low operational speeds have large impacts on battery size and range. Fleets often do not have the resources to investigate these impacts on their own. Advanced thermal system technologies such as localized climate control, air curtains, thermal storage, and heat pump systems merit investigation to mitigate battery impacts. Communication standardization could also help with preconditioning strategies.

Challenges to charging station installation – Challenges to station installation include long, labor-intensive permitting processes applied to unique site configurations (limiting transfer of lessons learned between sites); small existing site footprints; novelty/uniqueness of DC metering; and complex electrical grounding considerations. Overall, high costs to customers and utilities, as well as a lack of regulations and standards, present challenges to station installation.

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 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 over voltages, 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 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.

Apart from the above mentioned challenges, an important concern is the effect of fast charging on the battery pack. The usage of battery over time, results in the degradation of the SOH of the battery. The electro-chemical reactions taking place in the battery have a direct impact on the lifetime of the battery. The rate at which the chemical reactions take place for each of the battery chemistry is well defined. Since the battery is subjected to such high voltage and current during fast charging, it will experience greater thermal degradation as a result of the comparatively higher temperatures generated during this process. The degradation of the active material on the cell plates is due to: (i) The repeated processes of dissolution and re-crystallization results in the loss of active surface area on the plates (ii) Decrease in electrical contact between the metallic grids and active materials and (iii) Increase in the growth of inactive materials. There is a need for research to improve the calendar life of the batteries employing fast charging.

6 Conclusion

This project presents a review of the requirements to develop extreme fast charging systems and an overview of the challenges and opportunities of XFCs using SST technology to facilitate the next step for future charging solutions for future generation of EVs.

It can be concluded that with the evolution of new power conversion topologies, new standards, advanced control schemes, fast acting protective devices, the improvements in wide bandgap (WBG) power devices, digital controllers and magnetic materials make the XFC stations that are capable to mimic refuelling like gas stations a possibility.

However, operation, design and control of XFC stations must be addressed properly without affecting the stability of the grid.

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