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Review

Extreme Fast Charging Technology—Prospects to Enhance Sustainable Electric Transportation

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Abstract: With the 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. However, use of the service transformer in the existing fast charging architecture adds to the system cost, size and complicates the installation process while directly connected to medium-voltage (MV) line. With continual improvements in power electronics and magnetics, solid state transformer (SST) technology can be adopted to enhance power density and efficiency of the system. This paper aims to review the current state of the art architectures and challenges of fast charging infrastructure using SST technology while directly connected to the MV line. Finally, this paper discusses technical considerations, challenges and introduces future research possibilities.

Keywords: electric vehicles; energy storage; fast charging station; power converters; solid state transformer; transportation electrification

1. Introduction

Due to an increase in the fuel crisis and environmental concerns, governments and automotive manufacturers have announced various strategic plans to promote efficient vehicles with a lower carbon footprint [1]. The U.S Department of Energy (DOE) has initiated and updated a technology road map of 2025 for EVs that can compete with the conventional fossil-fuel based vehicles [2]. However, range anxiety has become a serious issue which has led to the need to re-think refuelling similar to the conventional gasoline stations. In order to provide a better performance in terms of range of the vehicle, two possible solutions come into picture. First one involving increasing the battery capacity resulting in the increase in the cost, size and weight of the vehicle [3]. The second one would be to enhance fast charging infrastructure around the world thus enabling the users the ability to recharge their vehicle more frequently. Out of these two possible solutions, the latter proves to be a more beneficial as well as economic [4–6].

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 [7] and their typical configuration is shown in Figure 1.

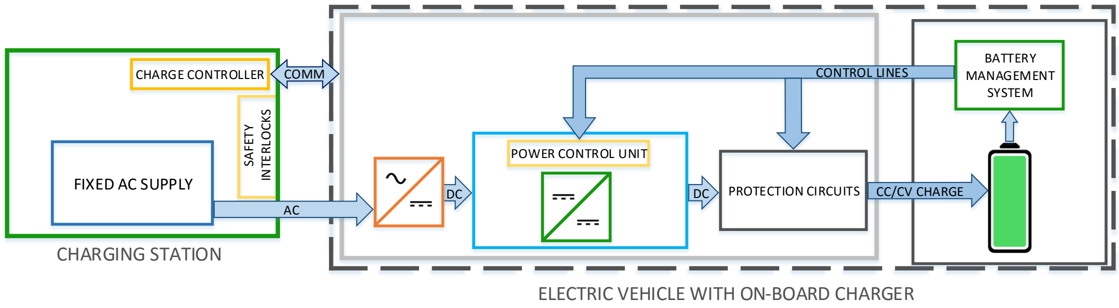

Figure 1. Conventional AC on-board charger configuration.

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 [8]. 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 [9,10].

Recently, some of the works have been carried out to increase the power level of chargers to 30 kW–200 kW by utilizing components of the propulsion systems since the propulsion and the charging process is not simultaneous [10,11]. These integrated battery chargers and motor drives include traction converter and machine modifications. Currently, Renault ZOE utilizes this technology in a charger called Chameleon charger capable of accepting 3 kW–43 kW through the traction motor as the role of the filter [11,12]. However, these chargers might increase stress on traction components and may reduce the life of the propulsion equipment. Moreover, torque production happens during charging, which can result into motor rotation. The other associated problems are acoustic noise and mechanical vibrations [13].

An alternative is the development of off-board chargers and the corresponding infrastructure that can mimic the functionality of a gasoline refueling station [14]. 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 2.

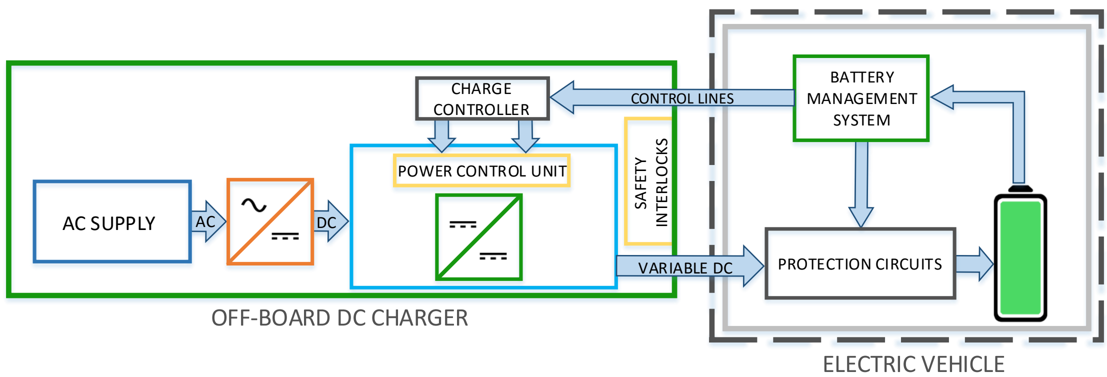

Figure 2. Conventional DC off-board charger configuration.

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 [15]. 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 [16].

To overcome the aforementioned problems, utilization of solid-state transformer (SST) technology to extreme fast charging (XFC) architectures help to achieve an improved power density and efficiency, thus eliminating the LF step-down transformer [17]. Moreover, it provides better power quality and additional functionality such as bi-directional power flow, fault current limitation and fault isolation. However, some issues and challenges include reliability of the LF transformer, integration of SST into existing power systems, power conversion equipment and fluctuations in the power demand for battery charging due to the connection of multiple EVs simultaneously to the DC micro-grid. Thus, it is compelling to perform an extensive review on requirements, challenges and opportunities for further improvements of SST-based XFC infrastructure systems.

The paper is organized as follows: Section 2 provides the background, standards and classification of charging infrastructure. Then, the state of the art and recent developments of DC fast charging architecture are reviewed and discussed in Section 3. Challenges and opportunities of XFCs are presented in Section 4. Finally, conclusions are drawn in the final section.

2. Background

2.1. Specifications of Popular EVs

The EV sales are mainly dominated by ten countries including US, Canada, Japan, China, France, Germany, UK, Netherlands, Norway and Sweden [18]. Table 1 shows the specifications of commercially available chargers in terms of motor rating, motor type, battery capacity and electric range [11,12,19–27]. It is evident that more research activities have been carried out to make EVs more cost effective while delivering an electric range of more than 200 miles. Concurrently, significant advances in battery technologies have empowered charge acceptance with faster charging rates.

Table 1. Specifications of Commercially Available EVs.

Vehicle Model	Motor Rating (kW)	Motor	Battery Capacity (kWh)	Electric Range (mil)
Smart FortoWo ED	55	PMSM	17.6	58
Hyundai Ioniq Elec.	88	PMSM	28	124
Mahindra Reva	35	IM	16	75
Kia Soul EV	81	PMSM	30	110
Renault Zoe	80	PMSM	41	250
Tesla Model 3	192	PMSM	75	220
Tesla Model S 70D BEV	100	IM	100	240
Chevy Bolt	150	PMSM	60	238
Chevy Volt PHEV	87	PMSM	18.4	420
Ford Focus Electric	107	PMSM	33.5	115
Nissan LEAF BEV	110	PMSM	40	151
BMW i3 BEV	125	PMSM	33	114
Audi A3 e-Tron PHEV	75	PM-SynRM	8.8	31
Toyota Prius PHEV	50	PMSM	8.8	640
Cadillac CT6 PHEV	250	PMSM	18.4	31
VW e-Golf	100	IM	35.8	125
Chery eQ	41	PMSM	23.6	157
NIO EP9	1000	PMSM	90	265
Tesla Model X	193	IM	100	325

2.2. Classification of Battery Chargers and Connectors

The batteries in EVs can be recharged through AC or DC chargers from the grid. Table 2 illustrates charging levels including slow, fast and extreme fast charging standards along with their ratings. Various connectors have been employed globally to enable these high charging rates. Figure 3 demonstrates the connectors currently used across the globe along with their power rating [10,11]. AC and DC fast charging techniques have been explained in the following sub-sections.

Table 2. Charging power levels, standards and configurations.

Charging Level	Voltage Level	Maximum Power (kW)	Charging Time	China	Europe	Japan	North America
Level 1 (Slow)	120 VAC	3.7	10–15 hrs	Private outlets (not specific for EVSE)			SAE J1772 (Type 1)
Level 2 (Slow)	220 VAC	3.7–22	3.5–7 hrs	GB/T 20234 (AC)	IEC 62196 (Type 2)	SAE J1772 (Type 1)	SAE J1772 (Type 1)
Level 3 (Fast)	3-ϕ 480 VAC	22–43.5	10–30 min	GB/T 20234 (AC)	IEC 62196 (Type 2)		SAE J3068
	200-600 VDC	<200		GB/T 20234 DC	CCS Combo 2	CHAdeMO	CCS Combo 1
		<150		Tesla and CHAdeMO			
XFC	>800	>400	~gas refuelling	CCS/CHAdeMO			

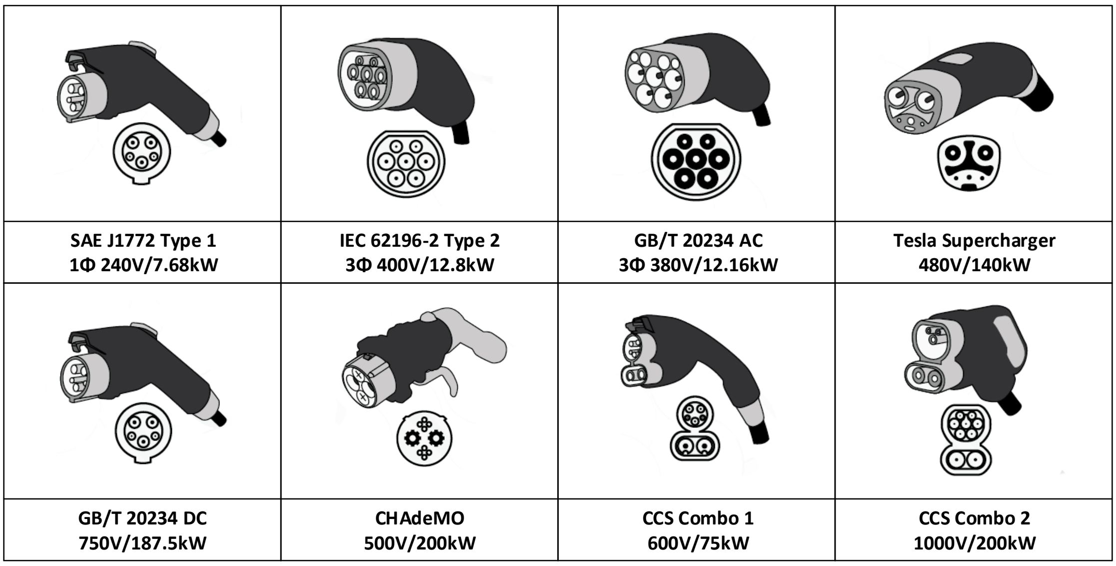

Figure 3. Global male and female battery charger connectors.

2.3. *AC Charging Connectors*

The EV industry has not yet come to an agreement in terms of using one universal AC connector. Depending on the EV manufacturer, country and the power level of the charger; the connector varies in terms of size, shape and pin-out. This is due to the very reason that various regions have their own AC mains voltage level and frequency. A typical AC connector has two and more large pins depending upon the voltage and a few smaller pins for communication. Currently, four types of AC connectors have been employed worldwide which will be discussed below.

2.3.1. Type 1 Connector

This connector is used specifically for AC single phase charging and has a round configuration consisting of five pins which include two AC lines, two signal lines and one protective earth path. The maximum voltage rating is 120 V or 240 V with current capabilities up to 80 A.

2.3.2. Type 2 Connector

This connector is capable of handling both AC as well as DC charging. Moreover, it is 3-ϕ AC compatible. The maximum voltage rating of single phase is up to 230 V with currents up to 80 A and 3-phase maximum rating of 400 V at 63 A.

2.3.3. Tesla US Connector

This connector is designed by Tesla to be specifically used in the US. This connector is capable of handling single phase AC as well as DC power. The maximum charging power is rated at 17.2 kW at 240 VAC maximum.

2.4. DC Charging Connectors

DC fast chargers are designed to supersede level 1 and level 2 chargers. They are rated between 50 kW to 500 kW depending on the manufacturer. With higher power capability, the power conversion and the control stage become more bulky and expensive. This is one of the main reasons why DC fast chargers are implemented off-board. The other reason being that of safety concern. With high power converters and increased size of power handling components, safety of the passengers becomes a key issue. There are mainly five variants of DC connectors and are discussed as follows.

2.4.1. CCS Combo 1 and Combo 2

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 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.

2.4.2. CHAdeMO

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.

2.4.3. Tesla DC Connector

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.

2.4.4. China GB/T Connector

China has their own DC charging connector based on the 20234.3-2015 standard. This connector communicates with the on-board power management system via the Controller Access Network (CAN) protocol. The main attraction of this connector is that it is equipped to charge 2 on-board batteries; the low-voltage auxiliary battery as well as the main high-voltage battery. Having a nominal voltage range of 750 V to 1 kV, it can deliver currents up to 250 A.

3. State of the Art DC Fast Charging Infrastructure

Due to various challenges such as cost, footprint and power levels, on-board fast charging of EVs today seems like an ambitious goal. Hence, it is essential to focus on the development of off-board fast chargers that can mimic the gas refuelling experience. This concept in partnership with battery technologies that are capable of accepting charging rates of more than 10–12 C and several thousands of charging cycles [28], makes fast charging a realistic possibility [29,30]. The conventional

DC fast chargers are installed in either in single or multi-stall charging units. Each stall is typically rated at 50 kW and powered from a three-phase low-voltage (LV) distribution grid through a LF distribution transformer.

The basic blocks of the conventional DC fast charger power stage is shown in Figure 4. It comprises of two conversation stages from three-phase AC to DC and a DC/DC stage with galvanic isolation. The AC/DC rectification stage includes Power Factor Correction (PFC) circuit, which ensures required power quality on the grid side complies with the grid codes. The DC/DC stage provides galvanic isolation between the EV and the grid and also incorporates the parallel connectivity at the charger output stage [17]. Table 3 illustrates the technical specifications of the commercially available high power DC-fast chargers [31–35]. Most of the chargers are available in 50 kW units and those are connected to meet the required power demands. For instance, Tesla's Terra HP super charger was made by combining various single units [31]. These chargers adopt different charging protocols and connectors based on geographical location, which is discussed in Section 2. The charging process will follow a particular sequence defined by charging protocol. It starts with signal hand shaking, then insulation testing and finally exchanging defined constraints between the EV and the charger. If above criteria is met, then EV closes its DC contractor. Even though there are different advanced charging profiles that exist in the literature, it is usually follows the constant current-constant voltage (CC-CV) method as is widely accepted approach in the case of lithium-ion batteries [4].

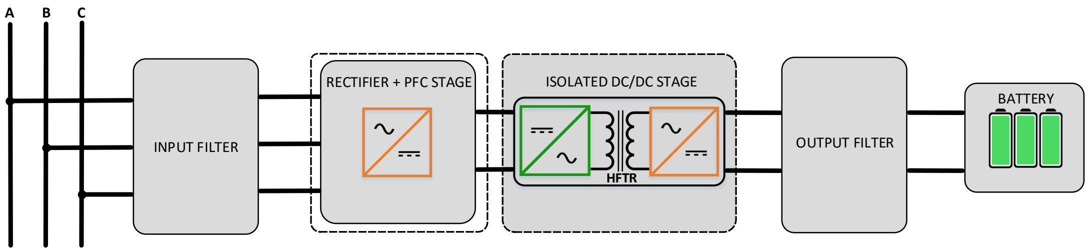

Figure 4. Basic blocks of DC fast charger power stage.

Table 3. Specifications of DC-fast chargers by equipment manufacturers [31–35].

Fast Charger	Tesla Terra HP	EFAECE-QC45	Tritium Veefil PK	Delta Ultra Fast	EVTec Espresso
Input Voltage Range (AC) [V]	3-ϕ 400	3-ϕ 480	3-ϕ 480	3-ϕ 400	3-ϕ 480
Full Load Power Factor	>0.99	0.98	0.95	0.99	0.93
Efficiency [%]	95	93	98.5	94	93
Output Voltage Range (DC) [V]	150–920	50–500	920	170–550	170–500
Output Current [A]	375/500	120	500	300	300
Output Power [kW]	150	50	475	150	120
Charging Connector	CHAdeMO 1.2	ChadeMO/Combo-1	CHAdeMO/CCS	CHAdeMO/CCS	CHAdeMO/CCS
Dimensions (H×W×D) [mm]	2103 × 1170 × 770	1800 × 600 × 600	1998 × 980 × 525	2079 × 998 × 852	2000 × 930 × 850
Weight [kg]	350	600	700	400	400

The design and configuration is crucial as the EV fast chargers should mimic the same infrastructure of gasoline refueling stations with a functionality of supplying multiple EVs. Therefore, two possible EV charging configurations are identified [36] and their classification is shown in Figure 5.

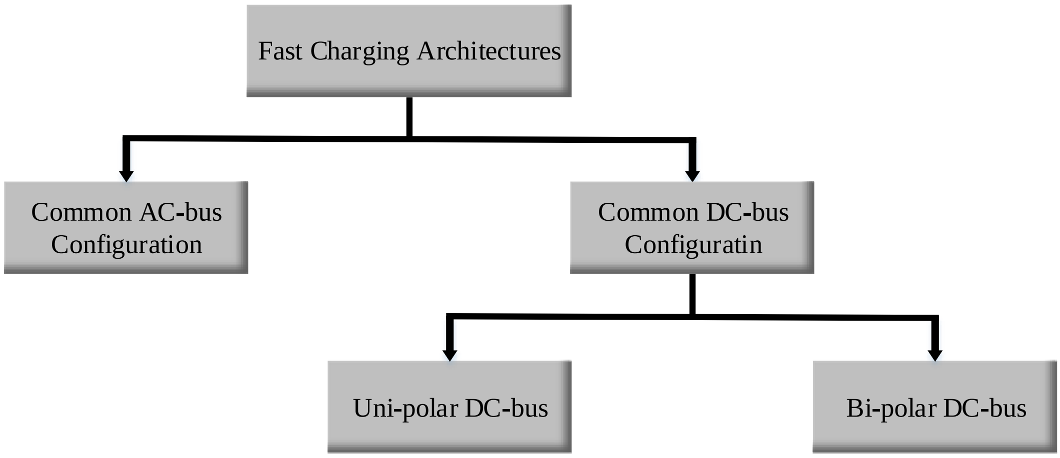

Figure 5. Classification of fast charging architectures.

3.1. Common AC Bus Configuration

One of the configurations that can be employed for fast charging is to use a common AC bus structure as shown in Figure 6. The grid voltage is stepped-down using a LF transformer. The secondary windings of this transformer is used as an AC bus to feed individual charging units. These charging units have their own individual rectification stages connected to the AC bus at a common coupling point. The use of such configurations not only allows use of low power rated stages in the front-end but also is simpler from an implementation point of view. Moreover, technical maturity and availability of switchgear and protection equipment with well established practices makes for more viable EV fast charger architecture. An example of such system is installed at Mountain View, CA, in the United States which comprises of six super chargers and energy storage of 400 kWh [17].

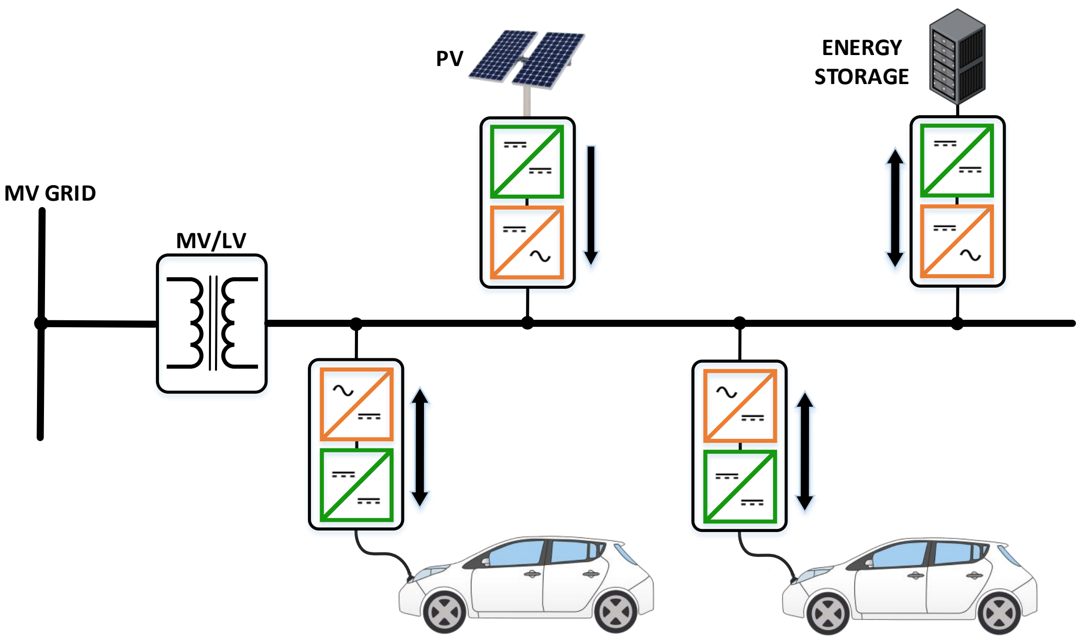

Figure 6. AC coupled charging station.

However, individual charging units with their own conversion stage displays poor power factor and may worsen the grid voltage [37]. Moreover, increased number of conversion stages reduces the efficiency and increases the complexity as each conversion stage need its own filters, control and sensing requirements. Addition of renewable and energy storage systems further increases the conversion stages and consequently complicates the system and increases the system cost [38]. In view of system control, control of AC systems are more complicated compared to DC systems which includes grid synchronization, reactive power control and islanding operation [39].

3.2. Common DC Bus Configurations

Alternatively, a single AC/DC stage with a higher power rating is used to form a common DC bus as shown in Figure 7. This structure is more flexible from the distributed sources point of view as these sources can be easily coupled with the DC bus using a local conversion stage at the distributed points. Another advantage of such a configuration is the elimination of synchronization issues and no reactive power exists. These salient features form an intelligent system that can work towards the stability of conventional utility grid [37]. Due to the elimination of many local conversion stages, the device count is less than the AC bus configuration, thus proving to be more economical. The overall efficiency of the system can also be improved because of the lesser power conversion stages. It is also beneficial especially under abnormal operation of the utility grid as it allows standalone operation in which the generated power is fed to the loads connected with the DC-bus [40]. However, the use of high power rectifier unit demands stringent grid requirements and impose on switching frequency limitation due to use of high power devices. Furthermore, it demands complex protection devices compared to the AC bus configuration due to the absence of zero crossing points [41]. The common DC-bus configuration is further classified as unipolar and bipolar dc bus [42]. Various significant research has been carried out in terms of innovative central active front end (AFE) converter topologies including dual two-level voltage source inverter (VSI) [43], single DC-link H-bridge converter [44], Vienna rectifier [45], multipulse rectifier with DC active power filter [15], three-level neutral point clamped converter [42], matrix front-end converter [46,47] and cascaded H-bridge converter [42,48]. The comparison of different charging station topologies are analyzed in Reference [49]. The two popular control schemes such as voltage oriented control (VOC) [50] and direct power control (DPC) [51] are used to control these converters in order to maintain power factor, bi-directional power flow and harmonic reduction. The summary comparison between the AC and DC coupled systems are listed in Table 4.

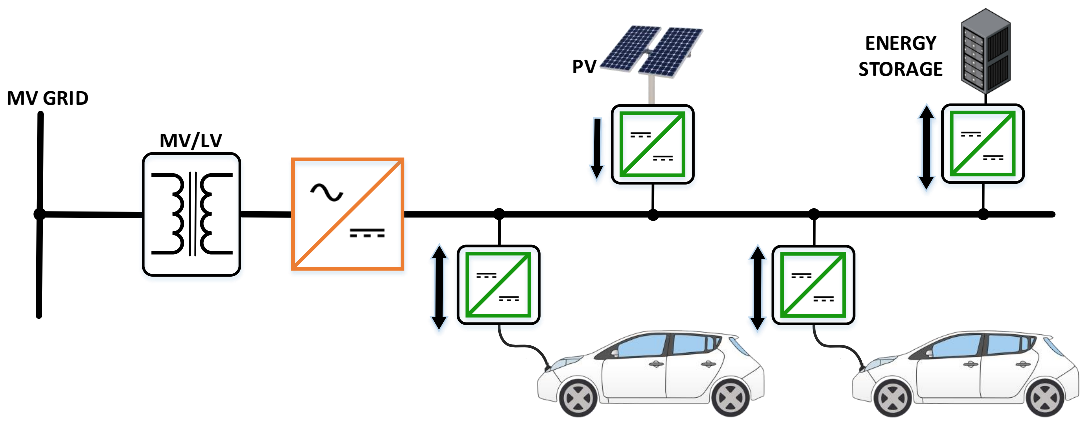

Figure 7. DC coupled charging station.

Table 4. Comparison between AC and DC coupled electric vehicle (EV) architecture.

Parameter	AC Coupled System	DC Coupled System
Technical Maturity	High	Low
Availability	High	Low
Complexity of Protective Devices	Low	High
Conversion Stages	High	Low
Efficiency	Low	High
Control Complexity	High	Low
Operation at grid abnormality	No	Yes
Cost	High	Low

4. SST-Based XFC Infrastructure

State of the art DC fast chargers are designed to connect three-phase system upto 480 V, which are not available in public areas. Hence, it requires a LF distribution transformer to step down the voltage required for a DC fast charger. The use of LF transformer increases weight and cost of the system. 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) [52] technology, which is already popular for railway traction [53] and DC distribution grids [54].

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 8. 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 [52].

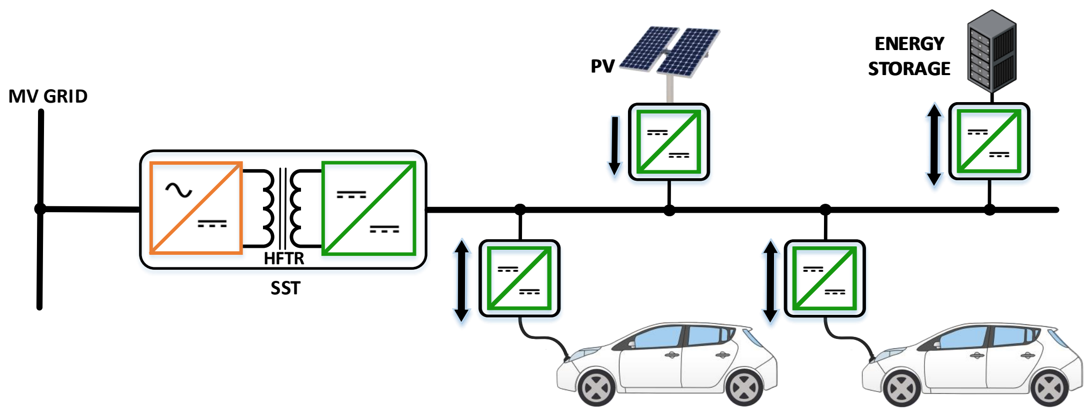

Figure 8. EV XFC stations based on SST technology.

Some early SST-based XFCs have been reported and a team at the North Carolina State University demonstrated 50 kW SST-based MV modular fast charger [17] of output voltage range of 200–500 V to charge the battery. This charger is powered by the 2.4 kV single-phase distribution line and utilizes SiC devices [55]. This developed system is able to achieve thirty times the reduction in volume and half the power losses in comparison to the existing system. Several studies are going on to extend this concept for the multi-mega watt SST based XFCs with estimated increase in efficiency of 5%. A list of key characteristics for comparison between LFT and SST-based XFCs is shown in Figure 9. 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 [49], among them cascaded H-bridge [56] and modular multilevel converters [13,57] 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 [58]. 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 [17].

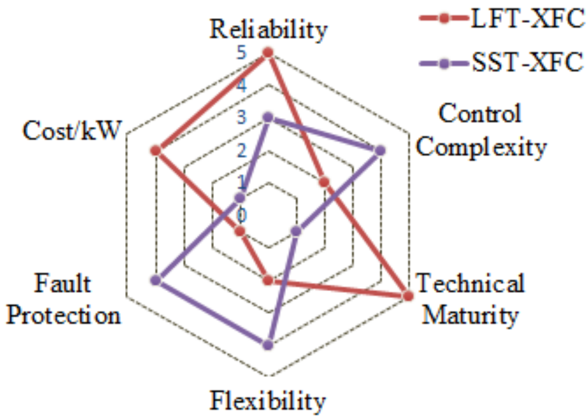

Figure 9. Comparison between LFT and SST based EV charging stations.

5. Challenges and Opportunities in Adopting SST-Based XFC Architectures

5.1. Challenges

Despite salient features, like the high power density and high efficiency of the SST technology, there are some serious concerns associated with it. The cost of the charging is directly proportional to its speed. Due to this economical reason, it becomes very important to weigh if the benefits of fast charging outweigh the cost of slow charging. There have been major deployments of fast charger across the globe in the recent years. Although the EVs will demand a lot of power from the grid as compared to the other loads they will inject harmonics into the grid which is undesirable. One of the studies predict that EVs will account for 80% of the European Union's passenger vehicle fleet will consume 9.5% of the total grid load [59]. This demands upgrading the conventional distribution systems and transformers to accommodate the fast charging needs. In addition, integration of multiple EV chargers can cause adverse effects on stability of the grid. The use of intelligent features to control the charging creates a sustainable, low-cost and effective environment. Smart charging techniques have gained significance due to proving to be very beneficial for the grid.

Another main concern is the integration of SST technology with the existing power systems, which needs modification of communication layers. Another significant challenge is lack of fast acting protective devices such as circuit breakers (CBs) to act against short circuit faults, circuit overloads and over voltages [60]. The CBs should be able to interrupt the fault current in several µs to protect MV power electronic systems. In addition to the above concerns, the standardization and establishment of proper practices for XFC infrastructure that directly connected to MV line are to be addressed.

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 [61]. There is a need for research to improve the calendar life of the batteries employing fast charging.

5.2. Opportunities

In the last decade, significant research contributions have been carried out to adopt the SST technology in various applications. However, there are many serious concerns in various components of SST technology to replace the conventional bulky LF transformer systems especially in power converter topologies, control schemes, power switching devices, digital controllers and HF transformer design. Recent trends in the aforementioned areas can adopt the SST technology in near future.

5.2.1. Wide Bandgap Devices

In order to directly connect SST-based AFE converter to the MV grid (6.6–15 kV) and have the ability to operate at high switching frequency, there needs to be exploration of wide-bandgap (WBG) devices such as SiCs and GaNs. The physical properties of WBG devices in comparison to Si-based devices are shown in Figure 10 [53,62,63]. The SiC devices are the preferred option for SST based systems as it can operate at higher switching frequency and operating temperature. These features significantly minimizes volume, size, weight of heat sink and magnetics size [62,63].

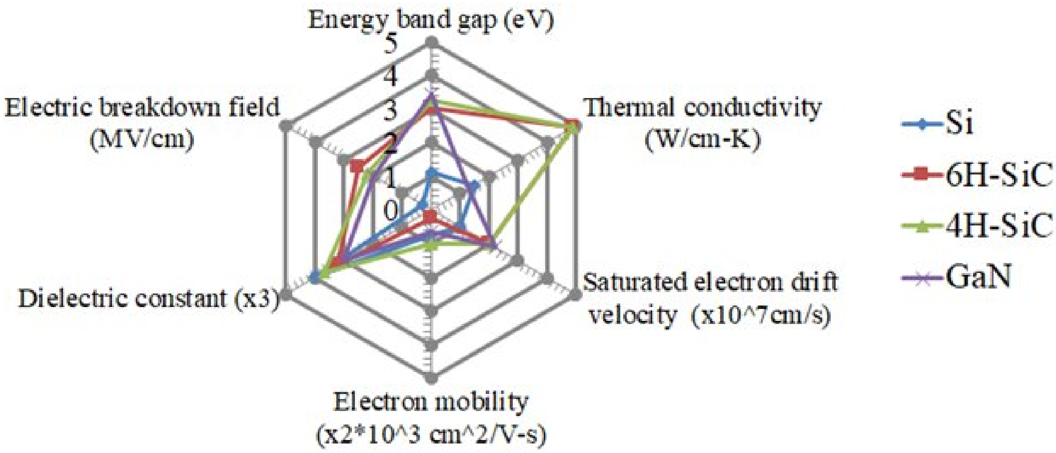

Figure 10. Comparison of wide bandgap devices.

Moreover, device utilization factor (>0.7) of SiC devices in comparison to Si-IGBT counterparts [53]. A preliminary comparison between SiC and Si-IGBT based SST designs are investigated in Reference [64]. A 1-MVA SST with SiC modules was developed in Reference [65], which has an efficiency of 98% with 70% reduction in weight. The design aspects of SiC inverters along with gate driver and the bus-bar is well described in References [66–68]. There is a trend towards smart gate drivers which rely on turn-on and turn-off slopes of SiC devices. Despite SiC devices being able to withstand high temperature, high voltage (HV) and high switching operation, there are some serious concerns that cause a hindrance for mass production. Due to the faster operation of SiC devices (10 kV/μs), some issues related to the short circuit protection, proper dv/dt and di/dt control need to be addressed [69]. Active gate control methods in gate drivers and laminated bus-bars are recommended for MV applications so as to minimize the conducted noise and parasitic rings.

Typically, laminated bus-bars are employed in MV applications so as to eliminate snubber circuits, HV arcing, critical design issues, and electro-magnetic interference issues. Furthermore, it provides flexible and error-free installation [70]. Another important consideration for power converter design is the design of an effective cooling system to achieve higher power density [71]. Advanced passive cooling methods have to be adopted in order to achieve high power density [72]. Overall, SiC devices have some technical challenges in terms of the gate driver design, reliability, manufacturing process, thermal management and bus bar layout which need to be addressed.

5.2.2. Advances in Magnetics

The high frequency transformer (HFTR) in the SST power stage allows for operation at higher switching frequency (>400 Hz to several kHz), which makes the energy conversion more efficient with higher power density. Furthermore, it reduces the voltage and current harmonic distortion due to core saturation of LF transformers [53]. However, there are some special design considerations that must be employed while designing the HFTR. The essential considerations including taking care while designing and optimizing the HFTR. The material should be loaded with lower flux density and proper insulation layers must be used to minimize losses and keep temperature within limits [73,74]. The core material should have high saturation magnetic flux density, low core loss and high permeability [74]. Table 5 illustrates the comparison of the different magnetic core material for HFTR design [53,75,76]. It is concluded that amorphous material will be the best option for HFTR design. However, initiatives are required to develop material and the structures, which are able to operate at a high frequency and can withstand higher temperatures.

Table 5. Magnetic core material comparison used in HFTR.

Parameters	Ferrite	Amorphous	Nanocrystalline
Permeability	1.5–15 k	1–100 k	20–200 k
Magnetostriction	(20–30) $\times 10^{-6}$	<0.2 $\times 10^{-6}$	(1–6) $\times 10^{-6}$
Curie Temperature (K)	493.15	>623.15	>823.15
Operating Temperature (K)	373–423	393–423	393-453
Saturation Flux Density (T)	0.3–0.5	0.8–1.5	1.1–1.3
Composition	MnZn	(Co)x(SiB)y	FeCuNbSiB
Loss (20 kHz, 0.2 T) (W/Kg)	15–20	5–7	4–8
Operating Frequency	High	Medium	Medium
Cost	Low	Medium	High

5.2.3. Smart Charging Techniques

Smart chargers allow the charging power to be controlled along with the charging time and the direction of flow. They not only help increase the efficiency but also to reduce the peak demand of the distribution network [77]. Adding to this, electric vehicles can be made even more sustainable by solar and wind generated power. The V2x technology allows the power from the battery to flow from a vehicle to a home, building or another load [78]. The most important benefits of the V2x technology is that it enables storage of electricity especially from renewable sources.The peak power demands can be fulfilled by utilizing these storage systems. Also, it is worth noting that V2G is currently a big challenge using the AC chargers due to the technological limitation as on-board bi-directional conversion stages will be necessary.

5.2.4. Applications of Smart Charging Techniques

1. Local Load Balancing—The local load balancing method is as simple as shifting the charging time slot to adjust the charging power by looking at the grid capacity and local demand of power from other loads [79]. For example, if the smart charger detects that the load of the power from other applications has reduced, the charging power can be increased in a controlled way. On the contrary, if the demand of the local load increases, the power of the charger is reduced in order to balance the load. The second method is to balance the charging of multiple points with priority assigning methods. Smart chargers can be sequentially activated with priority or with adjusted power.

2. Renewable energy utilization—The charging power of the car can be adjusted according to the availability of the renewable resources as well [80,81]. It may be wind energy, solar energy or any other source. Additionally, V2G technology can enable people to use their car as a massive energy storage in order to help the gird imbalance during peak loads.

3. Peak Shaving—As mentioned earlier, all electric vehicles can act as a massive storage from the grid's point of view. With implementation of proper control strategies, electric vehicles can be charged when there is extra energy from renewable sources and also this energy can be given back to the grid using V2G technology. This will help to shift the beak of both the consumption as well as the generation and thus fill the supply-demand gap.

4. Grid backup—Electric vehicles can act as backup power generators in the future. In the case where there is a failure of the grid for a very short period of time, electric vehicles can be used to power up the local loads thus providing emergency power during an outage.

5. Battery Swapping—It is a concept of switching out the depleted battery and replacing the same with a fully charged one. This process is done by driving the car into a battery switching bay where the car will be automatically aligned and then the old battery is swapped with the new one. This concept works on a business model where the vehicle is owned by individuals but the batteries are rented out on energy basis. This technique needs a good battery state of health (SOH) estimation algorithm for monitoring its usage pattern and to make sure that it is charged by authorised charging stations only. The main advantage of this concept is the elimination of range anxiety and the ability to mimic the refueling gas stations. However, it demands a requirement of having a standardized battery interface across all the car manufacturers.

6. Conclusions

This paper presents 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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