A Comprehensive Review on System Architecture and International Standards for Electric Vehicle Charging Stations

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Abstract: Electric Vehicles (EVs) are rapidly becoming an important facet in the drive for attaining sustainable energy goals. However, EV sales still constitute only a small proportion of vehicles in most countries. The expansion of DC fast-charging network will facilitate a sustainable transportation revolution by offering end-user a versatile choice to charge EVs for longer journeys. Power converters play a significant role in the design and operation of EV charging stations. Modern technologies in charging stations are promising, where state-of-the-art research allows idle batteries or EVs to operate as distributed energy sources. However, it is always important to ensure input current harmonics and power factors are within the standard specification. Solid-state switch-mode power converters have reached a level of maturity with regards to the improvement in power quality and precisely regulating voltage levels during bidirectional power flow operation. This paper presents an exposition of EV charging systems, including incentives for development, structures, power converters, standards, industrial applications, and emerging trends. Furthermore, state-of-the-art technologies, including both academic and real-world EV charging technologies, have been carefully chosen, and a quantitative assessment of the technologies has been provided in this paper.

Keywords: Electric Vehicles, Charging Stations, International Standards, Power Converters, Power Factor, Total Harmonic Distortion

Nomenclature

EVs	Electric vehicles
IEEE	Institute of electrical and electronics engineers
THD	Total harmonic distortion
BEVs	Battery electric vehicles
PHEVs	Plug-in hybrid electric vehicles
HEVs	Hybrid electric vehicles
IEA	International energy agency
XFC	Extreme fast charging
EVSE	Electric vehicle supply equipment
ESS	Energy storage system
VFD	Variable frequency drive
HVDC	High voltage direct current
BESS	Battery energy storage system
MV	Medium voltage
LV	Low voltage
LF	Low frequency
HF	High frequency
PWM	Pulse width modulation
PFC	Power factor correction
ICEVs	Internal combustion engine vehicles
ISO	International organization for standardization
UNECE	World forum for harmonization of vehicle regulations
UL	Underwriters laboratories
IEC	International electrochemical commission
SAE	Society of automotive engineering
WPT	Wireless power transfer
SEPIC	Single-ended primary-inductor converter
GaN	Gallium nitride
SiC	Silicon carbide
WBG	Wide band-gap
LCL	Inductor-capacitor-inductor
LLC	Inductor-inductor-capacitor
FB-LLC	Full-bridge LLC
ZVS	Zero voltage switching
ZCS	Zero current switching
DAB	Dual active bridge
EMI	Electromagnetic interference
SOC	State of charge
SOH	State of health
OBC	Onboard charger

1. Introduction

One of the major growing concerns of this era is environmental sustainability[1, 2]. Our ecosystem is partially degraded by various factors such as industrial waste, electricity generation processes, commercial and residential buildings, and agricultural industries [3]. A quarter of the world's greenhouse gas emissions come from transportation [4, 5]. However, the main challenge in mitigating Earth's rising climate effects is the lack of facilities for the public to engage. As a consequence of an increase in population, there is a dramatic rise in the number of vehicles on the road. Global warming is intensifying demand for EVs, and fossil fuel is often identified as a major cause for greenhouse gas effect and global warming, which is one of the major concerns in Sustainable Development Goals (SDG) – (Sustainable cities and communities (Goal-11)) [6, 7]. Even though electrical energy for the EVs is currently produced by conventional sources such as fossil fuel and coal, EVs are comparatively cleaner than conventional vehicles due to their efficiency in reducing CO_2 emission [8-13].

The International Energy Agency (IEA) reported that by 2035 global CO_2 emissions will exceed 37.0 gigatons. The CO_2 emissions are produced in multiple economic areas such as output from transportations, industry, buildings, electricity, heat production, and agriculture. The CO_2 emission from the production sector, such as electricity and heat production, accounts for 41.2% of the total CO_2 emission, as shown in Fig. 1 [14-17]. The global push for EVs is slowly gaining momentum as many countries around the globe are seeing an increase in EVs on the road compared to 2019 [18]. This can be attributed to greater environmental awareness among customers, as shown in Fig. 2. Fig. 2 indicates that Europe and China have the most number of EVs on the road in 2020 than in 2019 [19]. Fig. 3 shows the percentage of publicly available slow charging stations and fast-charging stations in various countries. Both slow and fast charging stations installed in China are higher (slow charging stations – 51% and DC fast-charging stations – 82%) than any other country [20].

With the advancement of technology, research interest, particularly in the field of EV charging, has grown with enhanced emphasis phased on charging station technology. A significant increment is observed as the publication in 2020 is 1.5 times higher than in 2019. Institute of Electrical and Electronics Engineers (IEEE) reported a total of 590 journal papers in year 2020 meanwhile, ScienceDirect reported 2219 in the same year. A steady increase in the growth of research in the field of EV charging stations in IEEE and ScienceDirect is shown in Fig. 4.

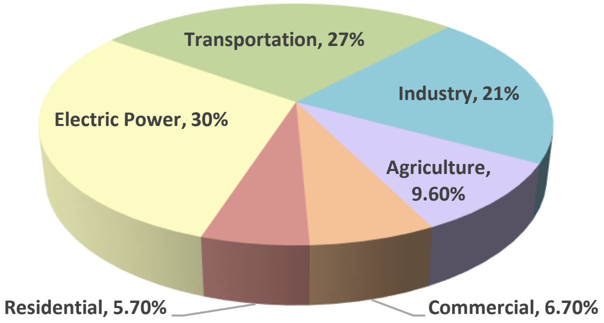


Fig. 1. Greenhouse gas emission by sector in 2020 [17].

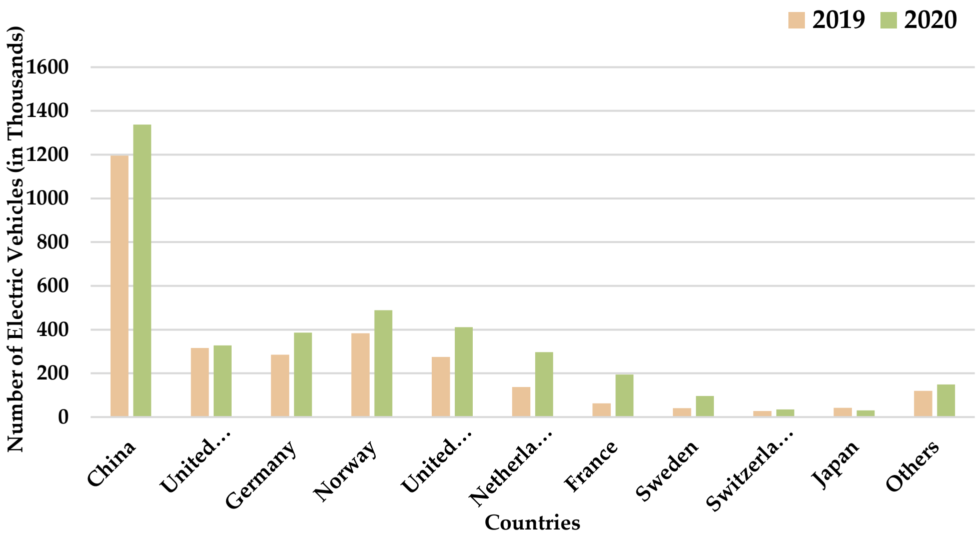
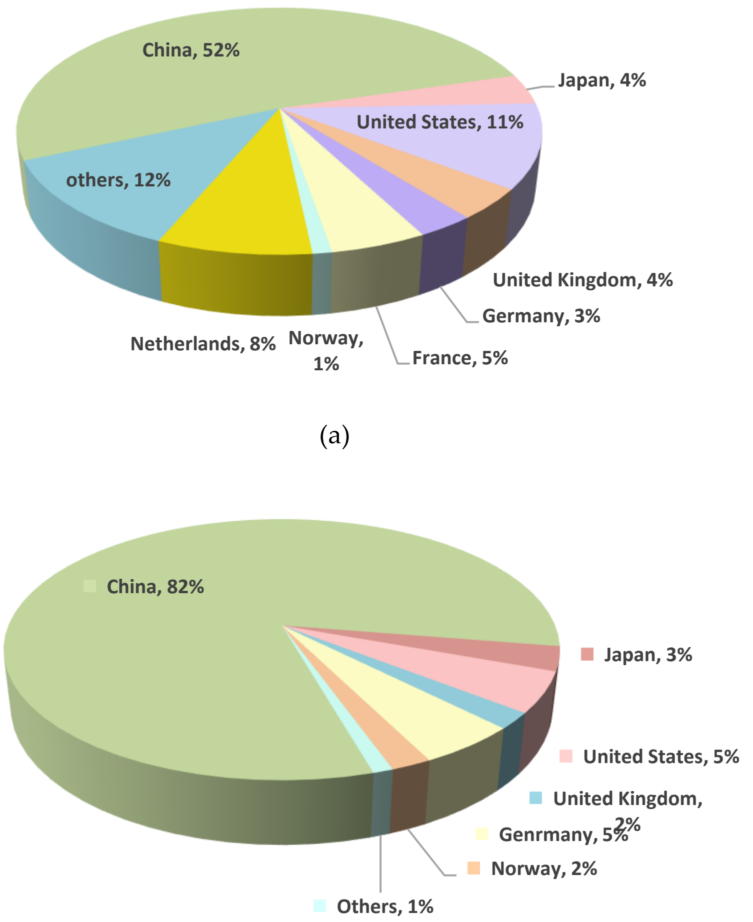


Fig. 2. The number of electric vehicles (in Thousands) in 2019 and 2020 on the road [19].



(a)

(b)

Fig. 3. Publicly accessible charging stations (a). Slow charging stations (b). Fast charging stations [20].

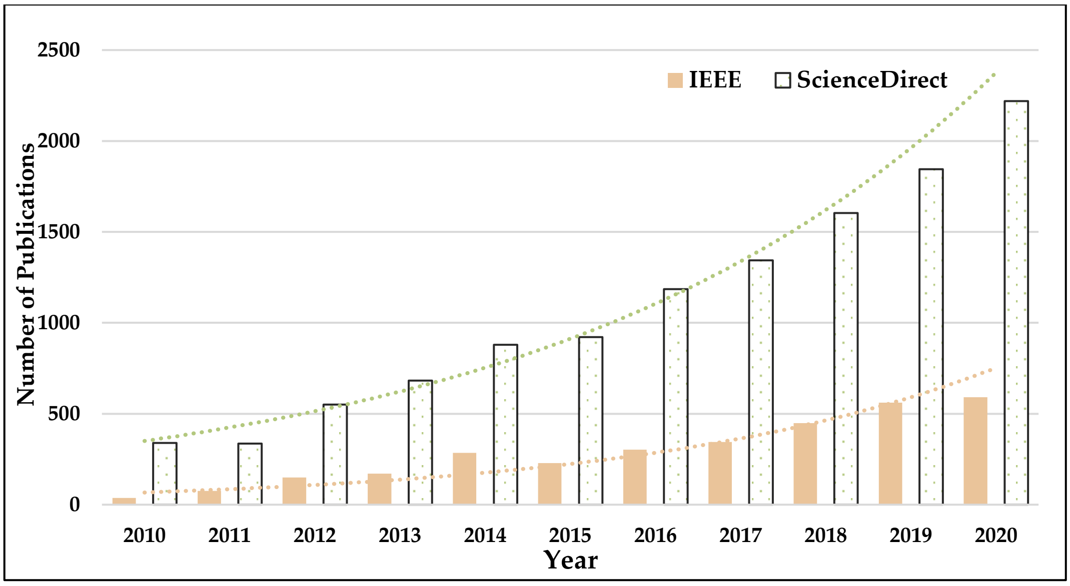


Fig. 4. Number of journal publications on EV charging stations in IEEE and ScienceDirect from 2010 to 2020.

Previously published reviews have given excellent analyses on EV charging generally [21] and EV fast charging with an emphasis on medium voltage (MV) grid [22], however, no review paper has focused on EV fast-charging stations with international standards, industrial patents on EV charging, and emerging technologies such as silicon carbide (SiC) and gallium nitride (GaN) power semiconductor materials based charging stations. Specific design parameters of charging stations have been significantly reviewed in this research area. The work of Sbordone et al. [23] presents design and implementation results of EV charging stations with an energy storage system and different power converters, and Buchroithner et al. [24] have discussed at length about charging stations with flywheel energy storage. Additionally, a review paper from Inci et al. [25] emphasizes only power electronic converters and power controllers for EV charging stations, while Tu et al. [26] have provided a technological overview on power converters for EV charging stations, however, these studies do not provide a detailed analyses. Thus, this review paper addresses a gap in the previous studies by providing a detailed discourse on EV charging stations presented with respect to the following areas:

- A comprehensive review of architectures, AC/DC power converters, and DC/DC power converters of EV charging stations (section II),
- A detailed discussion on international standards (section III),
- Various patents registered by different EV Charger manufacturers (section IV),
- Future trends in power electronic converters using different power semiconductor materials for EV charging stations (section V).
- The key takeaways from this work are summarized in section VI.

2. Architectures

EVs are at the forefront of technological developments that were produced to resolve environmental concerns [27, 28]. EVs have a significant impact on reducing air pollution, particularly in urban areas. The estimation is made to calculate the CO_2 due to transportation, which accounts for 27% of overall CO_2 emission. Owing to EVs promising technology and efficient performance, US and UK have recorded 0.9% and 1.4% EV sales, respectively, during the initial stage of EV penetration. Based on reports by IEA, there is an exponential trend in the number of EVs sold as 2 million EVs in 2016, 40 million in 2020, and 70 million EVs are expected to be sold in 2025 [29-33].

EVs are classified into three types which are battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs). Compared to BEVs, PHEVs and HEVs batteries are charged while the vehicles are operating (running on the road) [34, 35]. BEVs, meanwhile, are charged at charging stations, thus a charging facility is required. Common batteries used in BEVs are lithium-ion batteries, which have relatively higher energy and power density than other battery technologies [36]. The EV charging stations are classified into three types based on voltage levels are explained in detail in this study. Three types of EV charging stations, types of electric vehicles in the market, types of international standard cables are shown in Fig. 5.

There are two major charging systems for EV charging stations, namely: conductive charging system and inductive charging system. Conductive charging methods are more established and widely used than inductive charging technologies, which are still in the research stage and have yet to achieve widespread adoption in the area of electric transportation. Conductive charging utilizes direct contact with the vehicle to transfer the power. This charging technique is both modest and efficient. Conductive charging is broadly divided into two types: onboard charging and off-board charging. Onboard charging is mainly utilized for slow charging with all charging activity held inside the vehicle, while off-board charging offers fast charging. Off-board charging refers to the process of relocating the charger outside the vehicle. The onboard and off-board charging techniques are shown in Fig. 6. Conductive charging is utilized by EVs like Tesla Roadster, Nissan Leaf, Chevy Volt [37].

There are two architectures of Conductive charging stations for EVs, namely: AC charging systems and DC charging systems are discussed in this study. The two architectures for the EV charging station, namely AC charging systems and DC charging systems, are shown in Fig. 7. In AC charging systems, the secondary side of an MV-LV distribution transformer acts as a common AC bus which is connected to the onboard EV charger [22, 38]. AC charging consists of AC/DC converters which are part of onboard charger, whereas, in DC fast-charging systems, a common AC/DC converter is connected to the MV-LV distribution transformer. In DC fast-charging systems, a common AC bus rated at 400-480 V is connected to an off-board AC/DC converter [39, 40]. These power electronic converters provide rectifications, power factor correction, voltage control, isolation, and DC power to the EV port. The AC-bus architecture comprises of various power conversion stages, communicating with DC loads and sources [41]. Common DC bus connects all the EV chargers in DC charging systems, thus providing necessary isolation between the DC bus and EV port using isolated DC/DC converters. This DC-bus charging architecture is usually lower in cost and size and provides better dynamic performance than AC-bus charging stations [27, 42]. However, it is challenging to develop power converters for DC fast-charging stations as DC current does not have natural zero-crossings [43, 44].

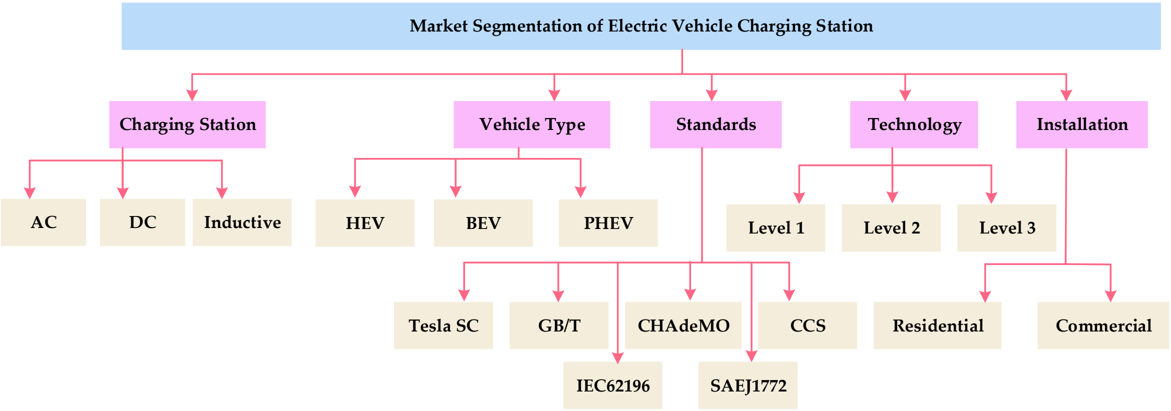


Fig. 5. Market Segmentation of EV charging stations [45-47].

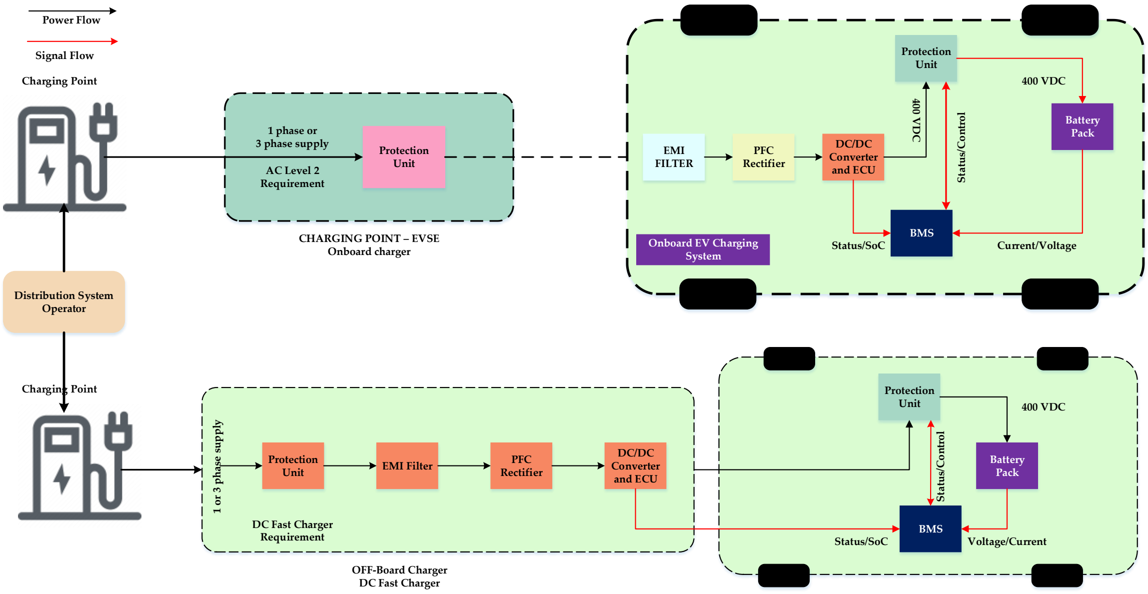
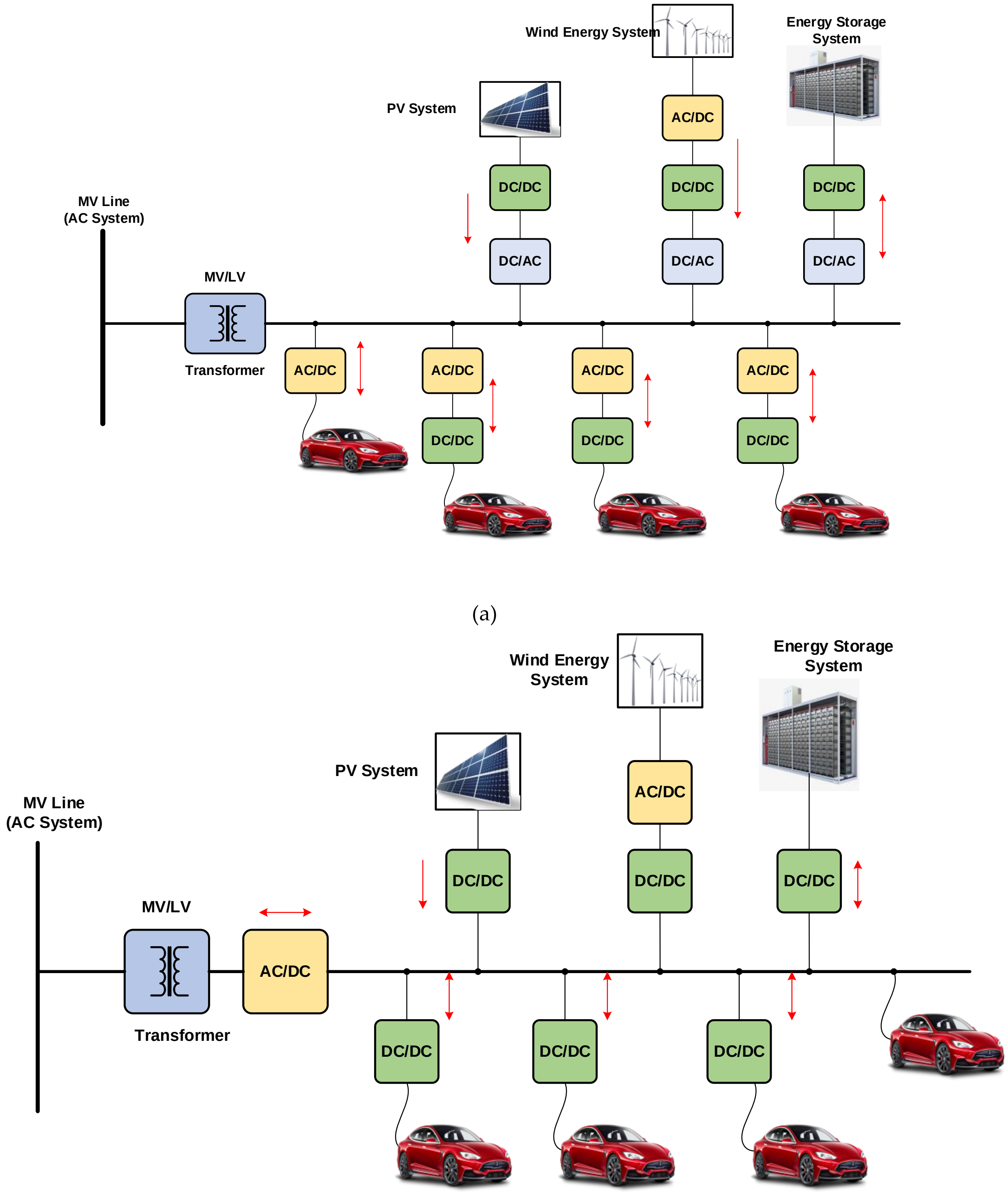


Fig. 6. On-board and off-board conductive charging system.

In inductive or wireless charging technique, the power is transferred through an electromagnetic field without physical contact between the power supply and the vehicle. Electrical safety is a major advantage of inductive charging over conductive charging. However, this mode of charging has many drawbacks, including significant power loss and poor efficiency [48]. Wireless charging enables automatic charging of electric vehicles in three distinct ways, namely: (1) static wireless charging [49, 50], (2) Dynamic charging [51], (3) Quasi – Dynamic charging [52, 53].

The static charging has the potential to avoid risk of electric shock associated with cables and can be installed in appropriate locations such as parking lots and residential garages. The dynamic charging system is capable of consistently charging the vehicle while it is in motion through designated charging tracks on the route, thus extending the EV's driving range and reducing the battery size. The Quasi dynamic charging system charges the vehicle when it is stopped for a short time, such as at traffic light, thus extending the driving range and allowing reduction in energy storage for EVs. Wireless charging technology with a maximum efficiency of 88.5% has enabled inductive or wireless power transfer with 230V AC (Level 2) charging and a power rating of 7.2 kW [54]. There are several technological difficulties involved with wireless charging infrastructure in terms of design, operation, and maintenance [55-57].



(a)

(b)

Fig. 7. Electric vehicle charging stations integration with electrical grid.
(a). AC Charging system. (b) DC Charging system.

Level 1 charging stations are classified as slow charging stations with an output voltage of 120V or 220 V AC, which takes between 10 to 12 hours for a full charge of EV battery. These charging stations are connected to the EV port using a standard J1772 connector [58]. The installation cost for level 1 charging stations ranges from $ 300-$ 1500 [59-61]. Even though installation cost is significantly low, the

EV battery charging time is longer. To overcome the problems faced by level 1 (slow) charging stations, level 2 charging stations are developed to reduce the charging time, also known as accelerated charging stations. Level 2 charging stations are designed for private and public facilities. It takes between 4 to 6 hours to fully charge the battery in the EV. The installation cost for level 2 charging stations ranges from $ 400 - $ 6500, while residential unit cost is $ 2150 [60, 62-64]. The standard connector SAEJ1772 is used for level 2 charging stations on AC side. Though time taken by level 2 charging stations is less than slow charging stations, it is still very long compared to filling fuel such as oil and gas in conventional vehicles. As a result, next level of charging station is introduced, which is known as DC fast-charging stations. The output of DC fast-charging stations is 480V DC or above.

DC fast-charging station takes approximately 30 minutes to charge the battery in the vehicles. The installation cost of DC fast-charging stations will range from $ 30,000 to $ 160,000 [65][61]. Maintenance is another consideration for DC fast-charging stations [66]. Operating cost of DC fast-charging stations is significantly high. The level 3 charging station is located outside the vehicle, whereas level 1 and level 2 charging stations are located on the EVs [67, 68]. High power charging stations can increase load demand and overload local distribution networks during peak hours [69]. When level 2 and level 3 charging stations are in operation, there will be an increase in distribution transformer loss, voltage deviation, harmonic distortion, peak demand, and thermal loading on the distribution systems. Due to the absence of adequate protection precautions, lifetime, reliability, security, and efficiency of the transformer are reduced [70]. Different charging levels classified by power levels, charging time, and vehicle technology based on J1772 standards are tabulated in Table 1.

Table. 1. Different types of charging stations [71, 72]

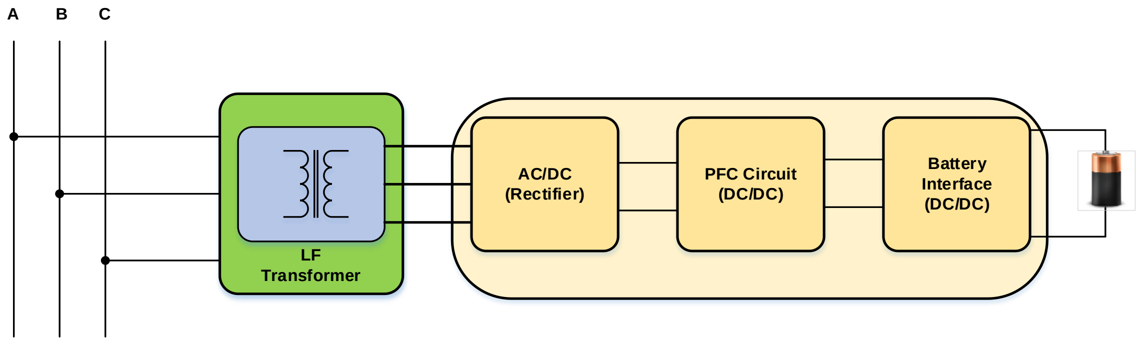
Power Level Types	Charger Location	Typical Use	Energy Supply Interface	Expected Power Levels	Charging Time	Vehicle Technology
Slow Charging Station (Level 1) (120 V AC supply 440 V AC supply)	On-Board Single Phase	Charging at Home or Office	Convenience Outlet	1.4 kW for 12A, 1.9kW for 20A	11- 36 hours 4-11 hours	PHEVs of 5 to 15 kWh EVs of 16 to 50 kWh
Accelerated Charging Station (Level 2) (440V AC supply)	On-Board Single Phase or Three Phase	Charging at Private or Public Outlets	Dedicated EVSE	19.2 kW for 80 A	2 to 3 hours	PHEVs of 5 to 15 kWh EVs of 16 to 30 kWh EVs of 3 to 50 kWh
DC Fast Charging Stations (Level 3)	Off-Board Three Phase	Commercial, Analogous to filling stations	Dedicated EVSE	50kW 100kW	0.4 to 1 hour 0.2 to 0.5 hour	EVs of 20 to 50 kWh

Standard SAE J1772 from Society of Automotive Engineers (SAE) addresses the general physical, electrical, functional, and performance requirements to facilitate conductive charging strategies [73]. AC level 1 and level 2 onboard chargers are developed with a power supply of 120 V and 240 V AC which is capable of generating 1.9 kW and 19.2 kW, respectively. These onboard chargers are ideal for charging throughout the day because of their low power levels. A DC fast charger with an ideal capacity of 50 kW and, more recently, up to 350 kW is constructed for offboard chargers. The DC fast charger controls the battery of the vehicle using isolated power converters outside the vehicle and can deliver adequate charging speed for EVs [74].

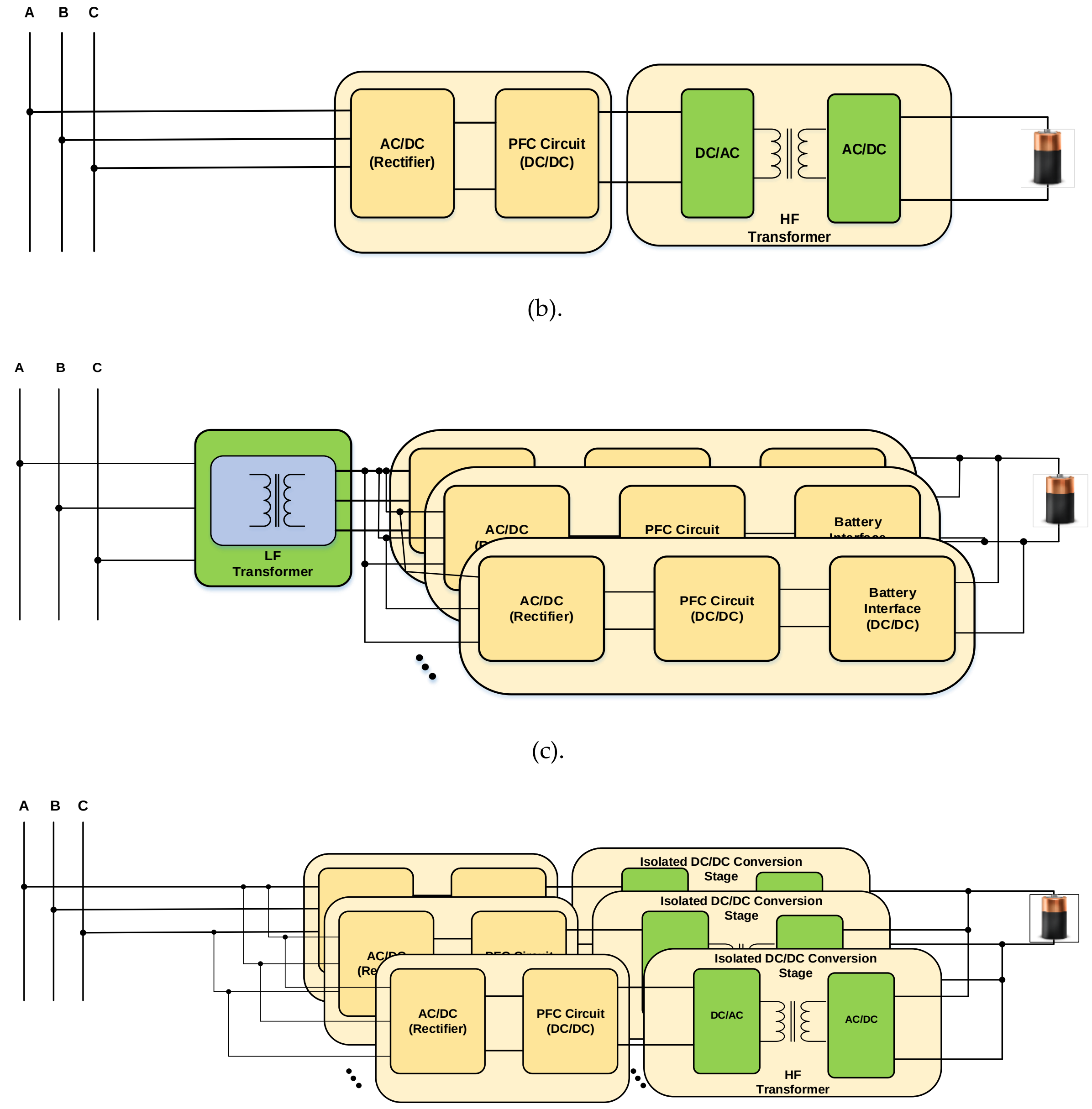
Table. 2. Technical specifications of the DC fast chargers

Manufacturer Model	**ABB**		**Tritium Veefil-RT**	**PHIHONG Integrated Type**	**Tesla Supercharger**	**EVTEC Espresso&charge**
	Terra 53	**Terra HP**				
Power	50 kW	350 kW	50 kW	120 kW	135 kW	150 kW
Supported Protocols	CCS Type 1 CHAdeMO 1.0	SAE combo-1 CHAdeMO 1.2	CCS Type 1 & 2 CHAdeMO 1.0	GB/T	Supercharger	SAE combo-1 CHAdeMO 1.2
Input voltage	480 V_{ac}	400 $V_{ac} \pm 10\%$	380-480 V_{ac} 600-900 V_{dc}	380 $V_{ac} \pm 15\%$ 480 $V_{ac} \pm 15\%$	380-480 V_{ac}	400 $V_{ac} \pm 10\%$
Output voltage	200-500 V 50-500 V	150-920 V	200-500 V 50-500 V	200-750 V	50-410 V	170-500 V
Output current	120 A	375 A	125 A	240 A	330 A	300 A
Peak efficiency	94%	95%	>92%	93.5%	91%	83%
Volume	758 L	1894 L	495 L	591 L	1047 L	1581 L
Weight	400 kg	1340 kg	165 kg	240 kg	600 kg	400 kg
Time to add 200 miles	72 min	10 min	72 min	30 min	27 min	24 min

Table 2 illustrates new technologies for DC fast chargers available in the market. Via two power electronic conversion stages, the DC fast-charger converts AC voltage into DC voltage; a power factor correction converter converts three-phase ac voltage into an intermediate DC voltage, and a mid-DC/DC phase converts intermediate DC voltage to a regulated DC voltage. Galvanic isolation between grid and EV battery is accomplished in one of the two following methods. Firstly, before AC/DC conversion stage, a line-frequency transformer is used for grid isolation, as seen in Fig. 8(a). Second alternative entails utilizing a high-frequency transformer to isolate DC/DC converter, as shown in Fig. 8(b). Multiple equivalent modules are connected in parallel to achieve the optimum performance when a single charger fails to satisfy the specifications of the DC fast-charging systems, as shown in Fig. 8(c) and Fig. 8(d). Tesla supercharger is also known as a “Tesla – Array,” is an example, which consists of 12 parallel modules [75]. Most manufacturers mentioned in Table 2 use a similar strategy.



(a).



(b).

(c).

(d).

Fig. 8. Block diagram of conventional DC fast charger power conversion systems. (a). Single-module charger with a non-isolated DC/DC converter. (b). Single-module charger with an isolated DC/DC converter. (c). Multiple paralleled modules are shown in (a). (d). Multiple paralleled modules are shown in(c).

Various governing boards have established uniform protocols and couplers to ensure the capability for dc fast charger systems. Fig. 9. describes the five standard dc fast charger systems. The IEC-62196 Standard identifies four different couplers for dc fast charger systems [76]. Configuration AA (CHAdeMO Association), Configuration BB (also known as GB/T and usable in China), Configuration CC (Type 1 combined charging system, adopted in North America), Configuration FF (Type 2, integrated charging system, adopted in Europe and Australia). Tesla Inc. charging standard was created and used specifically for Tesla vehicles, a patented design.

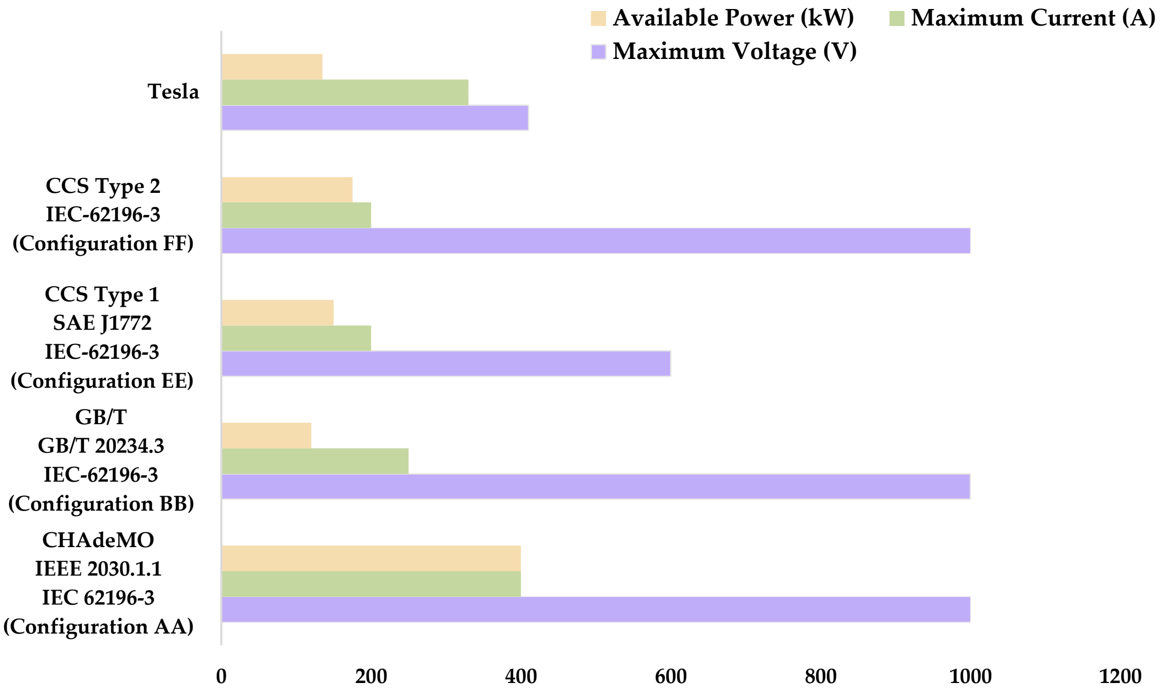


Fig. 9. Various standards for DC fast-charging systems

The significant issues restricting EV acceptance are high vehicle cost, range restrictions, and lack of public charging infrastructures. Although the range for travelling distance can be increased by improving the battery technology, the corresponding rise in vehicle weight and costs limits what is technically feasible – the battery can account for up to 50% of the total BEV expenditure [77]. Enhancing the availability of a highly efficient EV fast-charging network will minimize the range and load issues associated with long-distance travel in EVs [46]. While AC level 1 and level 2 charging stations are ideal for short trips, longer trips require multiple charging resulting in a longer amount of total charging time, which is a hassle for the drivers. An investigation was carried out on 500 Nissan customers to gauge the acceptability of EVs. The major concern of all the 62% of the customers was on the availability of charging facilities, and a further 56% from this segment of customers are concerned about the battery charging time required [78]. Thus, it is more desirable for manufacturers to produce more BEVs to address concerns on efficient EVs with shorter charging times, which is feasible for long journeys.

Battery charging circuit, which is the main component of EVs, is a complex electrical system. Current EV manufacturers produce EVs with 400V batteries. However, Aston Martin and Porsche are leading further to produce EVs with 800V batteries. This state-of-the-art battery system technology makes use of high-current and low-voltage utilization charging components, which can further reduce charging time. The higher voltage facilitates fast charging time as energy $E = V \times I \times t$, where V is voltage, I is current, and t is time. Faster charge time $t = E/V \times I$ can be achieved by increasing the voltage [79, 80]. Therefore, various charging levels for EVs are set to meet dual-purpose requirements of fast and high performance. Table 3 lists major BEV manufacturers such as Audi, Tesla, Nissan, and BMW, comparing the vehicle's efficiency, battery size, driving range, and duration of the full charge of the batteries [81]. Table 3 shows most manufacturers have developed level 2 charging stations with 11 kW AC systems, and it takes an average time of 8 hours to charge the battery in the vehicles.

The rating of DC fast-charging stations is in the range of 44 kW to 250 kW, and the charging time is significantly reduced as it only takes 47 mins and 21 mins, respectively, to fully charge the battery in the vehicles. The efficiency of EV is defined by ratio of battery usage of EV and driving range of EV. Tesla Model 3 has an efficiency of 167 Wh/km, which is 1.4 times higher than efficiency of Jaguar I-Pace EV400, which has efficiency of 232 Wh/km. It shows that Tesla model 3 takes only 167 Wh/km for charging the battery in the vehicle, whereas Jaguar I-Pace EV400 takes 232 Wh/km to charge the battery. Even though fast-charging stations are desirable, fast and ultrafast grid-connected charging systems or extreme fast-charging (XFC) systems are considered volatile loads to the electrical network [82-84]. Ultra fast-charging stations or XFC stations are defined as stations with a charging capability of 350 kW and above [85]. It is challenging to develop an ultrafast-charging system for EVs in rural areas since a robust electrical infrastructure is required [86]. Since the need for ultra-fast charging facilities will rise in the future, these charging stations can be located on major highways between towns[87].

The cost of constructing and installing high-powered electric vehicle supply equipment (EVSE) is a key factor in the performance of ultra-fast charging stations. The cost of constructing ultra-fast charging stations includes upgrading distribution lines, transformers, and other equipment, that increase the operation and maintenance costs of charging infrastructure [88]. An energy storage system (ESS), which acts as a buffer between the electrical grid and the vehicle, that minimizes the need for high maintenance cost improvement. In addition, ESS is advantageous in fast-charging stations because it prevents grid congestion while charging [89]. Multiple fast-charging ports in dedicated locations incur a high cost as the grid has to be expanded, but ESS technologies eliminate the need for grid expansion. ESS significantly reduces the cost of power supply generated by fast-charging by utilizing six 350 kW battery storage systems with chargers, saving $157,000 annually [90].

However, with the cost reduction of batteries, demand for batteries is anticipated to rise 14 times by 2030 as compared to 2018. In comparison with other applications such as ESS and consumer electronics (CE), the demand for EVs is dominating by almost 88%. On the other hand, for China, it is the key factor of the global demand for battery market, leading the demand by 42.7%, followed by 16.9% for the European Union, 13.6% for the United States (US), and 26.8% for the rest of the world.

It is imperative that in the near future, there will be a concern of probable waste of EV batteries due to their rapid proliferation. It is also predicted that the total accumulated battery capacity from used EVs might reach 185.5 GWh per year by 2025, according to a recent report by Bloomberg New Energy Finance. Another study from researchers estimated that the overall second life battery (SLB) capacity might be close to 1000 GWh by 2030, an amount that is akin to the amount of increase in EV sales. Nevertheless, the extensive use of SLB eventually raises several issues, such as the availability of identical SLB features at large scale and difficulties in appropriately analyzing SLBs. However, these problems could be resolved with the rapid expansion of the EVs industry, SLB standards automation of evaluations, and more economic research. The latest standards, UL 1974 and J2997 by SAE, are examples of such standards and are continuously being developed.

Table. 3. Specifications of currently available BEVs [81]

No.	Appearance	EV Model	Car Type	Price* (in USD)	Drive Range (km)	Efficiency (Wh/km)	Battery Capacity (kWh)	Battery Usage (kWh)	Duration for a full charge	
									Level 2 AC Charging	**DC Fast Charging**
1		Audi e-Tron sportback 55 quattro	SUV	39,500	375	231	95.0	86.5	9h15min for 11 kW	26 mins for 155 kW
2		BMW iX3	SUV	44,500	360	206	80.0	74.0	8 hours for 11 kW	27 mins for 150 kW
3		Tesla Model 3	Sedan	42,950	455	167	82.0	76.0	8h15mins for 11 kW	21 mins for 250 kW
4		Hyundai IONIQ Electric	Liftback-Sedan	29,500	250	153	40.4	38.3	6h15mins for 7.2 kW	47 mins for 44 kW
5		Jaguar I-Pace EV400	SUV	69,500	365	232	90.0	84.7	9h15mins for 11 kW	44 mins for 104 kW
6		Kia e-Niro 64 kWh	SUV	27,900	370	173	67.1	64.0	10h30mins for 7.2 kW	44 mins for 77 kW
7		Mercedes EQC 400 4MATIC	SUV	67,900	370	216	85.0	80.0	8h45mins for 11 kW	35 mins for 112 kW
8		Nissan Leaf e+	Hatchback	29,900	325	175	62.0	56.0	10 hours for 6.6 kW	35 mins for 100 kW
9		Porsche Taycan Plus	Sedan	92,000	460	182	93.4	83.7	9 hours for 11 kW	20 mins for 262 kW
10		Volkswagen ID.3 Pro S	Hatchback	36,500	450	171	82.0	77.0	8h15mins for 11 kW	36 mins for 125 kW

Note: The duration of full charge is from 20% SoC to 80% SoC of the Battery in the BEVs.

*The price listed in this table is obtained from manufacturer website (Ex-showroom Price)

2.1 Cost of charging infrastructures

Designing a basic home charger that can cope with more powerful gasoline vehicles and is therefore considerably cheaper while a time-of-use (TOU) energy tariff with reduced costs in peak hours is in effect. More powerful home charging is capital-intensive but comparable with moderately efficient ICEVs and significantly cheaper under TOU scheme [91]. However, developing public charging ports or stations is an issue as it requires considerable funding, supporting regulations, an effective business model, and central government initiatives and interventions in many places. Table 4 demonstrates the cost analysis of level 2 charging stations in different countries. It can be concluded from Table 4 is that basic home charging stations with 3.7 kW cost approximately US $ 500 in US, whereas 7.4 kW charging station, which takes 4 hours to fully charge battery in-vehicle, costs US $ 1000 in Europe and India. In India, cost of 22 kW or more power rating chargers is higher than US or Europe [92]. The level 3 or DC fast-charging stations reduce charging time compared to level 2 charging stations with increased total cost due to expensive equipment and installation costs.

Table. 4. Construction and installation cost of Level 2 charging stations in different countries [92, 93]

Countries (Currency)	Application	Costs	Report
United States (US$, 2017)	Level 2 home charging station	450-1000	RMI (2017)
	Level 2 parking garage	1500-2500	
	Level 2 Curbside	1500-3000	
France, Germany, Italy, Netherland, Spain, UK (Euro, 2017)	3.7 kW residential building charging station	1170-1280	CREARA Analysis (2017)
	7.4 kW non-residential building charging station	1760-2025	
Germany (Euro, 2017)	11 kW to 22 kW two charging port	5000	NPE (2018)
India (US$, 2019)	Bharat charger AC 001-1 points three-phase 415 V 3x3.3 kW	980	ISGF (2018)
	Level 2 AC charging station with 7.2 kW	1050	
	CCS-2-1 three-phase 415 V with 25 kW charging station	9800	

The cost of level 3 charging stations ranges from $ 10,000 - $ 60,000. The cost of DC fast-charging stations in different countries is analyzed and tabulated in Table 5. In Europe, DC fast-charging stations with 100 kW-400 kW power costs € 40,000 - € 60,000 whereas in the US, DC fast-charging stations with 300 kW-600 kW power costs $ 12,000 - $ 30,000 [94]. EVs are expected to become a huge load on power distribution systems and pose problems to the utility with rising EV uptake and ever-increasing charging speeds. An increase in daily peak load and a daily peak load shift occurred in power distribution system due to uncontrolled EV charging causes an overload of distribution transformer and feeder, accelerating aging of the transformer, and high-power loss. [95-97].

Also, distribution system stability, voltage unbalance, and poor power quality is caused by power electronics interface of EV chargers, which retains constant power [98]. One alternative approach to mitigate power demand and reduce the impact on grid due to EV charging is to develop suitable power converters. Power converters are used to mitigate harmonics in the input current, eliminating losses in the system. Consequently, voltage imbalance will be eliminated, and power quality of the system will be improved. Various power converters have been used to mitigate power losses and harmonics in the grid. These power converters are called power factor correction converters [99]. These converters play a significant role in reducing the harmonics and improving the quality of the power in the distribution systems.

Table. 5. Construction and installation cost of DC fast-charging stations in different countries

Countries (Currency)	Application	Costs
United States (US$, 2017)	DC fast-charging station	12,000-30,000
European Union (Euro, 2018)	DC fast-charging stations (20 kW-50 kW)	20,000
	DC fast-charging stations (100 kW – 400 kW)	40,000-60,000

In addition, economic mobility cannot be accomplished before renewable energy sources, such as solar and wind, have been responsible for power generators. ESS is able to store energy from renewable sources intermittently and can be used to charge an EV when required. The charging stations comprise of multiple conversion stages with AC/DC conversion and DC/DC conversion. The first stage is the rectification process, which converts AC voltage into DC voltage, followed by DC/DC converters in the second stage [100]. The conversion of electric power using rectifier is a promising technology used in variable frequency drives (VFD), uninterrupted power supplies (UPS), high voltage DC systems (HVDC), welding power sources, and renewable energy sources such as solar system, wind system, battery energy storage systems (BESS), telecommunication applications, data centers, and EV charging stations. Controlled and uncontrolled power semiconductor devices are used to design unidirectional and bidirectional converters. During the conversion process, power quality is jeopardized, resulting in low power factor at the source side, unbalanced voltage, increased losses, and high total harmonic distortion in the input current [101-105].

Due to the increasing number of different applications utilizing converters, various converter models are typically classified as power factor correction converter, pulse width modulation (PWM) converter, SWISS rectifier, Matrix Converter, and Multi-level Converter. The power quality has declined significantly by using these converters, and it does not meet the requirements based on IEEE standards [101, 103, 104]. The passive filters, active filters, and hybrid filters with conventional converters were introduced to improve the quality of the power at the ac mains [104, 106]. However, the construction and installation of filters are too costly, the size of the system increased, and losses are increased, which reduces the efficiency of the system [107]. Therefore, different converters are proposed to overcome the power quality issues during conversion. Newly introduced converters provide reduced system size and improved efficiency. Moreover, these converters require controllers to control the more complex systems to provide the desired output. Various power factor correction techniques are developed for converters and controllers [108-110]. Different power factor correction controllers are designed to enhance the quality of the power in the grid.

Power provided to the EV is constrained by battery charging, charger ratings, connector, and cable between vehicle and charger. The connector ratings are redefined based on standards, and the CHAdeMO standard is used as it currently supports maximum power capability. To avoid overheating, it needs higher charging current wires with wider diameters. The cable weight for a 50 kW dc fast charger is about 9 kg [111]. Cable with a power rating of 200 kW will weigh more than 22.7 kg with a charging voltage of 400 V. Power transfer at high voltage levels is one method to reduce the cable weight and deliver more power to the vehicle. Cable weight limits the charging capability below 350 kW for 800 V voltage level [88]. Liquid cooling is one of the most effective means of cooling a cable to decrease thermal stress without losing its efficiency for DC fast chargers. Wireless charging is seen on DC fast-charging stations that reduce the need for cables. Other wireless charging benefits provide innate galvanic isolation and ease [112, 113]. However, wireless charging systems have problems, including lower reliability and power density than conductive charging systems [114-116]. The study of wireless charging technologies is beyond the scope of this paper.

2.2 Power converters for charging station

There are three major configurations of power electronic converters for DC fast-charging stations.

1. AC/DC single-phase/three-phase conversion stage with a low power rating for small/large DC fast-charging stations with one or two charging ports reduces the size and cost of AC/DC conversion stage.
2. Unidirectional/Bidirectional AC/DC conversion stage for DC fast-charging stations to provide future cost-effectiveness using a DC fast-charging technology.
3. Isolated DC/DC converter is connected between the common DC bus and EV port for wide variations in input and output voltage range.

Three-phase AC/DC converters are widely used for different applications such as high voltage DC (HVDC) transmission, adjustable speed drives, Uninterrupted Power Supplies (UPS), EV battery charging, electrochemical processes such as electroplating, telecommunication power supplies, high capacity magnetic supplies, high power induction heating equipment, aircraft converters system, plasma power supplies, and converters for renewable energy conversion system including wind and solar energy systems. The common issues arising from AC/DC converter integration in the power grid are harmonic injection, low power factor at ac mains, unbalanced voltage, overloading of the distribution transformer, and ripples in the DC voltage. As a consequence of such issues, when conversion takes place, different industries like designers, manufacturers, and users adopt various standards and guidelines [117-121]. There are multiple ways to mitigate power quality issues using passive filters, active filters, and hybrid filters. Various types of filters are developed to solve power quality issues for low-power and high-power applications. However, for large power applications, filter ratings are similar to converters ratings, which increases cost of the components, losses, and reliability [122]. To solve problems associated with AC/DC converter integration in the power grid, converters must be modified at design stage using passive or active wave shaping of input currents [102, 103, 123-125].

2.2.1 AC/DC conversion stage

AC/DC conversion stages consist of all converters between AC grid and common DC bus. Buck-boost converter (SEPIC Converter) or two-switch boost converter topology requires a common DC bus for low power ratings. Although diode bridge rectifier with boost or buck-boost PFC can produce high power quality with improved power factor, the high conduction losses that are avoided by the bridgeless topologies. However, the fundamental boost converter suffers from common-mode noise relative to the conventional bridge rectifier[126, 127]. Back-to-back bridgeless PFC converters utilize soft switching technologies to minimize switching losses. Totem-pole bridgeless PFC provides an affordable option for low-power applications. With wide band-gap devices such as silicon carbide and gallium nitride, it reduces the losses in reverse recovery induced by silicon MOSFETs [128]. Recently, power converters for high power applications such as welding power sources, EV charging stations, telecommunication applications, and data centers are designed with reduced input harmonics [129]. These known as power factor correction (PFC) converters are developed with or without input and output filters to reduce the number of switches for high-power applications. As a result, rating of the components, size, cost, weight of the converters, input current THD, and DC output voltage ripples are reduced [130]. Harmonics in the input current were minimized, and power factor at AC mains is improved by two loops which are the internal current loop control and outer voltage loop control. Number of switches, THD value, power factor value, number of input and output filters, range of output dc voltage, controller mechanism, advantages, and disadvantages for commonly used converters are summarized in Table 6. To significantly note are the SEPIC converter has only one control switch in its circuit configuration among various power converters tabulated. However, power density of the SEPIC converter-based system is 4 kW/dm^3. It demonstrates that size of the power converter is larger when compared to the Vienna rectifier, which has highest power density of 12 kW/dm^3 among all AC/DC converters. Also, for Vienna rectifier, input current harmonics are less than 5%, which satisfies IEEE-519 standards. With high voltage capability at output side from a three-phase distribution grid, it is ideal choice, more specific for electric vehicle power electronics of the future [131].

- Three-phase single-ended primary-inductor converter (SEPIC converter) [132, 133].
- Bridgeless boost PFC converter [127].
- Totem-pole PFC with Gallium Nitride (GaN) Switches [134].
- Three-phase star connected three switch rectifier [135].
- Three-phase boost rectifier with an inverter network [135].
- Two-switch boost converter with AC side inductors and dual dc-rail output [136].
- Two-switch boost converter with DC side inductors and dc-rail, with a center tap switch [137].
- Three-level center-tap switch rectifier [137].
- Vienna rectifier [138, 139].
- Isolated bidirectional integrated dual three-phase active bridge PFC rectifier [140].
- Three-phase three switch buck - type PWM rectifier [141].
- Three-phase buck + boost - type rectifier [142].
- Integrated active filter matrix-type PFC rectifier [143].
- Isolated integrated active filter matrix-type PFC rectifier [144].
- SWISS rectifier [145].

.

Table. 6. Comparative analysis of different converters

Converter Topologies	**Bridgeless Boost PFC Converter [127]**	**Totem-pole PFC with GaN Switches [134]**	**SEPIC Converter [132, 133]**	**Three-phase star connected Three switch Rectifier [135]**	**3-phase boost rectifier with an inductor network [135]**
Number of PWM Switches	2	4 (two MOSFETs and two GaN devices)	3	3	6
Number of bidirectional Switches	-	-	-	-	-
Number of switches that requires an isolated gate drive	2	4 (two for MOSFETS and two for GaN devices)	3	3	6
Number of ac-side Inductors	2	1	3	3	3
Number of dc-side Inductors	-	-	-	-	-
Output voltage type	Single	Single	Single	Single	Single
Minimum output Voltage (in V)	>1.35V_{LL}	>1.35V_{LL}	>1.35V_{LL}	>1.35V_{LL}	>1.35V_{LL}
Harmonic distortion	~32%	~6.1%	~20%	~6.1%	Low (i.e., <10%)
Control type	Hysteresis, Constant Switching Frequency	Hysteresis, Constant Switching Frequency	Hysteresis, Constant Switching Frequency	Hysteresis, Constant Switching Frequency	Hysteresis, Constant Switching Frequency
EMI filtering	Required, high filtering Effort	Required, low filtering Effort	Required, high filtering Effort	Required, low filtering Effort	Required, small filtering effort
Power density	4 kW/dm^3 @ 22 kW	4 kW/dm^3 @ 22 kW	4 kW/dm^3 @ 22 kW	4 kW/dm^3 @ 22 kW	4 kW/dm^3 @ 22 kW
Input current	Continuous	Continuous	Continuous	Continuous	Continuous
Advantages	- Single switch - Low total component count	- Low harmonic distortion - Low switch conduction loss - Only 3 switches	- Single switch - Low overall component count	- Low harmonic distortion - Only 3 switches	Low Harmonic Distortion
Disadvantages	- Discontinuous input current - High component stresses	- Discontinuous input current - High component Stresses	- High component Stresses	- High component count - High component Stresses	- Very high component count - Six control switches

Converter Topologies	**Two-switch boost converters with AC side inductors and dual dc-rail output [136]**	**Two-switch boost converter with DC side inductors and dual dc-rail, with a center tap switch [137]**	**Three-level center-tap switch rectifier [137]**	**The VIENNA rectifier (three-switch three-level three-phase rectifier) [99, 139]**	**Isolated Bidirectional Integrated Dual Three-Phase Active Bridge PFC Rectifier [140]**
Number PWM Switches	5	5	4	3	24
Number of bidirectional Switches	-	-	-	-	6
Number of switches that requires an isolated gate drive	5	5	4	3	24
Number of ac-side Inductors	3	3	-	3	3
Number of dc-side Inductors	-	2	2	-	-
Output voltage type	Dual	Dual	Dual	Dual	Dual
Minimum output Voltage (in V)	>2.45V_{LL}	>2.45V_{LL}	>2.45V_{LL}	>2.45V_{LL}	>2.45V_{LL}
Harmonic distortion	Low (i.e., <10%)	Low (i.e., <10%)	5 – 10%	~3.2%	<10%
Control type	Hysteresis, Constant Switching Frequency	Hysteresis, Constant Switching Frequency	No reference	Hysteresis, Constant Switching Frequency	PFC controller
EMI filtering	Required, small filtering Effort	Required, low filtering Effort	Required, low filtering effort	Required, low filtering Effort	Required
Power density	4 kW/dm^3 @ 22 kW	8 kW/dm^3 @ 22 kW	8 kW/dm^3 @ 22 kW	14 kW/dm^3 @ 22 kW	8 kW/dm^3 @ 22 kW
Input current	Continuous	Continuous	Continuous	Continuous	Continuous
Advantages	- Low harmonic distortion - Only 2 high-freq. Switches	- Low harmonic distortion - Only 2 high-freq. Switches - Flexible topology	- Low harmonic distortion - Only 2 high-freq. switches	- Low harmonic distortion - Only 2 high-freq. Switches	- Buck-type converter. - Low rating devices - Low harmonics
Disadvantages	- Very high component count - 5 isolated gate Drives	- High component count - 5 isolated gate drives - High output voltage	- 4 isolated gate drives - 360Hz distortion (input current) - High output voltage	- High output voltage	- High component count - High output voltage

Converter Topologies	**Three-Phase Three-Switch Buck-Type PWM Rectifier [141]**	**Three-Phase Buck+ Boost – Type Rectifier [142]**	**Integrated Active Filter Matrix-type PFC rectifier [143]**	**Isolated Integrated Active Filter Matrix-type PFC rectifier [144]**	**SWISS Rectifier [145]**
Number PWM Switches	3	4	16	12	8
Number of bidirectional Switches	-	-	-	-	-
Number of switches that requires an isolated gate drive	3	4	16	12	8
Number of ac-side Inductors	3	-	3	-	3
Number of dc-side Inductors	2	2	1	-	2
Output voltage type	Single	single	Single	Single	Single
Minimum output Voltage (in V)	$>2.45V_{LL}$	$>2.45V_{LL}$	$>2.45V_{LL}$	$>2.45V_{LL}$	$>2.45V_{LL}$
Harmonic distortion	<10%	<10%	<10%	<10%	<10%
Control type	PWM controller	PWM controller	PFC controller	PFC controller	PFC controller
EMI filtering	Required	Required	Required	Required	Required
Power density	8 kW/dm^3 @ 22 kW	8 kW/dm^3 @ 22 kW	4 kW/dm^3 @ 22 kW	4 kW/dm^3 @ 22 kW	4 kW/dm^3 @ 22 kW
Input current	Continuous	Continuous	Continuous	Continuous	Continuous
Advantages	- Buck type converter - Low rating devices are required	Buck+ Boost Converter	- Buck type converter - Low rating devices - Low harmonics	- Buck type converter - Low rating devices - Low harmonics	- Buck type converter - Low rating devices - Low harmonics
Disadvantages	- Number of switches - More losses - Less efficiency	- Number of switches - Complexity in the controller - Less efficiency	- Number of switches - Complexity in the controller - More losses - Less efficiency	- Number of switches - Complexity in the controller - More losses - Less efficiency	- Number of switches - Complexity in the controller - More losses - Less efficiency

2.2.2. DC/DC conversion stage

The DC/DC converters, which may be utilized at both front and rear ends of EV charging systems, are used as a converter in the universal battery charger and renewable-based EV charging systems. This section explains the different topologies of DC/DC converters.

2.2.2.1 DC/DC Converters

The DC/DC converters are used as a battery charger in the rear end of the EV charging systems, and different DC/DC converter topologies are covered in this section. The DC-DC half-bridge converter is operated by buck/boost operating mode, as shown in Fig. 10 (a) [146, 147]. The advantages of this converter are low switching and conduction losses which make the converter higher efficiency. Also, interleaved half-bridge converter and cascaded half-bridge converter have been developed in Fig. 10 (b) and Fig. 10 (c), respectively. The thermal and electrical stress present in the basic half-bridge converter has been reduced by developing a cascaded half-bridge converter and interleaved half-bridge converter [148, 149]. The full-bridge converter is shown in Fig. 10 (d), which achieves zero voltage and current switching operations [150-152]. The transformer present in the full-bridge converter provides isolation between input and output. The higher efficiency under a wide range of output voltage and different load conditions is achieved by the full-bridge converter [153]. As a result, the full-bridge converter is the most favored topology among the four topologies described in this section to act as a battery charger. Table 7 shows the comparison of various DC/DC converter topologies for EV charger.

Table 7. Comparison of DC/DC Charger Topologies

Parameters	**Half-bridge DC/DC Converter**	**Cascaded half-bridge DC/DC Converter**	**Interleaved half-bridge DC/DC Converter**	**Full bridge Converter**
Efficiency	High	High	High	High even under a wide range of output voltage
No. of Switches	2	4	4	1
No. of diodes	2	2	2	7
No. of Inductors	1	1	2	3
Transformer	-	-	-	1
Cost	Low	Moderate	Moderate	High
Weight	Low	Moderate	High	High
Advantage	Low switching and conduction losses	Low thermal and electrical stress	Low switch stress	1. Isolation between input and output 2. Low switching losses
Disadvantage	High thermal loss and high electrical stress	No isolation between input and output	Complex control circuit	Costly and Bulky

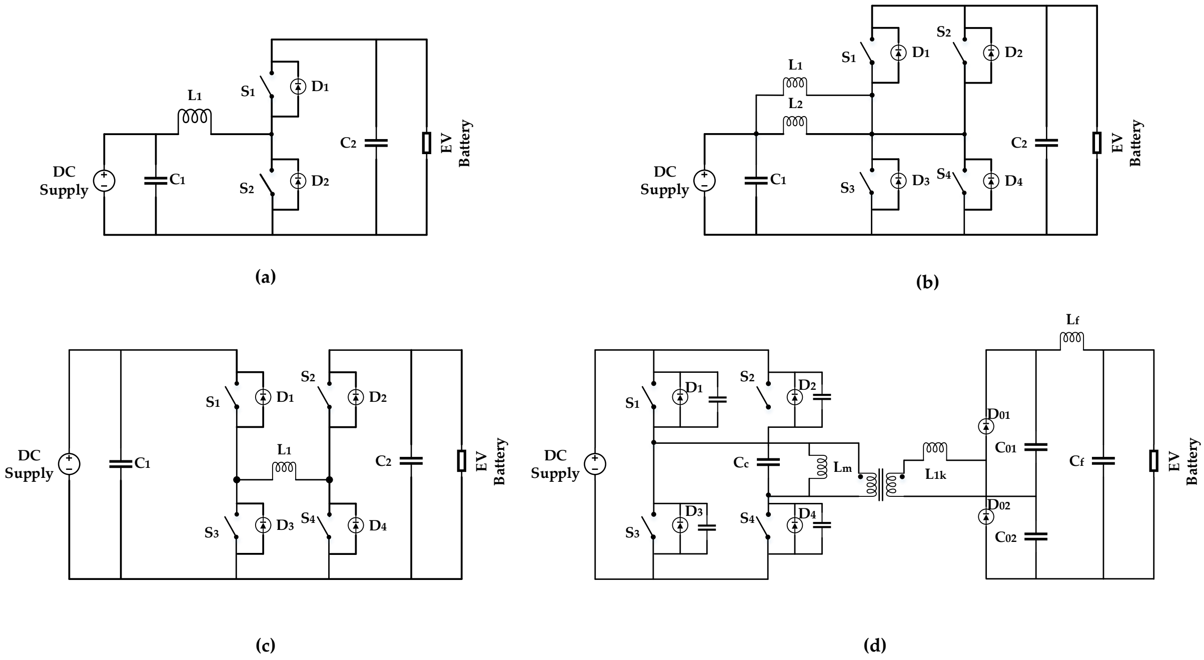


Fig. 10. Topologies of DC/DC charger. (a). Half-bridge converter [148]. (b). Interleaved half-bridge converter [148]. (c). Cascaded half-bridge converter [148]. (d). Full bridge converter with inbuilt transformer [153].

Along with the converters mentioned above, bidirectional DC/DC converters are utilized in EV charging systems to charge the EV battery from the DC bus in vehicle-to-grid (V2G) operating mode. Meanwhile, the power must be transmitted from the EV battery to the grid through V2G mode of operation. Thus, bidirectional DC/DC converters are required for power transmission in both directions, G2V and V2G operating modes. The basic configuration for both G2V and V2G operating modes, a DC/DC converter, must be selected based on the two-quadrant operating condition. Whilst charging, it operates as a buck converter; during discharging, it operates as a boost converter [154]. Various topologies for bidirectional DC/DC converters are proposed in the literature. These topologies are categorized as isolated and non-isolated DC/DC converters discussed in the following section.

2.2.2.2 Isolated DC/DC conversion stage

Renewable energy source interface, battery energy storages, or EV battery charging systems usually have a DC/DC converter followed by AC/DC conversion stage. Galvanic isolation is needed to maintain the insulation between the grid and battery for safety purposes. The battery must not be grounded (i.e., floating with respect to the ground) at all times, and this can be achieved by isolated DC/DC converters.

Phase-shift full-bridge DC/DC converter is a potential converter for application which requires only unidirectional power flow, as shown in Fig. 11. This converter operates in a zero voltage switching (ZVS) concept to reduce the switching loss, as the converter is driven by phase-shifted PWM gate signals [155]. The leakage inductance of an LCL resonance transformer, a parasitic capacitance of the reverse biased diodes, output inductor, turn-off losses of active switches, switching losses in the output diodes, and large ringing effect across the output diodes are the major drawbacks of phase-shift full-bridge DC/DC converter. A passive [156] or active [157] snubber circuit minimizes voltage overshoot and ringing effects of the power converter. As a result, overall losses in the system increases hence reducing overall system efficiency.

A new type of current fed phase-shift full-bridge converter is proposed by transferring inductor from output side to transformer's primary side and connecting Diode Bridge to the output capacitor, which reduces the voltage overshoot and ringing effect in the power converter [158, 159]. However, zero voltage switching range becomes highly load-dependent [160, 161]. The trailing edge pulse width modulation method maintains a wide operating range for EV battery charging [160].

The full-bridge LLC (FB-LLC) resonant converter is another isolated power converter for DC fast charging station. ZVS operation can be achieved over an extensive load range by FB-LLC converter [26, 162]. Unidirectional FB-LLC power converter is shown in Fig. 12. The variable voltage gain is achieved by voltage regulation using voltage division and frequency-dependent impedance. The power converter's narrower gain curve allows a wide output voltage range within a small frequency range. However, efficiency of the power converter is improved by ZVS operation at resonance frequency. The advantages of LLC converters over conventional ZVS converters are short circuit protection, better voltage regulation at light loads, and it has both zero voltage switching and zero current switching (ZCS) properties [163-165].

A bidirectional LLC converter can be used within the DC/DC conversion stage, as shown in Fig. 13. However, the gain curve of an LLC converter is decreased during bidirectional operation (regeneration mode) [166]. LLC converter's efficient operation in bidirectional mode (regenerative mode) is limited due to the wide variations in the operating switching frequency, reducing the efficiency. Since LLC power converters possess variable input and output voltage, the symmetry property is lost. In a bidirectional (regeneration mode), an additional capacitor at the secondary side of a high-frequency transformer in the modified LLC converter to retain the symmetry property [166, 167]. The half-bridge design of LLC converter can be applicable for DC fast-charging stations. [162]. However, resonant capacitor in LLC converter needs to carry high voltage-stress at high power, making component selection a complicated process. In order to overcome the abovementioned problem, a multi-level LLC converter [168], a three-phase LLC converter [169], and an LLC converter with paralleled modules [170] were designed.

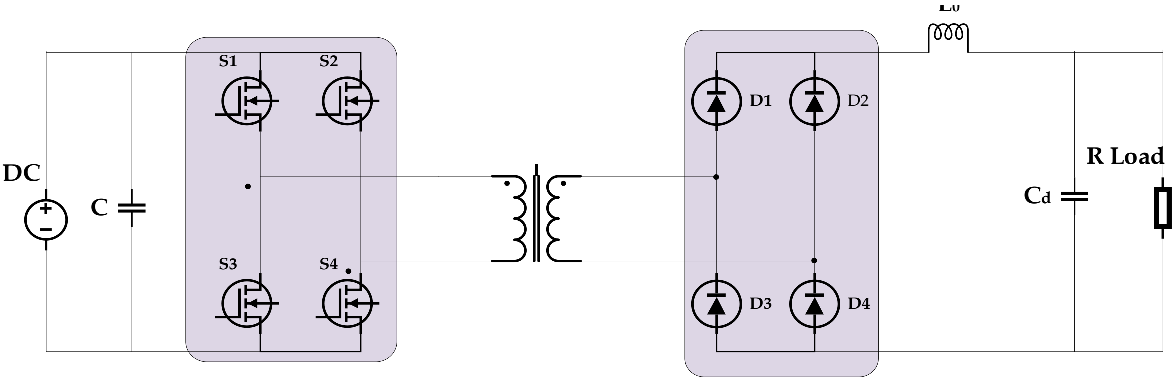


Fig. 11. Phase shift full-bridge converter.

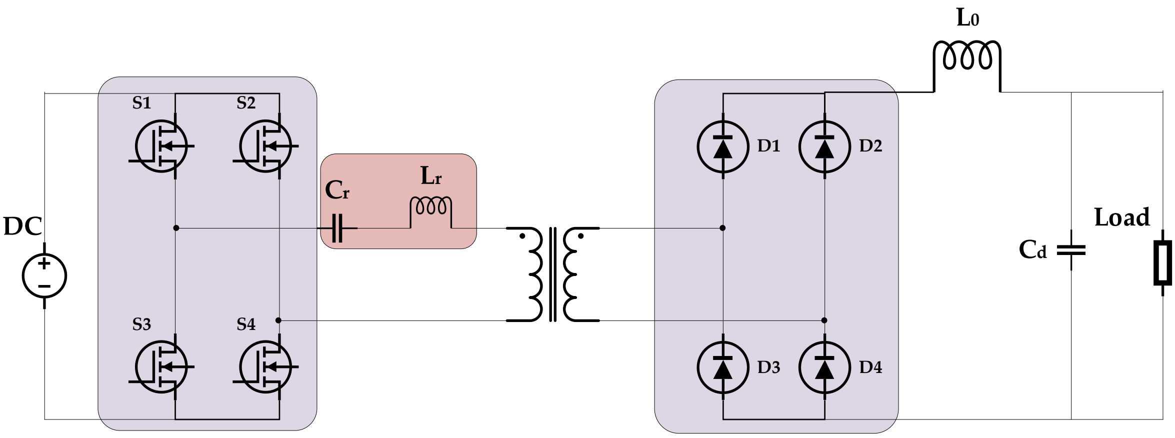


Fig. 12. Unidirectional full-bridge LLC converter.

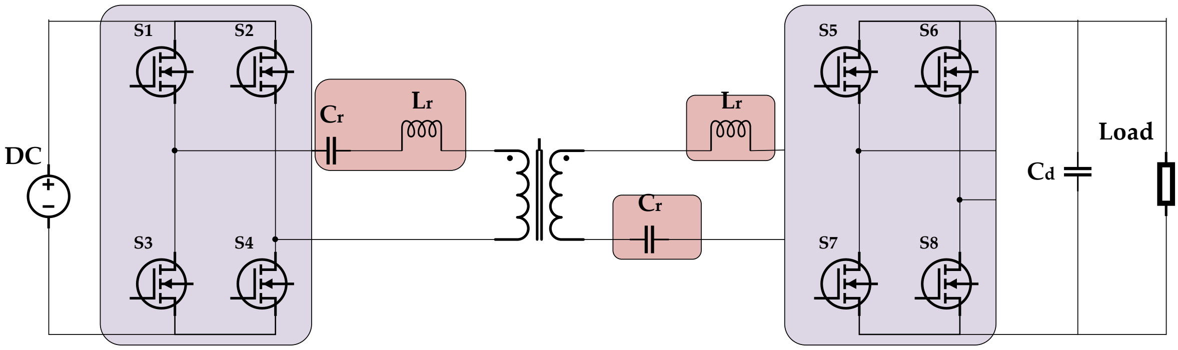


Fig. 13. Bidirectional full-bridge LLC converter.

As Dual Active Bridge (DAB) converter has many advantages, including high power density, high efficiency, less voltage stress on power semiconductor devices, require small size filter components, and low sensitivity to component variations, it is commonly used as DC/DC power converter for EV charging stations [171-176]. With material developments in SiC and GaN-based power semiconductor devices, DAB converters have gained more attention, allowing enhanced performance and improved power density [177, 178]. The power flow path in DAB converter is controlled by adjusting phase shift between primary and secondary voltage using transformer leakage inductance. DAB converter is commonly used in isolated bidirectional DC/DC conversion applications due to its simple structure and soft switching operation, control flexibility, low voltage stress, high efficiency, superior bidirectional power flow capability, as shown in Fig. 14 [179-181].

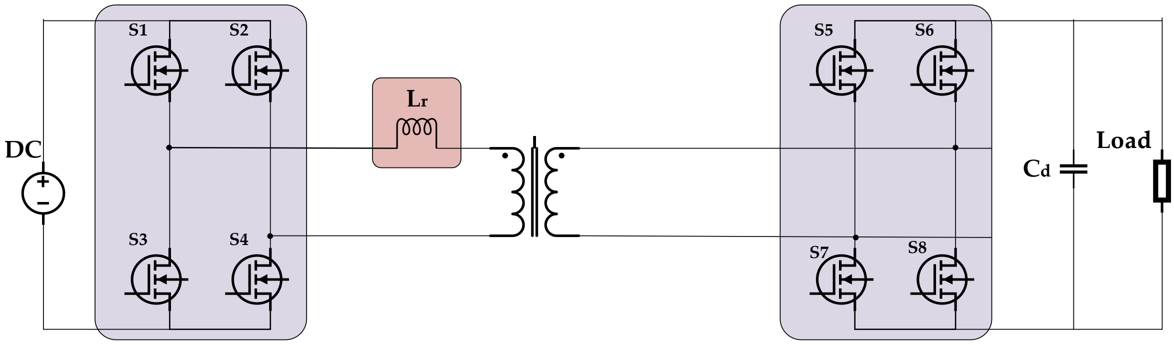


Fig. 14. Dual Active Bridge Converter.

Though the bidirectional converters have many advantages, there are few drawbacks that have to be addressed in future works as follows [182]:

1) Due to the fact that one converter structure is typically utilized to handle both modes of operation, a single controller cannot effectively handle grid voltage and load disturbances in both modes of operation when two converters (buck and boost) are employed.
2) The voltage gain in the bidirectional converter is not symmetrical. This imbalance is caused by the different circuit architecture in both modes. As a consequence, the converter should operate in both modes at different duty ratios, leading to an asymmetric and relatively sluggish control response during power flow transition. This problem is solved to some degree by choosing a battery voltage that is low enough relative to the grid voltage, resulting in a large voltage difference between the two sides. However, it is important to note that this potential difference leads to large current peaks in both switching operations, resulting in high current ripples, especially at high-load levels. This problem is typically solved by choosing a large inductor, which results in a greater capital cost.
3) In both step-up and step-down modes, the switches are modulated synchronously, resulting in higher converter switching losses, which reduces the efficiency of the converter and limits the converter to a lower power density level.

2.2.2.3 Non-isolated DC/DC conversion stage

As AC/DC converters have galvanic isolation, isolated DC/DC converters can be replaced by non-isolated DC/DC converters. This section addresses bidirectional non-isolated power converters as they have two advantages [183]:

- Efficiency of bidirectional converters is much higher than unidirectional power converters due to synchronous rectification.
- The complexity of the control unit is less than the isolated DC/DC converters.

Non-isolated boost converter topology will be connected to the battery in which the battery voltage is smaller than the output voltage of the AC/DC converter. These power converters have only one switch that carries a small current. As a result, the current ripple is increased due to the reduced power rating of the converter. To overcome this, a large inductor size is needed to reduce the current ripple.

A multi-phase interleaved boost converter can be formed by connecting two or more legs in parallel to increase the current carrying capability and reduce the current ripple in battery. An interleaved boost converter is shown in Fig. 15. This topology has a simple structure, good performance, and can be able to increase power capability. The interleaved boost converter is commonly used for EV charging applications because of its benefits [184-187]. It is reported that six-phase legs connected in parallel and interleaved to maximize power rating up to 30 kW for the EV charger prototype [185]. A three-phase interleaved boost converter with 100 kW is designed to work in a discontinuous conduction mode of operation [187]. The size and efficiency of the system can be enhanced by optimizing the inductor design in the converter.

Three-level bidirectional boost converter is also suitable for EV charging stations, which offers better harmonics performance than a conventional boost converter. Three-level bidirectional boost converter is shown in Fig. 16 [117]. The current ripple in a three-level boost converter can be minimized by a low power inductor, which is 0.25 times current ripple in a conventional boost converter. The performance of a conventional boost converter, a three-level boost converter, and a two-phase interleaved converter is reviewed in [188]. It is proven that a three-level boost converter has higher efficiency and smaller magnetic components size compared to other converters. Even though three-level boost converter is better than other boost converters, the electromagnetic interference (EMI) in these converters is high, affecting efficiency and lifetime of battery in the EV [189]. A Flying capacitor converter is another suitable converter for fast charging stations, as shown in Fig. 17. Size of the inductor in this converter is smaller compared to a conventional three-level converter. Power rating of this converter can be enhanced by increasing number of phase legs connected in parallel and interleaved. The most challenging part of this converter is a flying capacitor. A high-level short-circuit protection is required for this converter because of the flying capacitor. The undesired voltage overshoot during the converter's switching operation is caused by larger switching common loops of flying capacitor converter [190]. A 55 kW flying capacitor converter for a fast charger is proposed in [191], which improves the battery voltage by three times, and efficiency of the system is 96.5%.

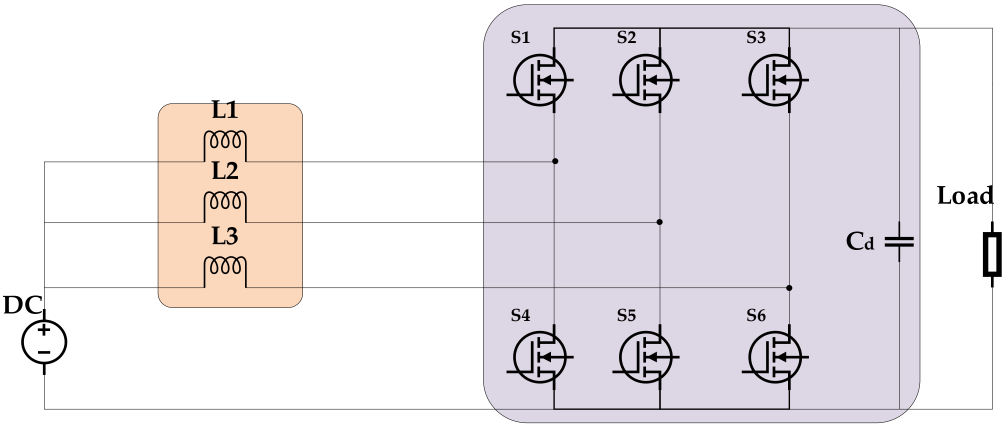


Fig. 15. Multi-phase interleaved boost converter.

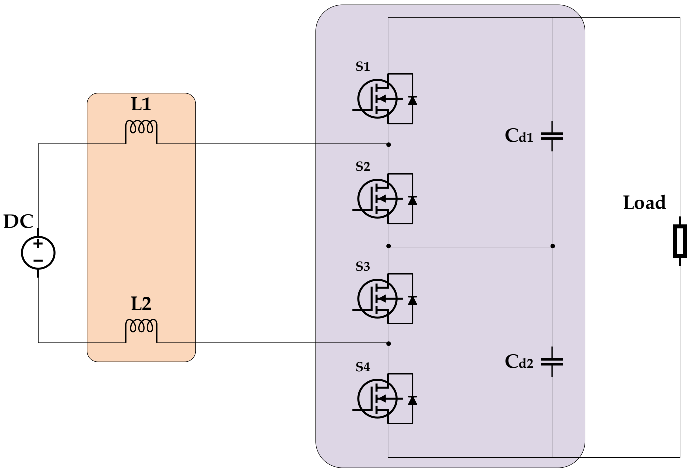


Fig. 16. Three-level bidirectional boost converter.

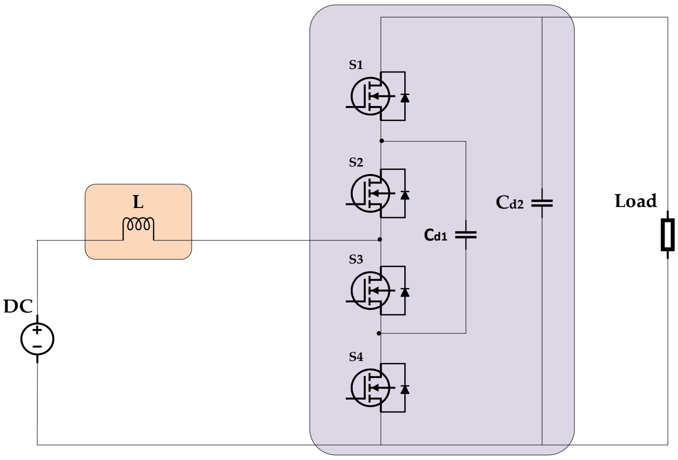


Fig. 17. Three-level flying capacitor converter.

3. International standards

An international standard is a document that is developed through the consensus of experts from many countries and is approved and published by a globally recognized body. It comprises rules, guidelines, processes, or characteristics that allow users to achieve the same outcome time and time again. International standards to meet the needs of EV industry are being established. International standards are well developed to resolve safety, reliability, and interoperability issues of EV industry [192]. Various international standards on EV charging stations are shown in Fig. 18.

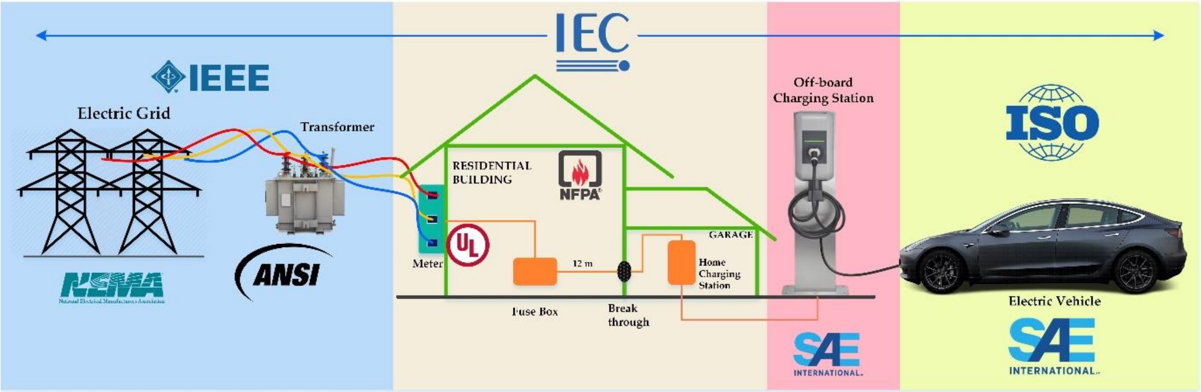


Fig. 18. International standards on EV charging stations

The international standards for EVs are used for making policies for the various industries as follows:

- vehicle manufacturers,
- battery manufacturers,
- vehicle component manufacturers,
- utility companies
- providers of EV charging stations,
- Battery switching station operators
- Code officials/Electrical inspectors
- Service technicians
- First responders
- Insurance companies

Different EV charging standards are provided by Institute of Electrical and Electronics Engineers (IEEE), International Organization for Standardization (ISO), Japan Electric Vehicle Association (JEVA), Underwriters Laboratories (UL), International Electrochemical Commission (IEC), National Electrical Manufacturers Association (NEMA), Standardization Administration of China (SAC), American National Standards Institute (ANSI), National Fire Protection Association (NFPA), and society of automotive engineering (SAE) are tabulated in Table 8. Among various international standards, IEC and SAE standards are two international standards which has developed comprehensive standards for EV charging stations. In this section, IEC and SAE standards for EV charging stations are explored in detail.

Table 8. International standards on EV charging stations

Organization	Standards	Description
IEC **[76]**	IEC 61851	General charging requirements
	IEC 61980	Wireless power transfer (WPT) for EVs
	IEC 62196	Plugs, sockets, and connectors for EV conductive charging technique
SAE **[193]**	J2293	EV and off-board EV supply equipment requirements for charging from utility grid
	J1772	Standard for conductive charging
	J2954	WPT for EVs
	J2894	Power quality requirements and testing procedures for EVs
	J1766, J2344	Safety requirements for charging
IEEE **[194]**	P1547	Standards for different aspects of grid connection of DERs
	P2100.1	WPT and charging system standards
	P2030	Standard for addressing the interoperability of smart grid
	P2030.1	Draft for electrified transportation infrastructure
	519	IEEE recommended practices and Requirements for Harmonic control in Electrical power system
UL **[195]**	UL2231	Requirements for protection devices for EV charging circuits
	UL2251	Requirements for charging plugs, receptacles, and couplers
	UL2202	Requirements for charging system equipment
	UL2594	Requirements for EV supply equipment
	UL1741	Specifications for inverter, converter, charge controller, and output controllers used in power system
	UL 1741 SA	Supplement draft of UL 1741, defining safety requirements of inverters for grid stability
	UL 62109	Safety requirements of inverters used in the grid-connected photovoltaic system
	2750	Outline of investigation for WPT equipment
	9741	Bidirectional EV charging equipment
ANSI/UL **[195]**	2202	Electric vehicle charging equipment (AC/DC)
	2594	Electric vehicle supply equipment (AC/DC)
NFPA **[196]**	70	Safety standards for grid integration of DERs
	70B	Contains safety measurement for electrical equipment
	70E	Electrical safety standards in workplace
ISO **[197]**	17409 : 2015	Electric vehicles – Connection to an external electric power supply – safety requirements and Electrical safety of the EV charging process
	19363: 2020	Electric vehicle – Magnetic field wireless power transfer (WPT) – safety and interoperability requirements
	15118-1: 2013	Communication between EVs and EVSE
JEVA (Japan) and CHAdeMO **[198]**	C601	Charging plugs and receptacles
	D001-002	Battery characteristics of EV
	D701-709	Instructions for battery testing
	G101-105	Fast charging standards

	G106-109	Wireless charging standards
SAC (China) **[199]**	GB/T 20234	Plugs, sockets, and connectors for EV conductive charging
	GB/T 18487.3-2001	AC/DC EV charging station standards
	GB/T 18487.2-2017	EMC requirements for off-board EVSE
	GB/T 27930-2015	Communication protocols standard for off-board chargers and BMS
	GB/T 37293-2019	EV charging/battery swap infrastructure specifications
	QC/T 895-2011	On-board conductive charger standard for EVs
	GB/T 33594-2017	Charging cable specifications for EVs
	GB/T 51313-2018	EV decentralized charging facility standard
	GB/T 50996-2014	EC charging station design specification

3.1 IEC standards

IEC has developed various international standards for EV charging as follows:

- Household and similar electrical appliances – Safety
- Low-voltage electrical installations
- Electric vehicle conductive charging system
- Electric vehicle wireless power transfer (WPT) systems
- Plugs, socket-outlets, vehicle connectors, and vehicle inlets - Conductive charging of electric vehicle
- Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 1: Performance testing
- Wireless power transfer - Management - Part 3: Multiple source control management, Road vehicles - Vehicle to grid communication interface.

IEC standard has developed various standards based on different sections in EV charging stations, as shown in Fig. 19. It consists of components, switches, plugs, connectors of EVs, communication between the cars and EV charging stations, batteries, capacitors, and fuel-cells, Electromagnetic compatibility (EMC), electric accessories, inductive charging, overall electrical safety, and protection from shocks, overvoltage and fires, functional safety of charging stations and EVs, and vehicle – to – grid communication and data protection.

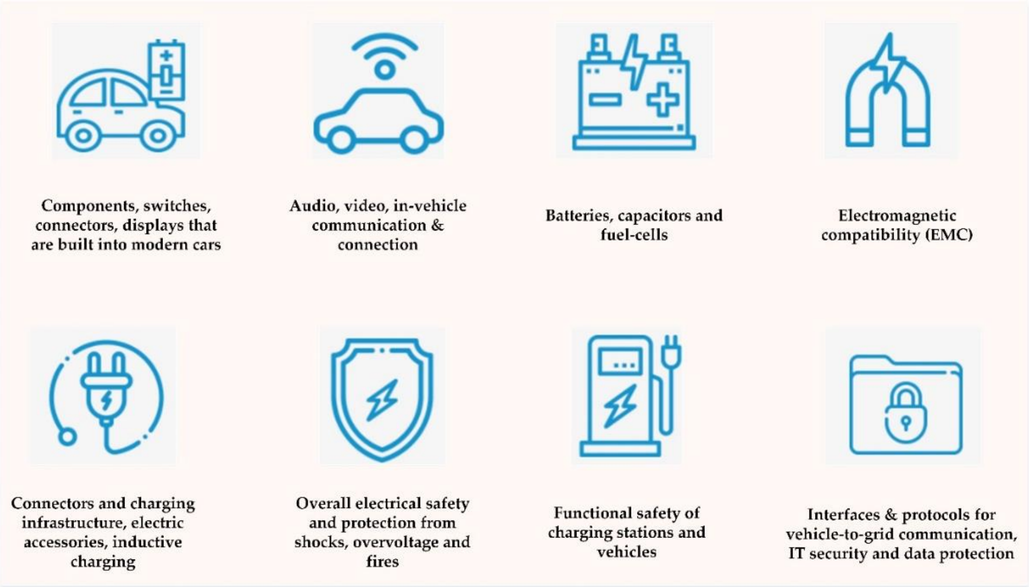


Fig. 19. Different sections of EVs for IEC standard [200]

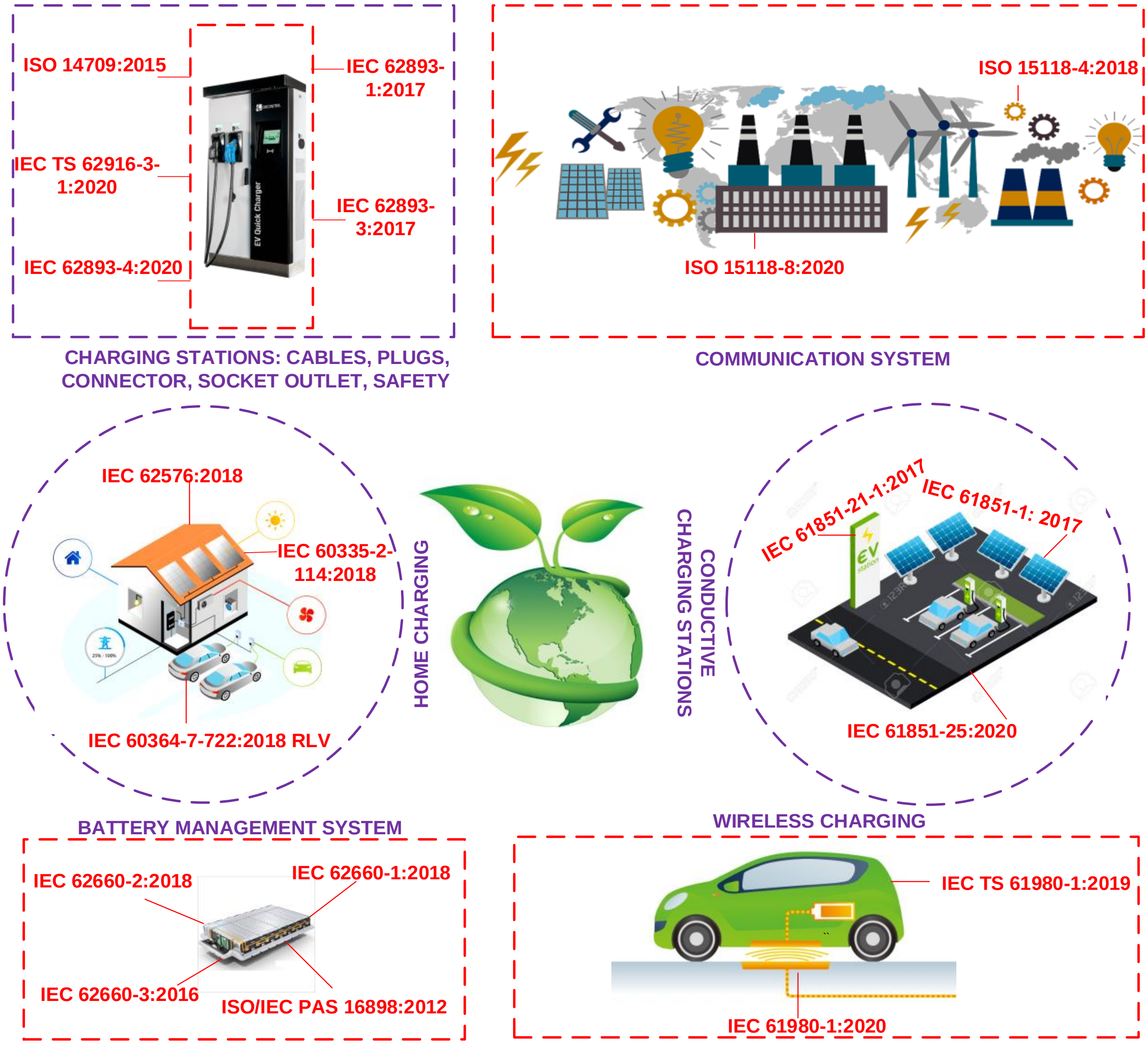


Fig. 20. IEC standards for EV charging stations.

Table 9 provides a list of IEC standards for EV charging stations. Standard IEC 60364-7-722:2018 RLV will describe the energy required for electric vehicles and energy supplied by the electric vehicles. Also, it explains the installation requirements for low voltage electrical equipment for charging stations. The general requirements of conductive charging stations have been described by standard IEC 61851. It includes characteristics and operating conditions of EV supply equipment (EVSE), specification of connection between EVSE and EV, and electrical safety for EVSE. The general requirements for EV wireless power transfer are explained by IEC TS 61980, which covers the characteristics and operating conditions of a supply device, the specification for required level of electrical safety of a supply device, communication between EV device and vehicle to enable and control WPT, efficiency, alignment, and other activities to enable WPT, and specific EMC requirements for a supply device. The performance testing, reliability, abuse testing, and safety requirement for the lithium-ion battery is addressed by IEC 62660. Characteristics and specifications of cables, plugs, socket outlets, vehicle connectors, and vehicle inlet are addressed by IEC TS 62196. It also covers the thermal management of the cables for the EV charging stations. Standard IEC 62440 is intended to guide customers on the safe use of cables in EV charging stations. The communication between vehicle and grid is addressed by ISO 15118. It includes physical layer and data link layer requirements for wireless communication and Network and application protocol conformance tests. Standard ISO 17409 specifies electrical safety for conductive charging stations. Fig. 20 shows an infographic view of IEC standards for EV charging stations.

Table 9. IEC standards for EV charging stations [201]

Designation	Title	Year
IEC 60335-2-114:2018	Household and similar electrical appliances - Safety - Part 2-114: Particular requirements for self-balancing personal transport devices for use with batteries containing alkaline or other non-acid electrolytes	2018
IEC 60364-7-722:2018 RLV	Low-voltage electrical installations - Part 7-722: Requirements for special installations or locations - Supplies for electric vehicles.	2018
IEC 61851-1:2017	Electric vehicle conductive charging system - Part 1: General requirements	2017
IEC 61851-21-1:2017	Electric vehicle conductive charging system - Part 21-1 Electric vehicle on-board charger EMC requirements for conductive connection to AC/DC supply	2017
IEC 61851-25:2020	Electric vehicle conductive charging system - Part 25: DC EV supply equipment where protection relies on electrical separation	2020
IEC 61980-1:2020	Electric vehicle wireless power transfer (WPT) systems - Part 1: General requirements	2020
IEC TS 61980-2:2019	Electric vehicle wireless power transfer (WPT) systems - Part 2: Specific requirements for communication between electric road vehicle (EV) and infrastructure.	2019
IEC TS 62196-3-1:2020	Plugs, socket-outlets, vehicle connectors, and vehicle inlets - Conductive charging of electric vehicles - Part 3-1: Vehicle connector, vehicle inlet, and cable assembly for DC charging intended to be used with a thermal management system	2020
IEC 62576:2018 RLV	Electric double-layer capacitors for use in hybrid electric vehicles - Test methods for electrical characteristics	2018
IEC 62660-1:2018 RLV	Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 1: Performance testing	2018
IEC 62660-2:2018 RLV	Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 2: Reliability and abuse testing	2018
IEC 62660-3:2016	Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 3: Safety requirements	2016
IEC 62827-3:2016	Wireless power transfer - Management - Part 3: Multiple source control management	2016
IEC 62893-1:2017+AMD1:2020 CSV	Charging cables for electric vehicles for rated voltages up to and including 0, 6/1 kV - Part 1: General requirements	2017
IEC 62893-3:2017	Charging cables for electric vehicles for rated voltages up to and including 0,6/1 kV - Part 3: Cables for AC charging according to modes 1, 2, and 3 of IEC 61851-1 of rated voltages up to and including 450/750 V	2017
IEC 62893-4-1:2020	Charging cables for electric vehicles of rated voltages up to and including 0, 6/1 kV - Part 4-1: Cables for DC charging according to mode 4 of IEC 61851-1 - DC charging without use of a thermal management system.	2020
ISO/IEC PAS 16898:2012	Electrically propelled road vehicles -- Dimensions and designation of secondary lithium-ion cells	2012
ISO 15118-8:2020	Road vehicles - Vehicle to grid communication interface - Part 8: Physical layer and data link layer requirements for wireless communication	2020
ISO 15118-4:2018	Road vehicles - Vehicle to grid communication interface - Part 4: Network and application protocol conformance test	2018
ISO 17409:2015	Electrically propelled road vehicles - Connection to an external electric power supply - Safety requirements	2015

3.2 SAE standards

Society of automotive engineering (SAE) has developed various international standards for EV charging stations. The standard covers different sections such as battery performance and power ratings, battery materials testing, battery size, identifications, and packaging, battery recycling, secondary battery use, battery testing methodology, EV hybrid vehicle crash safety, EV charging safety, EV charging, and grid communication, and EV power rating. Table 10 provides a comprehensive list of various SAE standards on EV charging stations. SAE J3073 and SAE J3178 address thermal management and adhesives of EV batteries. Battery size and packaging are addressed in SAE J1797, J3124, J2981, and J3004. Various testing methodology for EV batteries is specified by SAE J2758, J2380. The requirements for EV safety are addressed by SAE J3040, J1766, and J2990. SAE J1718, J2953/1/2/3 addresses safety measurements for EV charging stations. The performance of EV battery and required power rating for EV is specified by SAE J1978, J2758. The vibration durability testing of a single battery of EVs is described by SAE J2380. Standard SAE J2293/1 establishes requirements for electrical energy transfer of EVs and the off-board EVSE. Standard SAE J1798 provides common test and verification methods to determine EV battery module performances. SAE J537 serves as a guide for testing procedures of automotive 12 V storage batteries. SAE J551-5 covers the measurement of magnetic and electric field strengths over the frequency range of 9 kHz to 30 MHz and conductive emissions over the frequency range of 450 kHz to 30 MHZ. The SAE information report SAE J2836-1, 2, 3 establishes communication between plug-in electric vehicle and utility grid, EVSE, and distributed energy resource, respectively. The safety requirement for EV batteries is addressed by SAE J2929, J2464, J3009 [202]. Fig. 21 shows the SAE standard for EV charging stations.

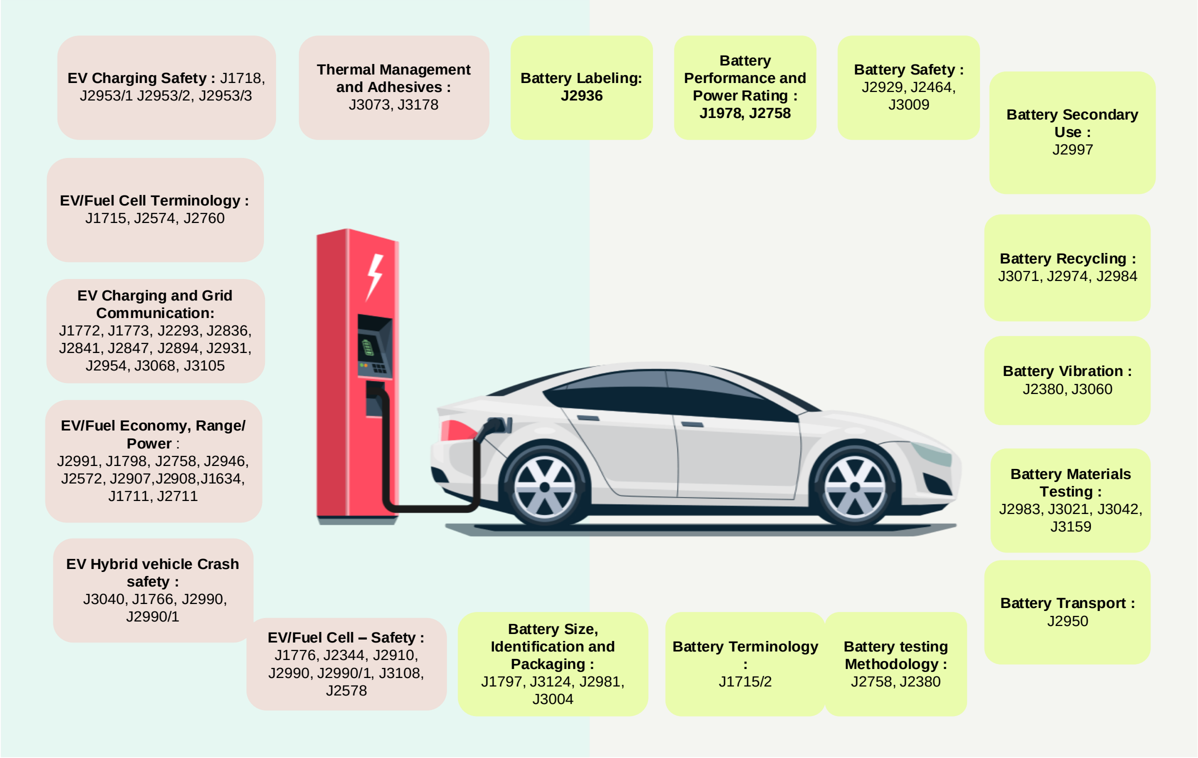


Fig. 21. SAE Standards on EV charging stations.

Table 10. SAE standards for electric vehicle charging stations [202]

Standard	Title	Year
J1715_201410	Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) Terminology	Oct 06, 2014
J1772_201710	SAE Electric Vehicle and Plug-in Hybrid Electric Vehicle Conductive Charge Coupler	Oct 13, 2017
J1773_201406	SAE Electric Vehicle Inductively Coupled Charging	Jun 05, 2014
J2293/1_201402	Energy Transfer System for Electric Vehicles - Part 1: Functional Requirements and System Architectures	Feb 26, 2014
J2293/2_201402	Energy Transfer System for Electric Vehicles - Part 2: Communication Requirements and Network Architecture	Feb 26, 2014
J2344_202010	Guidelines for Electric Vehicle Safety	Oct 13, 2020
J2836/1_201907	Use Cases for Communication Between Plug-in Vehicles and the Utility Grid	Jul 15, 2019
J2836/2_201109	Use Cases for Communication between Plug-in Vehicles and Off-Board DC Charger	Sep 15, 2011
J2836/3_201701	Use Cases for Plug-In Vehicle Communication as a Distributed Energy Resource	Jan 18, 2017
J2836/4_201706	Use Cases for Diagnostic Communication for Plug-in Electric Vehicles	Jun 26, 2017
J2836/5_201505	Use Cases for Customer Communication for Plug-in Electric Vehicles	May 07, 2015
J2836/6_201305	Use Cases for Wireless Charging Communication for Plug-in Electric Vehicles	May 03, 2013
J2836_201807	Instructions for Using Plug-In Electric Vehicle (PEV) Communications, Interoperability, and Security Documents	Jul 18, 2018
J2841_201009	Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data	Sep 21, 2010
J2847/1_201908	Communication for Smart Charging of Plug-in Electric Vehicles Using Smart Energy Profile 2.0	Aug 20, 2019
J2847/2_201504	Communication Between Plug-In Vehicles and Off-Board DC Chargers	Apr 09, 2015
J2847/3_201312	Communication for Plug-in Vehicles as a Distributed Energy Resource	Dec 10, 2013
J2847/6_202009	Communication for Wireless Power Transfer Between Light-Duty Plug-in Electric Vehicles and Wireless EV Charging Stations	Sep 29, 2020
J2894/1_201901	Power Quality Requirements for Plug-In Electric Vehicle Chargers	Jan 23, 2019
J2894/2_201503	Power Quality Test Procedures for Plug-In Electric Vehicle Chargers	Mar 17, 2015
J2907_201802	Performance Characterization of Electrified Powertrain Motor-Drive Subsystem	Feb 12, 2018
J2908_201709	Vehicle Power Test for Electrified Powertrains	Sep 19, 2017
J2931/1_201412	Digital Communications for Plug-in Electric Vehicles	Dec 11, 2014
J2931/4_201410	Broadband PLC Communication for Plug-in Electric Vehicles	Oct 21, 2014
J2931/6_201508	Signaling Communication for Wirelessly Charged Electric Vehicles	Aug 27, 2015
J2931/7_201802	Security for Plug-In Electric Vehicle Communications	Feb 15, 2018
J2953/1_201310	Plug-In Electric Vehicle (PEV) Interoperability with Electric Vehicle Supply Equipment (EVSE)	Oct 07, 2013
J2953/2_201401	Test Procedures for the Plug-In Electric Vehicle (PEV) Interoperability with Electric Vehicle Supply Equipment (EVSE)	Jan 22, 2014
J2954_202010	Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology	Oct 20, 2020
J2990/2_202011	Hybrid and Electric Vehicle Safety Systems Information Report	Nov 04, 2020
J2990_201907	Hybrid and EV First and Second Responder Recommended Practice	Jul 29, 2019
J3068_201804	Electric Vehicle Power Transfer System Using a Three-Phase Capable Coupler	Apr 25, 2018
J3072_201505	Interconnection Requirements for Onboard, Utility-Interactive Inverter Systems	May 19, 2015
J3105/1_202001	Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices Infrastructure-Mounted Pantograph (Cross-Rail) Connection	Jan 20, 2020
J3105/2_202001	Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices Vehicle-Mounted Pantograph (Bus-Up)	Jan 20, 2020
J3105/3_202001	Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices Enclosed Pin and Socket Connection	Jan 20, 2020
J3105_202001	Electric Vehicle Power Transfer System Using Conductive Automated Connection Devices	Jan 20, 2020
J3108_201703	xEV Labels to Assist First and Second Responders, and Others	Mar 02, 2017

4. Recent Trends and Industrial Developments

In 2020, the EV charging station market expanded at a faster pace compared to 2019 [203]. Global EV charging station market is valued approximately USD 5.03 billion in 2020 and is projected to achieve USD 36.87 billion by 2026. Due to rising environmental issues and demand for sustainable energy-efficient transportation, EV market has seen significant expansion. Asia-Pacific is leading the charging station market, followed by Europe. China is the largest EV market in Asia-Pacific and delivered 872,000 units of EVs in 2019 at a rate of 20.8% over the first nine months. In January 2020, Tesla Motors opened an EV manufacturing unit in Shanghai valued USD 2 billion, which can manufacture approximately 3000 EVs per week [204]. Many industries such as Qualcomm, LG Electronics, Apple Inc, Canon, Xerox Corp, Intel Corp, Ericcson Telefon Ab L M, Samsung Electronics Co Ltd, and Sony Corp have registered various patents on EV charging stations. Fig. 22 shows that number of patents in industries are gradually increasing every year. The number of patents on EV fast-charging stations in 2020 is 19,986, which is 1.3 % higher than in 2019 [205].

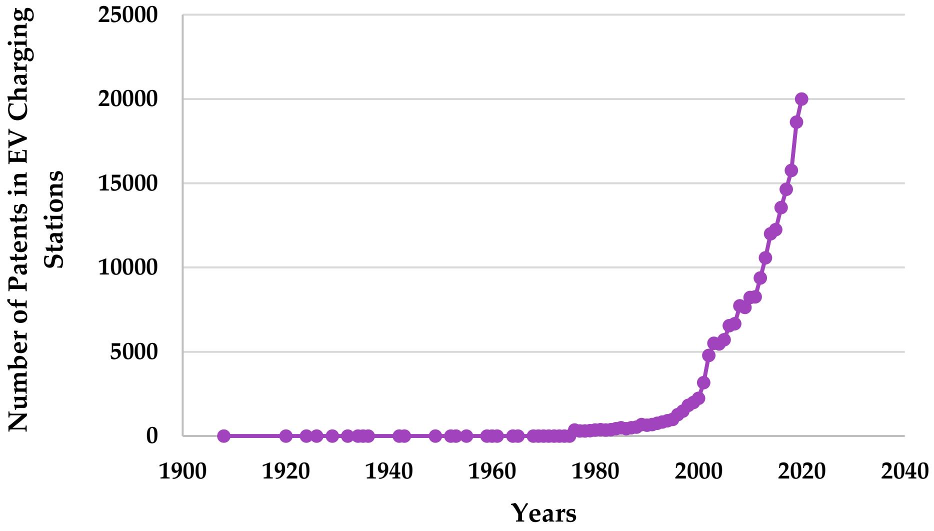


Fig. 22. Number of patents on EV charging stations.

In 2020, most of the manufacturers patented technologies such as wireless communication for EV charging stations and EVs, cyber security threat, navigation on EV charging stations, collecting data from charging stations such as voltage, current, connector type, power level, and battery performance, and a pre-cooling system for battery in EVs. The EVSE is controlled by a microprocessor inside an EV charging station. ABB, one of the leading manufacturers of EV charging stations, has published patents on the protection of EVSE, charging connectors, cables, and loss detection techniques. ABB also patented technology on loss reduction in cable using different cooling systems and proposed new technology to identify cybersecurity threats in EV charging stations.

Samsung Electronics Co. Ltd has proposed a new method to determine the number of EV charging ports for EVs based on the state of the battery, such as a state of charge (SOC) and state of health (SOH). The proposed method helps determine whether fast-charging of the battery is appropriate based on the state of the battery, as shown in Fig. 23.

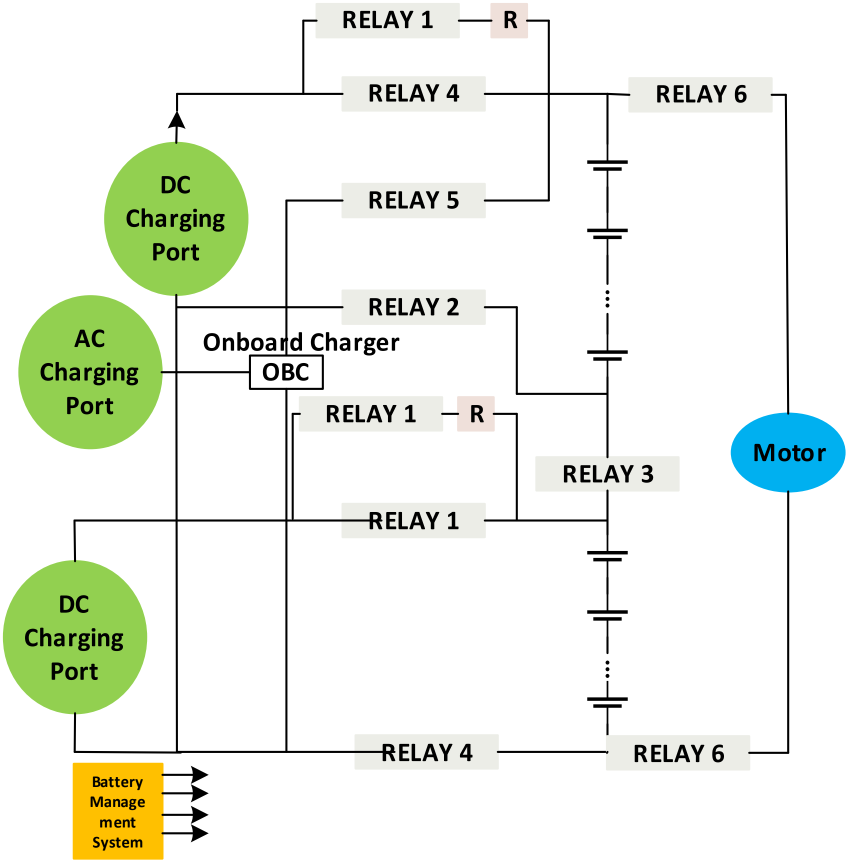


Fig. 23. Battery charging methods and apparatus by Samsung Electronics Co. Ltd [206].

Honda Motor Co. Ltd proposed a new technology known as reservation request system for EV charging stations based on an account associated with an EV. They also offered membership for EV customers to prioritize EV charging stations, which is more beneficial compared to non-member EV owners. Texas Instrumentation Inc has proposed new methods, systems, and apparatus to increase the common-mode transient immunity for isolation devices in EV charging stations. Wireless communication between EV charging station and EV is proposed by Qualcomm Inc, which collects parameters from both EV and charging stations. The proposed system consists of two wireless communication networks. The first communication link transmits a unique EV identifier to charging stations in proximity, whereas the second communication link transmits signals from charging stations to EV. Chargeway Llc has proposed a method to communicate with users to identify the charging options for them and receive charging station queries by accessing charging station database, connection type, and power level of charging stations. General Electric Company proposed an EV charging station location optimization process for autonomous EVs. Porsche Ag., one of the leading manufacturers of EVs and EV charging stations, has proposed home charging stations for their customers. They have proposed new power electronic converter system for EV charging stations with galvanic isolation and two DC/DC converter to improve the system efficiency. Ford Global Technologies Llc has proposed a system that detects the controller of the vehicle and measures the temperature of the battery in the vehicle. They have also implemented a communication system to monitor the charge level, travel route, charge waypoint, environments, location data, vehicle data, and battery performance data. Various patents registered by different manufacturers are listed in Table 11.

Table 11. Various Patents on EV charging stations by different Manufacturers

No.	Title	Applicants	Year	Claim	Ref.
1	Systems and methods for charging station management	Honda Motor Co. Ltd	2021	The system claims a module for reservation requests from an account associated with a vehicle and a schedule module configured to schedule a charging session based on the reservation request and membership benefits	[207]
2	Battery charging method and apparatus	Samsung Electronics Co. Ltd	2021	The claimed charging method includes determining a number of charging ports to charge the battery in EVs based on the state of the battery.	[206]
3	Electric vehicle (EV) fast recharge station and system	The NOCO Company	2020	A first EV charger is receiving power from the secondary electric reservoir. A first EV charger is receiving power from the tertiary electric reservoir.	[208]
4	Fast charging battery pack and methods to charge fast	Nguyen James, Nguyen Jack	2020	Two or three charging ports at one charging station enable fast charging for EVs simultaneously.	[209]
5	Systems and methods for adaptive EV charging	California Inst of Techn	2020	An adaptive EV charging station comprising one or more EVSE processors to collect EV charger parameters from one or more EVSE and control the EV charging routines.	[210]
6	Method and system of predicting recharging of battery of vehicle at charging station and correspondent pre-cooling of the battery using cold storage as the vehicle is being driven to the charging station	Ford Global Technologies Llc	2020	A company claims an automatic detection for a controller of the vehicle in the EV charging stations. Also, the pre-cooling traction system for an EV battery.	[211]
7	Solar energy based mobile electric vehicle fast charger system	Qin Yu, Du Shanshan	2020	Solar energy-based mobile EV charging system installed in a truck which has bidirectional multi-functional power converter system (MFPCS), onboard battery, multiple DC inductors, an alternate power interface, and a universal battery interface.	[212]
8	Vehicle power supply system	Mazda Motor Corporation	2020	The proposed vehicle power supply system controls the charging voltage equal to or more than a predetermined lower limit.	[213]
9	Galvanic isolation in the power electronics system in a charging station or electricity charging station	Porsche Ag	2020	Galvanic isolation in the power electronics system in the EV charging stations. A galvanically isolating DC converter has a high switching frequency and is connected to the rectifier.	[214]
10	Technologies for detecting abnormal activities in an electric vehicle charging station	ABB Schweiz Ag	2020	The technology proposed by the company is used to identify the cybersecurity threat level for the EV charging stations. Also, it protects the EV charging stations from cybersecurity threats.	[215]
11	Method for initializing a DC charging process of a battery by means of an inverter	Porsche Ag	2020	The proposed inverter in EV is connected to the battery in the EV, and an induction motor is connected to the inverter. The proposed system is used to increase the low charging voltage into a higher voltage for charging the battery.	[216]

12	Methods, apparatus, and systems to increase common-mode transient immunity in isolation devices	Texas Instrumentation Inc	2020	Methods, systems, and apparatus to increase common-mode transient immunity in isolation devices	[217]
13	Displaying charging options for an electric vehicle	Chargeway Llc	2019	The system claims that the method to identify the charging option for a user, receiving charging station queries accessing charging stations database, connector type, power level for charging connector.	[218]
14	Protective earth loss detection	ABB Schweiz Ag	2019	The protection of electric vehicle supply equipment, charging connector, charging cable, and loss detection method for electric vehicles is claimed.	[219]
15	Electric vehicle cloud-based optimal charge route estimation	Ford Global Technologies Llc	2019	A hybrid electric vehicle (HEV) from Ford includes a communication unit that monitors the charge level, travel route, and charge waypoint. The system also includes one or more charging stations, environments, location data, vehicle data, and battery performance data.	[220]
16	Adaptive DC charging cable loss compensation for EV charging	ABB Schweiz Ag	2019	An electrical vehicle charging system with DC energy. The proposed system claims reduced cables loss compared to the conventional EV charger.	[221]
17	Use of two DC/DC controllers in the power electronic system of a charging station or electricity charging station	Porsche Ag	2019	The charging stations consist of two DC/DC converters is proposed. First DC/DC converter for connection of the battery to the charging stations and second DC/DC converter connected to the first DC/DC converter for connection of an EV to the charging station.	[222]
18	Charging station system for electric vehicles	Porsche Ag	2018	The company claims home charging stations for electric vehicles.	[223]
19	Systems, methods, and apparatus related to mutual detection and identification of electric vehicle and charging station	Qualcomm Inc	2018	Wireless communication between EV charging stations and EV to collect parameters from EV charger and EVs.	[224]
20	Energy-efficient hands-free electric vehicle charger for autonomous vehicles in uncontrolled environments	General Electric Company	2018	The system provides options for EVs to navigate the desired location of charging stations autonomously based on the charge available in EVs.	[225]
21	Electric vehicle distributed intelligence	Accenture Global Services Limited	2017	The distributed intelligence system helps to receive data from EV charging stations and EVs at distributed locations throughout a power grid. The proposed system analyzes the location of the EV charging station and EV customer and sends commands to the EV customer. Also, the system helps to reallocate power to assets of the power grid to handle fluctuations in power demand based on the analysis.	[226]

5. Near to Future Advancements and Future Roadmap

Wide Band-Gap semiconductors achieve prominence in the automobile industry. Wide Bandgap (WBG) power semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) can be considered more suitable for EV charging applications as they have many advantages over conventional silicon (Si) devices, such as high-power density, high efficiency, and good thermal performance. Fig. 24 shows the properties of Si, SiC, and GaN power semiconductor devices [178]. Both SiC and GaN devices have high breakdown field property, which allows them to operate at low leakage currents and high voltages. Higher frequency operation can be achieved by higher electron mobility and electron saturation velocity of the materials. In addition, increased thermal conductivity ensures that the material is superior for thermally effective conduction. The combination of high thermal conductivity with wide bandgap and high breakdown field makes SiC power semiconductor material suitable for high power applications, particularly for EV charging stations [35]. SiC-based power converter consumes 20 to 30% less circuit area compared to Si-based power converter for EV charging stations. Also, the conduction and switching losses of SiC based power converters are 73% less compared to the power converters made by Si based IGBTs [227]. For example, a 15 kW SiC-based EV charger delivered 33% higher power and 25% smaller area compared to a similarly rated Si-based EV charger [228-230]. Although GaN and SiC devices are known to be the most advanced technologies, other semiconductor materials such as diamond and gallium oxide show significant potential and are currently being investigated in several number of laboratories [231]. These modern semiconductor materials overcome many well-known Si based semiconductor device limitations in terms of blocking voltage, operating temperature, and switching frequency, all of which are linked to the primary physical parameters used in the power system design: critical electric field, band-gap energy, charge carriers, saturation velocity, and thermal conductivity [232-235].

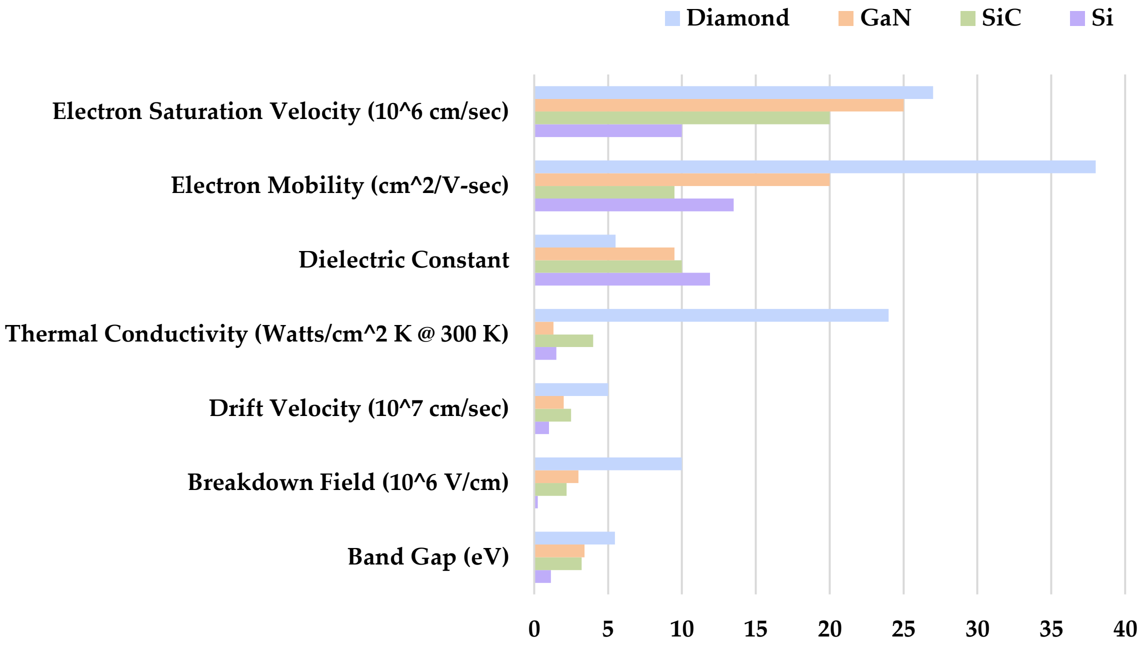


Fig. 24. The material properties of Si, SiC, and GaN power semiconductor.

In recent years SiC and GaN devices have improved their performance, such as lower conduction and switching loss, higher operating temperature, and better parameter stability. They are also used for various high voltage/ high power applications such as electric aircraft, railway, wind energy application, EV/HEV application, welding power sources, Data centers, solar energy applications [227]. Applications of SiC and GaN devices used in various parts of EVs and EV charging stations are shown in Fig. 25. Furthermore, the comparison of weight, volume, and peak efficiency of Si, SiC, and GaN isolation converters were presented in [236]. It shows that the GaN device based isolation converter has reduced volume by 53% weight by 79%, and increased power density by 170%, and increased specific power by 500% compared to Si device based isolation converters is shown in Fig. 26 [236].

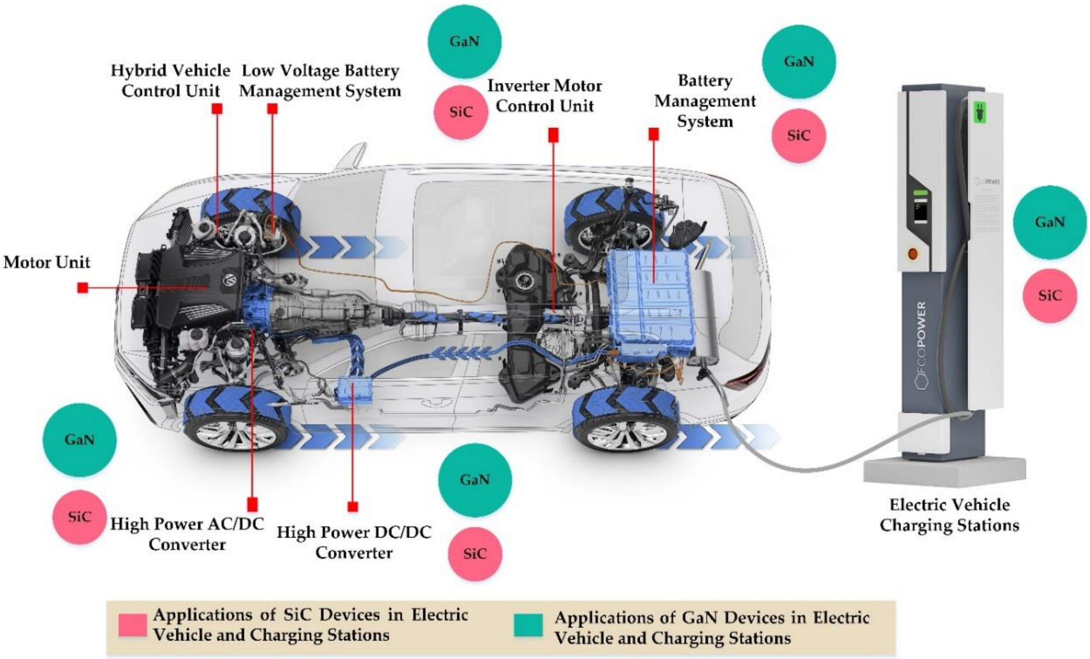


Fig. 25. Applications of SiC and GaN devices in EV charging stations [237].

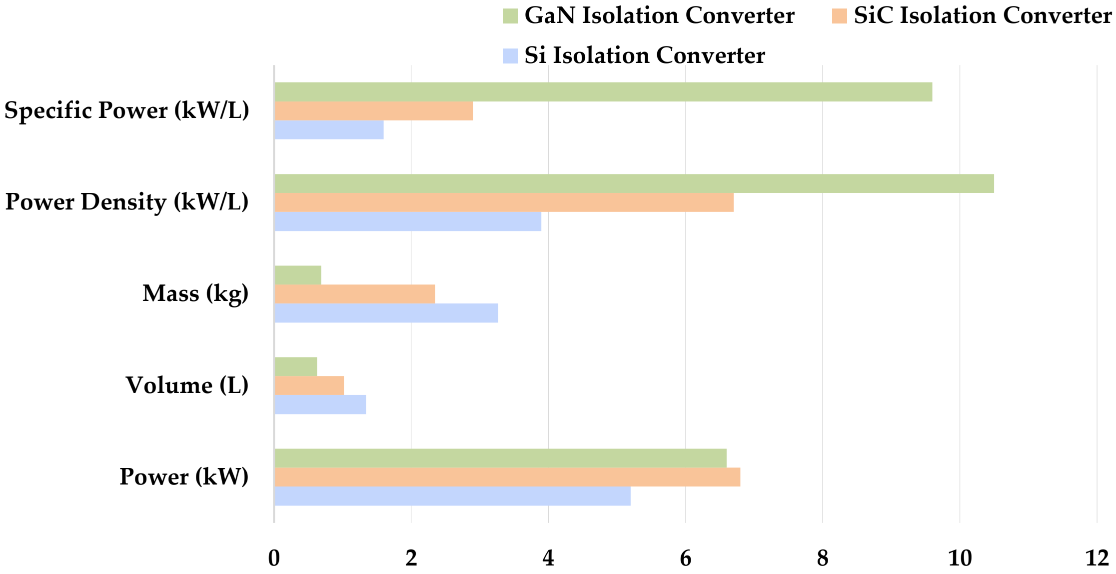


Fig. 26. Comparison of Si, SiC, and GaN based isolation converters [236].

According to the international energy agency study, the number of electric vehicles in the globe is projected to increase gradually and reach its peak in 2050. As shown in Fig. 27, most of the countries have implemented various policies aimed at increasing the number of electric vehicles on the road and achieving net-zero emissions by 2050. Additionally, Fig. 28 illustrates the reduction in greenhouse gas emissions by the transportation sector and the percentage of electricity required for transportation sector by different countries.

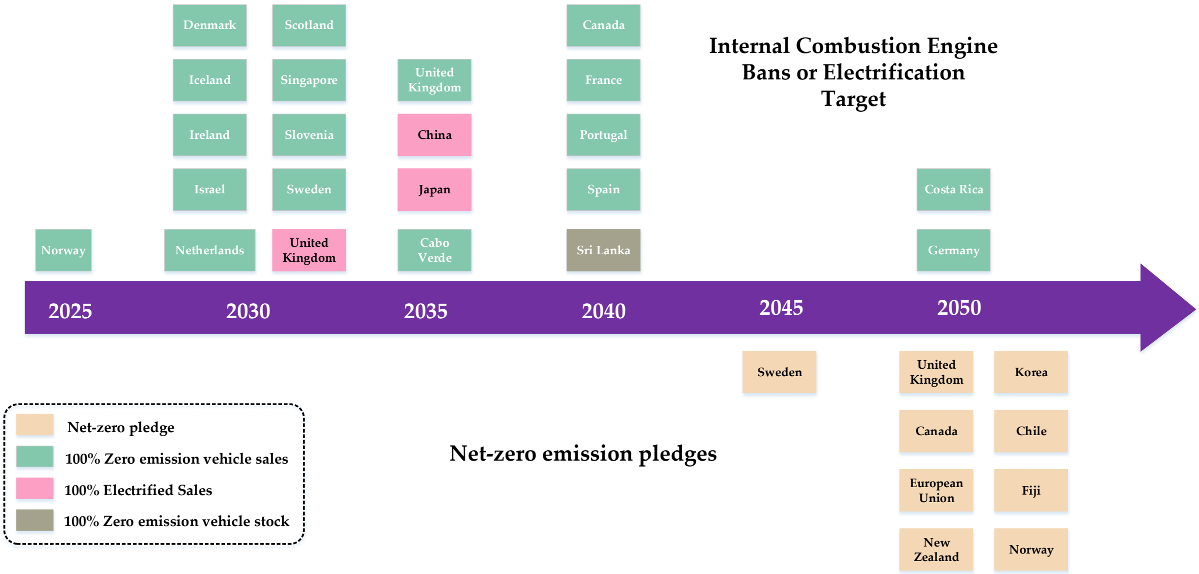


Fig. 27. Future roadmap of electric vehicles in different countries between 2025 and 2050 [238]

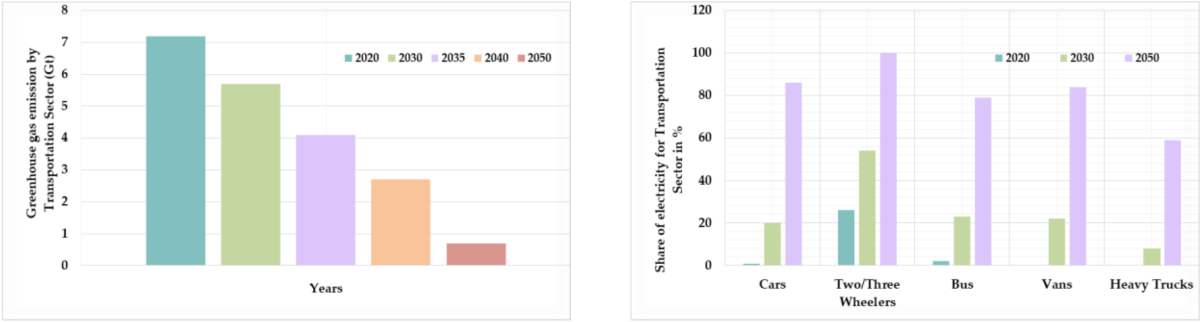


Fig. 28. Greenhouse gas emission reduction by Transportation sector and share of electricity for transportation sector between 2020 and 2050 [238].

6. Conclusions and suggestions

In this paper, a review of EV charging stations based on architectures, standards, AC/DC power converters, DC/DC converters, and future aspects of EV charging stations is presented. With greater sense of awareness on global warming and climate change and to reduce dependency on fossil fuel as the primary source of energy, investment and technological advancement on alternative energy sources are gaining momentum. Transportation, a major economic driver, takes up a major share of global electricity usage. Electrical vehicles (EVs) are poised to become a major automobile choice due to their inherent ability to provide a positive impact by reducing fossil fuel dependency and reducing carbon emission. This lead to a rise in the number of EVs on the road, enabled by government policies in different countries and techno-economic advancements.

EVs have various benefits such as lower fuel and maintenance costs, low noise levels, and are extremely efficient because they use electric motors instead of internal combustion engines. Despite a rise in number of EVs on the road, there is still a shortage of charging infrastructure, and the usual long charging period limits EV usage to regular commutes and short-distance trips. A cost-effective and pervasive charging system is required akin to current-gasoline-driven refueling infrastructure to solve this problem. Analysis shows an incremental trend in research focus pertaining to EV charging stations, and in 2020, a 1.5 % increase in publication is reported compared to the previous year.

Various architectures for EV charging stations are analyzed in detail. Although the installation cost of AC charging stations is low compared to DC fast-charging stations, many automobile manufacturers are installing DC fast charging stations as it takes less time to fully charge EV batteries because of higher power capacity. In addition to that, types of charging stations are chosen based on the requirement of the EV customer. Level 1 charging station is chosen for the range of 0-10kms in the household outlets. The level 2 charging station is chosen for the range of 50kms. The DC fast charging station is chosen for the range of 100-200kms.

Technological challenges and trends in EV fast-charging stations are analyzed in detail. Considering installation cost, charging time, and power levels, three types of charging stations have been analyzed. On average, level 1 (AC charging) and level 2 (AC charging) charging stations take approximately 11 hours and 3 hours, respectively, whereas level 3 (DC fast charging) charging station takes only 30 minutes to fully charge the EV batteries. Furthermore, various models for DC fast-charger, including their power levels, output voltage and current, peak efficiency, volume, weight, and charging time, and different power conversion stages for DC fast-charging stations, are analyzed in detail.

AC/DC charging converters are often facing harmonics and power factor deterioration issues. To overcome these challenges and improve prospects of higher EV penetration, a comprehensive analysis of AC/DC power converters is carried out based on the number of controlled switches, harmonics in input current, and filter requirements. Research shows that the Vienna rectifier is the most promising converter topology for AC/DC conversion stage for EV charging stations due to input current THD of less than 5%, and it has the highest power density of 12 kW/dm^3 among all AC/DC converters. As it has many advantages in the AC/DC conversion stage, Vienna rectifier can be used for high-power applications making it ideal for EV DC fast-charging stations. Furthermore, isolated and non-isolated DC/DC converters for EV charging stations are analyzed in detail. For DC/DC conversion of EV charging stations, an isolated converter is more reliable than non-isolated converters in order to maintain insulation between the grid and battery. Dual Active Bridge converter is the most promising converter for EV charging stations as it has many advantages, including high power density, high efficiency, and small size of filter components.

Various international standards have been established to harmonize EV charging patterns, EV charging safety, power quality, communication between EV and charging stations, and ensuring universal EV acceptance. International Electrochemical Commission (IEC) and Society of Automotive /-Engineers (SAE) standards are widely used as international standards for EVs among them. IEC has provided standards for general requirements for EVs AC/DC conductive power supply system, DC-off board conductive power supply system, battery swap system, and communication systems. Also, it has established various standards for plugs, socket-outlets, vehicle connectors, and vehicle inlets for EV charging systems. In addition, IEC standard has covered requirements for the magnetic field power transfer systems for WPT application. Furthermore, the combination of IEC and ISO has established standards for vehicle–to–grid communication interface systems for EVs. On the other hand, SAE has provided international standards for wireless charging communication, power quality requirements, safety requirements for charging stations and batteries, digital communication, technical reports for automotive battery recycling, and test procedures for EVSE systems.

The introduction of wide band-gap technology such as SiC and GaN has opens up new research and development opportunities to advance high-power bidirectional converters, enabling super-fast-charging or discharging of EV batteries. These devices can enable higher power density for the Si-based EV charger, which can yield promising outcomes for future applications. Various industries such as Samsung Electronics Co. Ltd, ABB Schweiz Ag, Porsche Ag, Ford Global Technologies Llc, Honda Motor Co. Ltd, and Texas instruments have been conducting extensive research on EV charging stations and registered patents on different areas and subsystems, including wireless communication, navigation systems, power converters, cybersecurity protections, pre-cooling system for batteries and renewable energy-based charging systems. Furthermore, a renewable energy-based smart-grid infrastructure can be developed based on ongoing research on various smart charging and discharging methods of EVs. Future research and technical analysis in EV charging stations would be on the following aspects:

- Obtaining high efficiency, low carbon-footprint by replacing fleets of conventional vehicles with EVs in the transportation sector,
- Implementing wireless charging stations for EVs,
- Developing WBG device based high efficiency, high power density AC/DC and DC/DC power converter to overcome limitations of conventional converters,
- Eliminating power quality problems for the grid-connected EV fast-charging stations.

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