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Published in:
Sustainable Energy Technologies and Assessments

DOI (link to publication from Publisher):
10.1016/j.seta.2022.102177

Publication date:
2022

Document Version
Early version, also known as pre-print

Link to publication from Aalborg University

Citation for published version (APA):
Mutarraf, M. U., Guan, Y., Xu, L., Lien Su , C., Vasquez, J. C., & Guerrero, J. M. (2022). Electric cars, ships, and their charging infrastructure – A comprehensive review. *Sustainable Energy Technologies and Assessments*, *52*(Part B), Article 102177. https://doi.org/10.1016/j.seta.2022.102177

Electric Cars, Ships, and their Charging Infrastructure – A Comprehensive Review

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Abstract

The environmental concerns and reduction in fossil fuels have become a major concern due to which a large number of electric and hybrid vehicles are being built to minimize the contribution of greenhouse gas emissions from the transportation sector and to increase the efficiency of the overall vehicles. Electric vehicles (EVs) play an important role in today's development of smarter cities and hence, there is a rapid growth of EVs all around the globe. Although they are found to be environmentally friendly and energy-efficient in comparison with internal combustion engine vehicles but lack of availability of a large number of charging stations at present time limits the use of EVs in the wider perspective. The broader use of EVs would require a huge amount of power from the existing power grids that may hit the prevailing distribution system. Further, charging such EVs equipped with huge battery packs, high power charging stations are essential to charge them at a speed comparable to the conventional oil/gas refueling system. The EVs considered in this study restricts to electric ships and electric cars being two major contributors towards greenhouse gas emissions. In order to address the aforementioned concerns, this study, therefore, presents state-of-the-art based on conventional and current technologies relating to EVs and their charging infrastructure. Further, possible configurations based on the integration of renewable energy sources and stationary energy storage systems are presented to aid the existing power grids. Lastly, challenges along with possible solutions and the future perspective are part of this study.

Keywords: **electric vehicles, electric ships, charger, charging station, charging station topologies, V2G, ultra-fast charging station, smart cities.**

Nomenclature

AEC	All-electric car
AES	All-electric ship
BMS	Battery management system
CAN	Controller area network
CMU	Cell monitoring unit
EC	Electric car
ES	Electric ship
EU	European union
EV	Electric vehicle
GaN	Gallium nitride
GHG	Greenhouse gas
HEC	Hybrid electric car
HES	Hybrid electric ship
ICE	Internal combustion engine
LFT	Line frequency transformer
LV	Low voltage
MMU	Module management unit
MV	Medium voltage
PFC	Power factor correction
PHEC	Plug-in hybrid electric car
PHES	Plug-in hybrid electric ship
PMU	Pack management unit
RES	Renewable energy sources
SiC	Silicon carbide
SoC	State of charge
SST	Solid state transformer
THD	Total harmonic distortion
V2G	Vehicle-to-grid

1. Introduction

Electric vehicles (EVs) have been introduced in the market and more EVs are being launched to promote minimal local emission vehicles, which will bring fringe benefits for the society, environment, and the economy [1]. EVs can be categorized into Electric cars (ECs), electric ships (ESs), Electric buses, Electric trucks, etc., but for the scope of this study, we have considered ECs and ESs only. The increased use of these vehicles over traditional petrol/diesel/liquefied natural gas-based vehicles can provide certain benefits. The first advantage that can be gained is cheaper to run these vehicles as the e-Gallon price of electricity is approximately three times lower as compared to that of gasoline [2] and the threat involved in oil prices instability will also be minimized. Secondly, lesser use of mechanical parts such as fuel injection systems, starter motors,

[☆] This work was supported by VILLUM FONDEN under the VILLUM Investigator Grant (no. 25920): Center for Research on Microgrids (CROM); www.crom.et.aau.dk.
[☆☆] The work of Chun-Lien Su was funded by the Ministry of Science and Technology of Taiwan under Grant MOST 107-2221-E-992-073-MY3.
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radiators, etc., in EVs results in minimizing the maintenance cost and are hence, beneficial for the owners. Thirdly, introducing an electric drive-line in EVs allows storage of the kinetic energy produced by braking that is generally being lost to mechanical brakes in traditional gasoline-equipped vehicles. During the regenerative braking condition, the electric motor turns into power generation mode and the braking energy is redirected back to battery packs [3]. Lastly, conventional vehicles produce emissions, which pollutes the environment and harms the inhabitants living particularly in urban areas. The addition of EVs would therefore help in minimizing emissions from the cities and seaports.

The transportation sector of the European Union (EU), particularly passenger cars, and the maritime sector is a significant contributor towards greenhouse gas (GHG) emissions accounting for approximately 73% and 13% respectively [4]. As for today, the transportation of goods from the marine sector of the EU is more than 90% and there are high chances of a further increase in international trade by sea [5], due to which, the marine sector is responsible for around 2.89 % of the global CO_2 emissions and is expected to increase up to 90-130% by 2050 as compared to 2008 levels [6]. To minimize emissions, the *Paris agreement* aims for both developed and developing countries with a short-term plan to minimize global warming up to 2°C with an intention to further reduce it up to 1.5°C [7]. To follow the regulations, and plans imposed by authorities such as *Paris Agreement* and along with international marine organization to minimize emissions (short term) and/or to achieve net-zero emissions (long term), the EU, therefore, agreed to follow the road map such that the emissions from road transport, houses, and agriculture will be reduced up to 30% by 2030 in comparison with 2005 levels [5]. Additionally, the climate change conference (COP26) held in Glasgow agreed upon the following goals of the *Paris Agreement*, minimizing the use of fossil fuels, rapid transition from coal-based sources to renewable, elimination of activities linked to deforestation, selling of zero-emission new cars by 2040, limiting methane emissions, and moving towards net-zero emissions [8].

Where there are benefits of adopting EVs over conventional vehicles, there are still some challenges and concerns over high cost, weight, the durability of batteries, and lack of a huge number of public charging infrastructures [9]. Although several charging stations are installed in the last few years for ECs but compared to gasoline stations, these numbers are far less and considered as one of the major obstacles in the vast use of EVs [10]. Similarly, the lack of a number of charging stations at seaports limiting the ship owners to build ESs in huge numbers, knowing the fact that at present they are in the range of few hundreds only. Another key challenge is the charging time, which generally takes several minutes in the case of off-board fast-charging stations to several hours in the case of on-board chargers. Hence, there is an utmost need for ultra-fast charging stations both for ECs and ESs that can recharge EVs at a speed equivalent to the conventional gasoline refueling system along with autonomous connection ways to minimize the overall charging process. Along with the aforementioned concerns, several other challenges such as cost, complexity, local grid condition, standardization, policies need to be considered for their increased usage. In addition, the large-scale integration of EVs with the existing distribution network may affect loading as well as the power quality [11]. The increased load demand from the charging infrastructure may result in limiting the grid and can have a negative impact on other customers linked to the grid. Additionally, bi-directional flow of power and difficulties in forecasting load demands (high penetration) requires a complex energy management system [12] such that proper coordination between EV units is required to be taken into account. Therefore, key features energy management systems should address include optimization of charging sequence of plug-in EVs, coordination between different power sources, minimizing cost, maximizing efficiency, dynamic loading, and forecasting of EVs [13].

Several reviews based on either EVs [14–18] or charging infrastructures [19–22] and their technologies are available but none of them covers all these aspects together. This study, therefore, reviews current state-of-the-art technologies for ECs, ESs, and their charging infrastructure and provides possible configurations considering the condition of the local grid and the locality. Additionally, most of the literature covers only ECs and their related technologies whereas ESs and their related technologies owing to be one of the major contributors towards emissions after ECs are not investigated to that extent.

In summary, the main goal of this study is:

- To present an overview of different types of EVs restricting to ships and cars owing to be among the main contributors towards emissions. Further, their different architecture and characteristics are discussed to allow readers to differentiate between these two in terms of their characteristics, voltage, and power levels.
- To provide possible solutions for building charging infrastructure with high power (MW range) and low voltage (LV), i.e., $\leq 1000V$ range. Hence, to cover aspects related to charging infrastructure we have considered the following points:
  - Types of Charger and Charging station.
  - Charging Connectors and Possible ways.
  - Commercially available charging station and incentives.
  - Power electronics stages in a charger/charging station.
  - Galvanic isolation and charging methods.
- To provide vehicle-to-grid (V2G) solution based on conventional line frequency transformer (LFT)-based and modern solid-state transformer (SST)-based solution.
- To come up with possible configurations based on locality and condition of the grid.
- To deliver challenges along with possible solutions and future perspectives.

The rest of the paper is organized as follows. In Section II, the architecture of different vehicles is presented, which includes ECs and ESs. Section III discusses types of charging stations for EVs, connectors, and commercially available charger and charging stations. The power electronics stages for building charging infrastructure along with galvanic isolation and charging methods are part of this section. The modernized smart cities concept where vehicles may provide ancillary services to support local grids, which is also referred to as V2G is presented in Section IV. In section V, possible configurations for building charging infrastructures are presented based on the locality and condition of the local grid. The challenges along with possible solutions and the future perspective are discussed in Section VI, lastly, Section VII concludes the overall study.

2. Architecture of electric vehicles

Owing to the environmental concerns, reduction in fossil fuels, and fluctuation in prices of oil have urged the use of EVs at a larger scale particularly in developed countries. Due to this, several countries such as China, United Kingdom, EU countries, and the USA in the last decade have promoted the further use of EVs and are providing plenty of support from their local and national bodies at consumer levels [44]. The characteristics of such EVs are shown in Table 1.

2.1. Architecture of electric cars

Conventional cars equipped with fossil fuels are generally considered the highest contributor to GHGs emissions around the globe in the transportation sector [45]. To cope with noise pollution, GHGs emissions, and the smooth operation of cars, several types of battery-equipped cars have been introduced in the last decade or so. These cars are mainly classified into All-electric cars (AECs), Hybrid Electric cars (HECs), and Plug-in hybrid electric cars (PHECs) as shown in Fig. 1. Yet another category, i.e., fuel cell-based EVs having lesser emissions and higher efficiency are available but due to the cost of production of hydrogen, infrastructure, and its lesser commercial availability are the reasons behind ignoring in this study. The automobile companies such as Toyota, Honda, Ford, Mitsubishi, BMW, Nissan, and Volkswagen have more models focused on HECs and PHECs whereas Tesla models are concentrated towards AECs.

2.1.1. Architecture of Hybrid electric cars

HECs are equipped with fossil fuel-based internal combustion engines (ICE) along with a battery pack, these cars are currently being the most utilized battery interfaced cars in the world and are considered as the right step towards minimizing emissions from the urban areas. Such types of cars rely on fossil fuel-based resources and battery packs, where installed battery packs are charged using ICE instead of any external charging source as illustrated in Fig. 1 (a). Along with a high-power battery pack, an electric motor is integrated such that to have better energy efficiency and storing the kinetic energy produced by cars [46]. Conventionally, when brakes are applied to slow the speed of a car, kinetic energy is produced during braking, which is generally wasted into heat to decelerate the car, the phenomenon is usually termed as regenerative braking. In modernized HECs, this kinetic energy is sent back to the battery pack and is suitable especially in highly populated urban areas where due to high traffic, brakes are frequently applied. The efficiency of HECs ranges from 15–32% from mild hybrid to strong hybrid cars [14].

2.1.2. Architecture of plug-in hybrid electric cars

PHEC is a type of HEC that is equipped with both a fossil fuels-based engine and battery pack as depicted in Fig. 1 (b). The battery pack in such a type can be charged by an external source placed outside, which is connected with the grid or a standalone charger. This sort of hybrid car can be operated in two modes, all-electric mode, and hybrid mode. The battery pack is considered the primary source of power that is used for comparatively shorter routes. For longer routes, when the state of charge (SoC) of the battery pack is below the certain pre-set limit, the car would switch to a hybrid mode [15]. Therefore, PHEC in an all-electric mode and hybrid mode has better fuel economy in comparison with the conventional fossil fuel equipped cars [16]. Further, the kinetic energy produced by applying brakes can also be stored in the battery.

2.1.3. Architecture of all-electric cars

AECs use battery packs as their sole energy source and electric motors for traction purposes as shown in Fig. 1 (c). AECs have several benefits over conventional ICE cars, HECs, and PHECs such as smooth operation, higher efficiency, absence of noise pollution, and minimal local GHG emissions. The efficiency of AECs is found to be 60–70%, which is quite higher as compared to ICE-based cars that are in the range of 15–18% [17].

2.2. Architecture of electric ships

Similar to ECs, the ESs can also be categorized as all-electric ships (AESs), hybrid electric ships (HESs), and plug-in hybrid electric ships (PHESs). The batteries have developed in the last decade along with an immense reduction in their prices to that extent that it is now being used in ships and are providing several benefits not only limited to the use for emergency purposes but also for powering propulsion and service loads. Along with these benefits they are even capable to be integrated for spinning reserve, peak-shaving purposes, and further helps in the smooth operation.

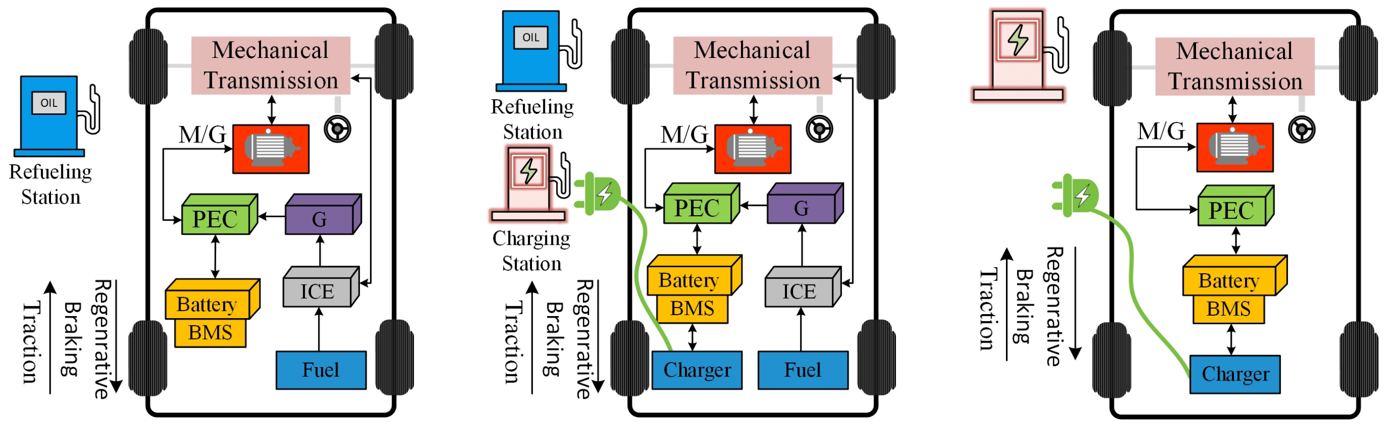
2.2.1. Architecture of hybrid electric ship and Plug-in hybrid electric ship

The type of hybrid ships whose battery packs can not be recharged from any external source is referred to as HESs. The battery packs installed in these kinds of ships are charged using onboard ICE during the low loading operation of the ship and supplies power during high loading conditions. On the other hand, if battery packs installed in a ship can be charged through an external source, i.e., charger/charging station placed on the shore or onboard is termed as PHES. In the case of ships, most

Table 1: Characteristics of different EVs [23, 24]

Features	Types of ECs			Types of Electric Ships	
	HECs	PHECs	AECs	HESs & PHESs	AESs
Energy Sources	• Petrol/Diesel • Battery Pack.	• Petrol/Diesel • Battery Pack.	• Battery Pack. • Ultra-capacitor & Flywheel (Future possibility of use)	• Battery Packs. • MGO/MDO • Methanol • Solar power	• Battery Packs. • Solar power • Ultra-capacitor & Flywheel (Future possibility of use)
Propulsion System	• Internal combustion engine • Electric motor	• Internal combustion engine • Electric motor	• Electric motors	• Internal combustion engine • Electric motors • Hybrid propulsion	• Electric motors
External Energy Source	• Gasoline fuel station	• Gasoline fuel station • Charging station	• Charging station	• Onshore Gasoline fuel station • Onshore Charging station	• Onshore Charging station
Characteristics	• Higher efficiency than ICE cars. • Multiple energy sources • Low emissions • Long-range • Regenerative braking [25] • Battery voltage (12, 48-160, 200-300 V) [26]	• Multiple energy sources • Lesser fuel usage and very low emissions • Regenerative braking. • Battery voltage (300-400 V) [26] • Range (16-80 km) [27]	• Minimal local emissions • Short-range • Rely solely on batteries • Regenerative braking • Battery voltage (Tesla Roadster (375 V) [28], Nissan Leaf (360 V) [29], [30]) • Range (100-640 km)	• Multiple energy sources (Diesel & Battery packs) • Longer routes • Regenerative braking • Battery Voltage (Happiness Ferry (500-720 V)) • Few km range only in All-electric mode.	• Minimal local emissions • Lowest maintenance cost [31] • Lowest noise pollution • Battery Voltage (Ellen (550-750 V)) • Few km only.
Major concerns	• Cost of gasoline • Emissions • Energy sources management • Engine and battery size optimization	• Emissions • Cost of gasoline. • Cost of batteries.	• Cost of battery packs • Range • Lesser public charging stations • High price • Charging time	• Emissions • Cost of battery packs • Charging infrastructure cost	• Cost and life-time of battery packs • Low range (few kms) • High installation cost • Higher cost for building ultra-fast charging infrastructure • Short stay at ports.
Capacity (kWh)	• Toyota Prius (1.3) [32] • Toyota Camry Hybrid (1.6) [32] • Ford Fusion Hybrid (1.4) [32]	• Mitsubishi Outlander PHEV (12) [33]. • Chevrolet Volt (17.1) [34] • Toyota Prius Prime (8.8) [32]	• Nissan LEAF (40) [35], Nissan LEAF e+ (62) [36] • Tesla Model S (85) [37]	• Silent 80 (240) [38] • Scandlines hybrid ferry (1500) [39] • Happiness hybrid ferry (100) [40]	• E-ferry (4300) [41] • Ampere (1090) [42] • Future of the Fjords (2400) [43]

Note: MGO=Marine Gas Oil; MDO=Marine Diesel Oil;



(a) Power train architecture of HEC. (b) Power train architecture of PHEC. (c) Power train architecture of AEC.

Note: PEC=Power electronic converter; BMS= Battery management system; ICE= Internal combustion engine; M/G = Motor/Generator

Figure 1: Power train architectures of ECs.

of the modern era ships these days can be charged through an external source using semi-fast, fast or ultra-fast type of charging, hence, the upcoming discussion is based only on PHES which are somewhat valid for HES also. *Viking Lady*, *Vision* *of the Fjords*, *Viking Princess*, *MS Color Hybrid*, *Happiness Ferry*, and *M/V Prins Richard* are some examples of hybrid ships.

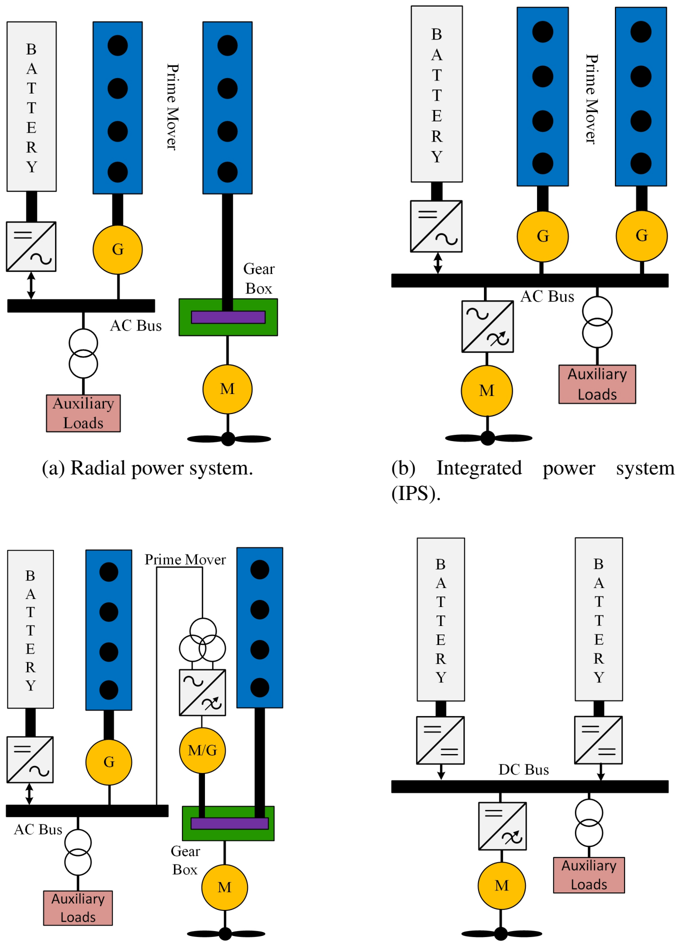
The conventional shipboard power system relied on segregated and radial power systems having independent generation systems for auxiliary and propulsion loads. *SS Canberra* also well known to be an ocean liner is an illustration for such a radial distribution system [47]. The auxiliary system generally supports hotel loads, communication systems, and control systems. Although such a segregated structure has the advantage of lower operation cost, maintenance, and further restrain oscillations in the propulsion system to propagate into the auxiliary power system. However, the radial system has a drawback such that a single point of failure can cause a blackout or may result in severe accidents. Further, under low-speed operation, the resources are not well utilized and hence the efficiency of the overall system decreases as well. The addition of battery units with the auxiliary system as shown in Fig. 2 (a) will help to run diesel engines close to their fuel-efficient point by supplying power during high-loading conditions and absorbing power during low-loading conditions.

Electric propulsion brings fuel savings as ships generally operate on varying operation profiles such that for optimal operation of prime movers, several units are turned on and off during the whole voyage. Such an architecture that uses an integrated power system for both propulsion and auxiliary loads is referred to as an integrated power system (IPS). *Queen Elizabeth II* was the first ocean liner to use an IPS system that was initially steam-powered which later on converted to diesel-electric propulsion for better fuel efficiency [48]. This architecture further helps in increasing efficiency by minimizing the number of prime movers. Further, the integration of battery packs along with the IPS as shown in Fig. 2 (b) will help to minimize fuel consumption and emissions.

On the other hand, the hybridized power system (HPS) as illustrated in Fig. 2 (c), which uses electric and mechanical engines integrated to power auxiliary and propulsion loads helps to optimize the overall fuel efficiency of ships having variable power demands. An assault ship *USS Makin Island* commissioned in 2009 is an illustration of the hybrid power system, which uses diesel-electric propulsion 70% of its operational time at a speed of 12 knots that ultimately increase the fuel efficiency [49]. Diesel-based mechanical propulsion is generally designed to work at the maximum power demand, which is often installed in cargo vessels due to its most of the time operation at a fixed profile [50]. Hence, the mechanical propulsion is less efficient during low speeding times of a ship and therefore electric propulsion can help save a considerable amount of fuel during low power demands [49]. The overall efficiency can be further increased by integrating battery units with this sort of power system such that during low loading operation of ships batteries could act as a purpose of load leveling.

2.2.2. Architecture of all-electric ship

The increased environmental concerns and fuel economy have imposed the ship's industry to quest for fuel-efficient and minimal emission solutions. Hence, AES is introduced, which



(a) Radial power system.

(b) Integrated power system (IPS).

(c) Hybrid power system (HPS).

(d) All-electric ships with IPS.

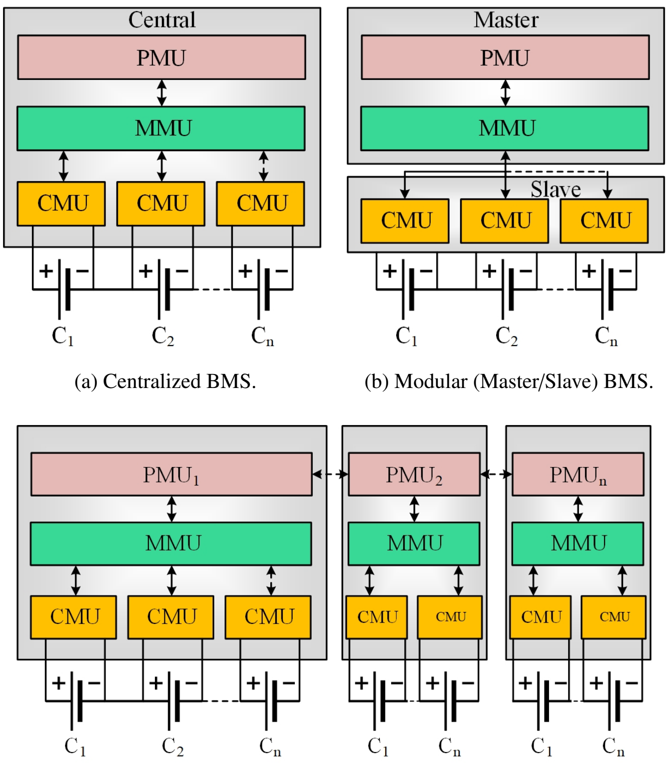
Figure 2: Architecture of ESs.

uses battery units as their sole energy source and electric motors for traction purposes as shown in Fig. 2 (d). AES will provide several benefits over other types of hybrid ships equipped with battery and diesel engines such as smooth operation, higher efficiency, absence of noise pollution, and minimal local GHG emissions. *MV Ampere* is the first battery-equipped ferry with an installed capacity of around 1 MW, which was set in operation in 2015 between Lavik and Oppedal. *Ellen*, *Future of the Fjords*, *MF Tycho Brahe*, *Movitz*, *Aditya* are some of the ESs that use battery packs as their sole energy source.

2.3. Battery management system

In the transportation sector, most EVs are interfaced with Li-ion battery modules where each module compromises of several cells, which are interconnected in parallel and series fashion and are connected to power-electronics converter units [51], [52]. The control system of these modules consists of two main parts such that one is the battery management system (BMS) and the other is the power converter system.

BMSs is a real-time system controlling, protecting, and monitoring several functionalities such as temperature and voltage levels that are necessary for the safe operation of the battery pack installed. Upon any uncertainty in the operation of the battery, the BMS will isolate the battery system. Two main requirements need to be fulfilled to enhance the lifetime of the battery unit, i.e., energy balancing of each cell in a module and SoC of the whole module balanced. The former can be attained using BMS whereas the latter one is achieved using power converter units. The aforementioned entities can be controlled in a hierarchical manner where the cell monitoring unit (CMU) is responsible to measure entities at an individual cell level whereas the module management unit (MMU) refers to managing a group of cells. Lastly, different modules of MMUs are managed by a pack management unit (PMU) along with communication with an external system [53]. These categorizations are implemented using topologies such as centralized BMS as shown in Fig. 3 (a) (all features on one PCB), Modular (master/slave) as shown in Fig. 3 (b) [54],[55], distributed (several PMUs) as shown in Fig. 3 (c) [56], and decentralized (every cell with its own board) [57, 58].



(a) Centralized BMS. (b) Modular (Master/Slave) BMS. (c) Distributed BMS.

Figure 3: Architecture of different types of BMS.

In summary, BMS should have the capability to perform the following features:

1. To monitor the cell voltage and operating temperature of an individual cell along with current flowing through the whole battery pack to attain within a certain range.

2. To achieve cell balancing in battery packs using active, passive, or hybrid ways along with galvanic isolation between two different potential circuits [59, 60].

3. Voltage balancing among several cells connected in series, and parallel.

4. To ensure safety against short-circuit fault and protection (fuse) against higher charging or discharging current.

5. Wired or wireless communication between internal (SoC, state of health, state of power, state of function, number of cells, connection status) and external entities using communication protocols such as controller area network (CAN).

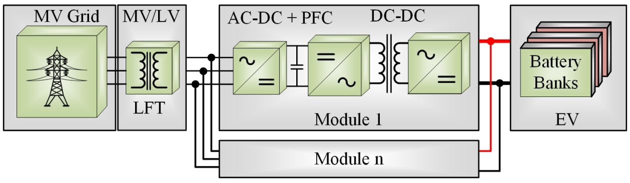
6. A thermal management system, to employ active or passive ways for the safe operation of cells within a certain temperature range. The active way of thermal management is a conventional way that uses forced air, water, and liquid to tackle during high charging and discharging rates [61]. For instance, Nissan LEAF uses an air cooling method whereas Tesla uses liquid tubes passing through each cell filled with Glycol [62]. The weight, complexity, and higher maintenance cost of conventional methods lead to novel passive methods such as phase change material (transforming solid-liquid) type cooling such that excessive heat generated by batteries is absorbed, which allows the battery to operate at a nearly constant temperature [63].

3. Electric Vehicle Charging Infrastructure

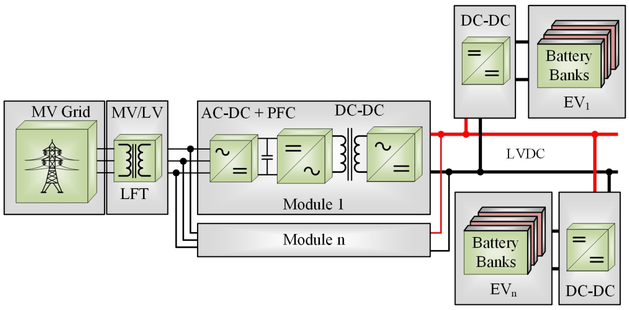
The energy supplied from the grid using LFT and power electronics-based converting units to EVs is referred to as either an EV charger or an EV charging station. A charger is a single unit that can charge one vehicle at a time as shown in Fig. 4 (a) whereas a charging station can charge two or more vehicles at the same time as illustrated in Fig. 4 (b). The term charging station is similar to the gasoline station with multiple nozzles such that multiple vehicles can be refueled at the same moment.

3.1. Types of charging stations

The charging stations can be categorized as onboard, off-board grid-connected, or a stand-alone/mobile unit (supplied through RES and stationary battery packs). The onboard charger is installed in the vehicle and is of low power due to cost, weight, and space restrictions. On the other hand, off-board chargers or charging stations are installed at public places such as shopping malls, motorways, etc [64]. This category can either be a three-phase AC or a DC-based charging unit. The main challenge occurs while installing charging stations in remote areas where access to the main grid requires a huge amount of investment. Hence, instead of laying and investing in long underground or overhead transmission lines standalone/mobile charging stations are proposed which are formed by integrating renewable energy sources (RES) along with stationary battery packs. It is found that fuel cell (FC) could be one of the best suitable options among RES along with solar and stationary battery packs [65, 66]. The overall classification of charger/charging station is depicted in Fig. 5.



(a) Configuration for a charger.



(b) Configuration for a charging station.

Figure 4: Comparison between charger and a charging station.

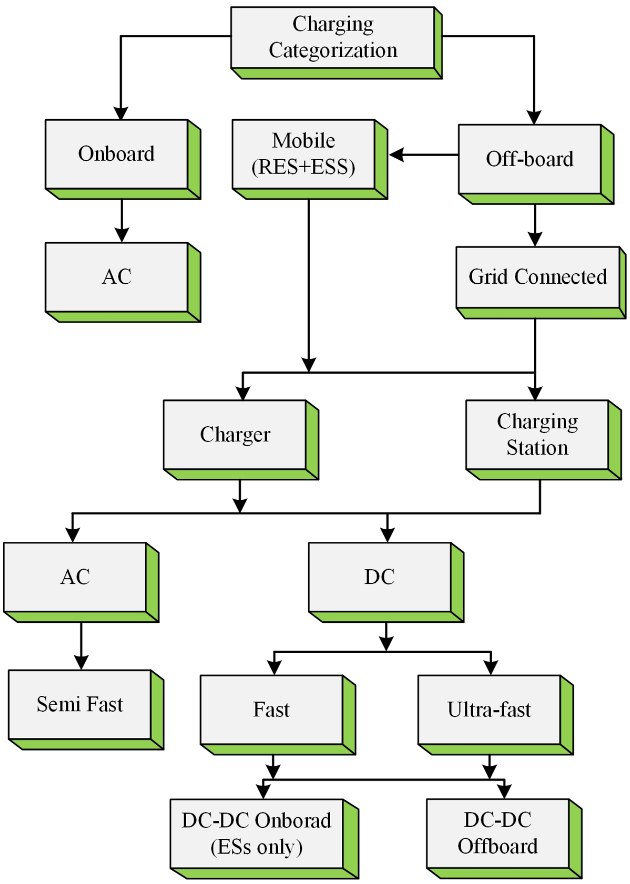


Figure 5: Overall categorization for charger & charging station.

Further, charger or charging station can be categorized into different levels such as slow, semi-fast, fast, and ultra-fast as shown in Table 2. The slow charger is an onboard category of the charger and is referred to as Level 1 in which EVs are plugged into an outlet placed at homes which takes several hours to charge EV batteries. Level 2 also known as semi-fast charging stations (240 Vac in the US and 400 Vac in EU) are found in both private and public outlets. Level 3 and Level 4 charging stations are found at public spots and are referred to as fast and ultra-fast charging stations. Level 1 can be used for ECs only whereas level 2, level 3, and level 4 can be used for both ECs and ESs.

Table 2: Charging levels of EVs [21], [30], [67–69]

Type	Voltage (V)	Outlet	Maximum Power (kW)	Charging Time (h)	Standard
Level 1 (Slow)	120 US (AC)	Home	1.9	4-11	SAE J1772
	230 EU (AC)	Home	7.4	11-36	IEC 62196-2 (Mennekes)
Level 2 (Semi-fast)	240 US (AC)	Private/Public	19.2	2-6	SAE J1772
	400 EU (AC)	Private/Public	43	2-3	IEC 62196-2 (Mennekes)
Level 3 (Fast)	208-600 (DC)	Public	50-350	0.16-0.5	SAE J1772, CCS, CHAdeMO, Tesla
Level 4 (Ultra-fast)	≥800 (DC)	Public	>400	~ gas refueling	

3.2. *Charging connectors and possible ways*

EVs can be connected to the charging outlets placed off-board either by using conductive (connectors and robotic arm) or by wireless (capacitive and inductive) ways. Another possible approach that might be used is to swap battery packs, the whole procedure will take much less time in comparison even with fast or ultra-fast charging ways. In the case of ECs, it is hard to implement at the current moment as each brand of EC has a different capacity of the battery, its shape, and the way of installing it in the EC. It could be only possible and beneficial if ways of installing batteries in an EC can be standardized and based on it companies may follow on one standard. On the other hand, battery swapping can be much suitable or beneficial for ESs especially ferries. As the layover time for ferries is short, i.e., 5–20 mins [70, 71], which can further be reduced using battery swapping ways. The extra battery packs may be kept on either end or at both ends depending on either the operation of the ferry is on a short or long route. Further, the operation of a ferry is limited to one specific route only, which is a plus point for using this kind of technique. In this way, operation time and voyages of the ferry and domestic cargo ships can be increased.

The conductive way of connecting EV with charging station is done through charging plugs which are categorized into AC & DC types and robotic arms as illustrated in Fig. 6. The AC connector Type 1 category is with single-phase feature only and this type of connector is mostly used while charging ECs at homes. Another type of AC connector, which supports single-phase as well as three-phase, which is also referred to as Mennekes named on the makers of this design mainly used in EU. This type of charging is categorized under the slow or semi-fast category. The plugs for fast charging are categorized as combine charging system (CCS) combo 1 and 2, CHAdeMO [18], Tesla, and GB/T 20234-2015 [72]. Currently, CCS combo 1 and 2 used in the US and Europe respectively can provide power

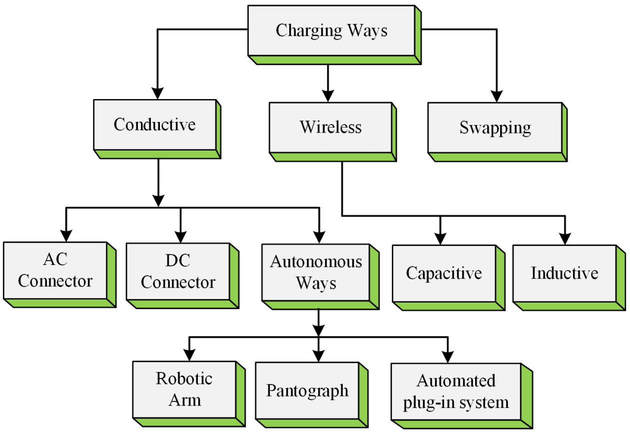


Figure 6: Possible charging ways.

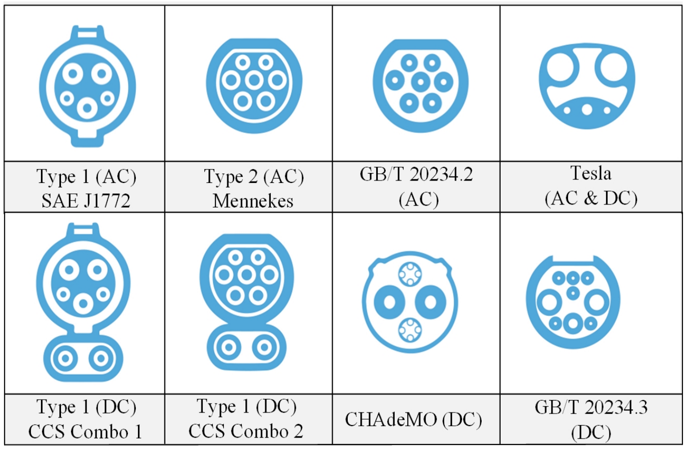


Figure 7: Connectors for charging stations AC & DC.

up to 350 kW at the voltage range between 200 to 1000 V. The CHAdeMO charging plug introduced by Japan is another most used plug, it has the capability to provide power in the range of 200 to 400 kW. On the other hand, Tesla DC connectors have the feature to use the same plugs for charging through AC and DC and they can provide power up to 120 kW. CHAdeMO and CCS Combo 2 connectors are also compatible with the latest models of Tesla such as Model S and Model X [73]. China has its own charging connector named as GB/T 20234-2015, it can provide up to 250 A [72]. The plugs used to charge EVs such as CCS utilizes PLC [74] whereas CHAdeMO [75], Tesla, and China GB/T [76] use CAN bus for digital communication between charging infrastructure and vehicles. The summary of connectors used for connecting ECs is shown in Fig. 7.

The plug for ECs uses two signals named as control pilot and proximity pilot over charging pins for communication purposes. The proximity pilot signal enables an EV to detect when it is plugged in with a charging station. The control pilot on the other hand is implemented by using an extra conductor in the charging plug. The main functionalities of the control pilot include:

- Checking whether EV is connected properly with the charging infrastructure.
- The earth of an EV is properly connected with the charging infrastructure.
- Charging rate selection.
- Energizing and de-energizing of system.

The aforementioned connectors are suitable for ECs application only whereas for ESs application owing to have shorter layover time, huge battery packs particularly for commercial ferries, an autonomous shore connector is needed instead of a manual solution. It will not only minimize the connection process but also will improve safety. Some of the autonomous solution being used in commercial ships are illustrated in Table. 3. Automatic shore connection of ABB is one of the examples where the manual process takes 7 minutes to connect and charge batteries (1.2 MW) upon providing 10.3 MW of power. On the other hand, using an autonomous approach the whole charging process is completed in 10 mins upon providing 7.2 MW power for similar-sized battery [77]. Some other automatic plugs such as NG3 plug for Color hybrid, Automated plug-in system for MF Elektra (Cavotec), and pantograph for MF Ampere are some solutions being used in commercial ships to minimize the connection time by using an autonomous connection approach. For providing onshore connection to vessels or charging the ESs, IEC/IEEE standard 80005-1 applies to high voltage shore connection (HVSC), and for low voltage shore connection (LVSC) IEC/IEEE standard 80005-3 is applied. The main requirement for HVSC according to the standard is that one or more transformers are needed with a nominal voltage of either 6.6 kV or 11 kV with a cable management system [78]. The LVSC standard 80005-3 limits the current limit up to 250 A (max 125 A per cable) and the voltage level should not exceed 300 V. Any parameter exceeding these values will be categorized in an HVSC [79]. For the communication, and control of high and low voltage shore connection, IEC/IEEE standard 80005-2 is developed. The smaller vessels rated up to 1500 kVA demands for LV connection. For such a connection, parallel feeders are required in order to meet the requirements [80].

Table 3: List of automatic ESs connectors [81].

Connector type	Battery Capacity (MWh)	Ship	Country
ABB Robotic Arm	4.16	MF Tycho Brahe	Denmark
NG3 Plug	5	Color Hybrid	Norway
Cavotec plug and pantograph	1	MF Ampere	Norway
Mobimar Robotic arm	4.3	Ellen	Denmark

Another approach to minimize the connection time, bulky cables and connectors are replaced with wireless power transfer such that it does not require any physical connection for transferring the electrical energy. This can be achieved either by capacitive coupled plates or via inductive coupled plates.

The capacitive coupling operates at a high frequency that are smaller and less expensive but having a low range and power makes it not suitable for EV applications. Further, the inductive way of transferring power uses magnetic fields for transferring the power and hence is relatively safer than capacitive power transfer. The world's first wireless technology to charge hybrid electric ferry was completed in Sep 2017 [82]. The Wärtsilä inductive charging system has the capability to deliver 2.5 MW power with an efficiency of approximately 95 %. Although inductive charging has several benefits over conventional wired charging but this technology gives rise to three main safety concerns, which are magnetic field exposure that is harmful to human body, fire hazards, and electric shocks [83]. To cope with human exposure to electromagnetic fields, IEEE standard C95.1-2005 [84] and ICNIRP guidelines were introduced. Other standardizations including UL 2750, SAE J2954, and ISO/IEC PT61980 follow the guidelines introduced by ICNIRP [85].

3.3. Commercially available charger/charging stations and incentives for EVs

There are several charger/charging stations both for cars and ships that have been installed as shown in Table 4 in the last decade. It can be inferred that charging stations for ECs are in the range of a few kW to 475 kW whereas, in the case of ships, most of them are in the range of a few MWs.

Table 4: List of EV chargers and charging stations.

Charging Station	Voltage (V)	Power (kW)	Location	Ref
Terra 54	150-500 (DC), 400 V (AC)	50 kW (DC), 22 & 43 kW (AC)	Denmark	[86]
Terra HP 175	150-920 (DC)	175 kW (DC)	Denmark	[87]
Porsche	800 (DC)	350 kW (DC)	Germany	[88, 89]
Tritium HPCS	920 V	475 kW (DC)	–	[90]
DELTA	170–550 (DC)	150 kW (DC)	Thailand	[91]
Ellen	1000 (DC)	4 MW (DC)	Denmark	[43]
Future of the Fjords	1000 (DC)	2.4 MW (DC)	Norway	[43]
MF Tycho Brahe & MS Aurora	10000 (DC)	10.5 MW (DC)	Denmark	[43]
Vision of the Fjords	400 (DC)	1.2 MW (DC)	Norway	[43]
Wärtsilä	690 (AC)	2.5 MW (AC)	Norway	[92]

To promote the use of ECs over fossil fuel-based vehicles in different countries, several incentives for the buyers and production companies are being given. Among several countries in Europe especially Netherlands, France, Germany, and United Kingdom are the main contributors and their market is growing rapidly since the last few years as shown in Fig. 8.

One of the key benefits for the buyers is the tax reductions or exemptions that are generally one-time or annually based taxes mostly paid while purchasing the vehicle. Other benefits that customers can avail themselves include of parking facilities, free charging from public charging infrastructures, and so on. The Netherlands, for example, provides an exemption for paying the registration tax whereas for AECs, road tax is completely waived as well and for PHECs the waiver is reduced to 50%. Further, in order to aid the private companies, benefits are

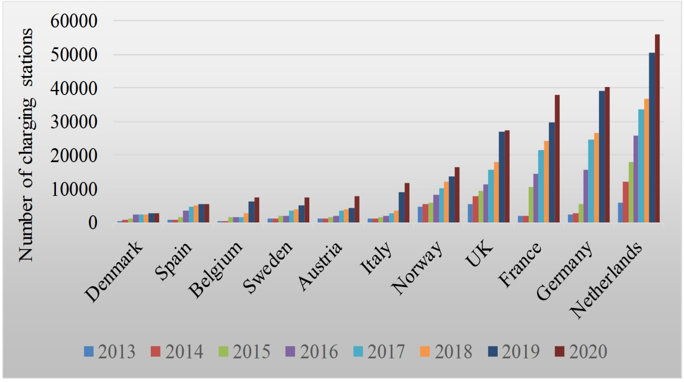


Figure 8: Charger and charging stations in Europe [93–95]

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provided in terms of reduced income taxes for building charging infrastructures. To promote the use of ECs, Austria provides aid in the purchase of AECs such that €4000 (€2,500 by the federal government and €1,500 by the industry). Other benefits for AECs include free parking, 100% tax benefits excluding VAT, and waiver in the registration tax as well. In Germany, ECs are exempted from the annual tax for the first five years from the first registration of the car. Purchase subsidy (€4,000), free parking, reserved parking spots, and bus lane use are some other advantages that buyers can get. An initiative set up by BMVI to promote public charging stations. A total amount of €300 million is spent between 2017–2020 for standard as well as DC fast-charging stations at the public places [96]. For that, €100 million subsidies are provided for standard charger infrastructure and €200 million for DC-based fast-charging infrastructure [97]. A summary of incentives provided by different governments are illustrated in Table 5. In the US, AECs and PHECs purchased after 2010 are eligible for a federal income tax credit up to an amount, i.e., $7,500 [98] whereas up to 10,000 CNY subsidy is provided for each EC in China [99]. The amount is based on the capacity of the battery installed in the vehicle. In China, several provinces are providing 20-30% subsides for EV infrastructure as well [99].

On the other hand, regarding zero or low emissions ESs government of the UK and other EU countries are thinking of provide non-tax benefits in order to support the transition to zero-emission shipping [100]. Further by introducing a tax on producing emissions at the ports will help in the transition to zero-emission shipping [101].

3.4. Power electronics stages in a charging station

The power electronics stage in a charging infrastructure comprises of two main stages. First, is the non-isolated rectification stage (AC-DC) with an addition of power factor correction (PFC) unit and second is the isolated-based DC-DC conversion stage. These stages comprised of several active and passive components and their combinations (capacitors, inductors, and semiconductor switching devices) result in many different topologies.

Table 5: Incentives by different countries on ECs and their infrastructure [95].

Country	Purchase Subsidy	Vat benefits	Registration benefits	Company tax benefits	Infrastructure
NL	✓	✓	✓	✓	✓
DK	✓	X	✓	X	✓
FR	✓	X	✓	✓	X
GR	✓	X	X	✓	X
BE	✓	X	✓	✓	X
AT	✓	✓	✓	✓	X
IT	X	X	X	X	✓
SP	✓	X	✓	✓	✓
SW	✓	✓	✓	✓	✓

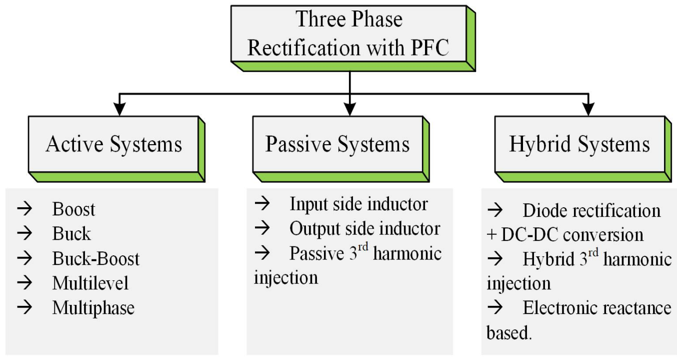


Figure 9: Classification of three phase PFC rectification system.

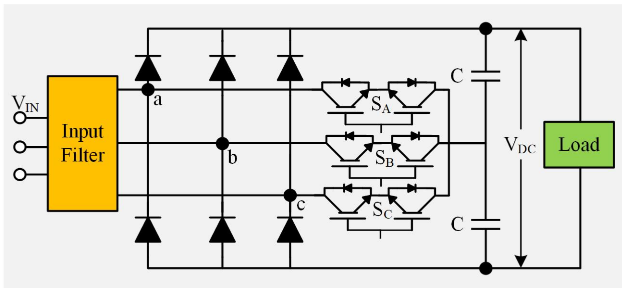
3.4.1. *Rectification Stage*

The rectification stage is generally a non-isolated AC-DC conversion, which maintains DC-link voltage and harmonic regulation. If the need for a charging station is a uni-directional, un-controlled rectification based on H-bridge diodes is preferred as it is considered quite simpler and a cost-effective way. On the other hand, if the need for a charger or charging station is bi-directional such that to supply back power from EV to grid, diode H-bridge is replaced with semiconductor-based switching devices such as IGBTs. These converting units behave like a non-linear load to the utility grid due to the current harmonics that result in poor power factor. In order to obtain high efficiency and power factor close to unity, the PFC unit need to be integrated with the rectification circuitry.

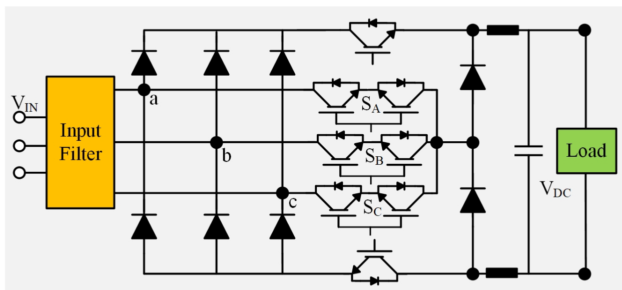
The conventional 6-pulse diode rectification method is the cost-effective method along with its robustness nature and simplicity. However, the input currents become non-sinusoidal, which creates issues for the input side equipment and hence, detonates the quality of the input supply [102]. Further, this type of rectification has the disadvantage that output voltage can not be regulated owing to the use of only diodes in the circulatory. The PFC stage here is critical as it needs to maintain input currents, the PFC-based rectification is generally classified into passive [103], active, and hybrid rectification systems as illustrated in Fig. 9 [104]. In passive filtering, low-frequency passive components are added at the input and the output side of rectifier circuitry to minimize input side current harmonics and to smooth output voltage. To further eliminate input and output side power quality issues the 12 and 18-pulse diode rectification along with large passive components is proposed in the literature for high power applications but the cost and weight along with inefficient passive components limiting the use of it [105].

In order to incorporate the deficiencies of passive filters, a hybrid system is formed using a rectifier with low-frequency passive components and switching frequency active switches in order to regulate the output voltage and to eliminate/minimize harmonics in the input side current [106]. The above two approaches have a drawback in a way that bulky passive filters are added to regulate total harmonic distortion (THD).

To provide minimal THD at the input AC side, improved PFC, and output voltage regulation, the conventional diode rectification along with passive filtration methods are replaced with active PFC methodologies [107]. The rectification based on active PFC are mainly categorized into buck (SWISS rectifier), boost (Single switch boost, Vienna, Minnesota), buck-boost (conventional buck-boost, flyback, Cuk), multi-level, multi-phase topologies for both uni-directional and bi-directional flow of power. Vienna, a three-phase rectifier topology that was proposed by Kolar in 1994 with the features of low current distortion and high power factor is suitable for high power applications such as traction, EV chargers, and telecom rectifiers [108], this type of topology as shown in Fig. 10 (a) supports the transfer of power from the grid to DC side only. Among buck type topologies, SWISS rectifier as shown in Fig. 10 (b) combines buck DC-DC converters along with active 3rd harmonic current injection [109].



(a) Vienna rectifier [108].



(b) SWISS rectifier.

Figure 10: Three-phase rectification topologies with active PFC.

For a bi-directional flow of power, the most widely rectification technique adopted in literature is a three-phase PWM converter with an input side filter. It offers a bi-directional flow of power whose output voltage is higher than the input voltage, which is adopted in several fast charging stations [110] as illustrated in Fig. 12. It has a drawback of a bulky filter at the input side to regulate the input THD. Another topology, which is frequently applied in the literature for traction and EV charging application is three-level Neutral-point-clamped (NPC) as illustrated in Fig. 11. The three level rectification will help to minimize voltage stress across switching devices and losses at higher switching frequencies. The increase in the magnitude of output voltage, bi-directional flow of power, and robustness are some of the key benefits [111].

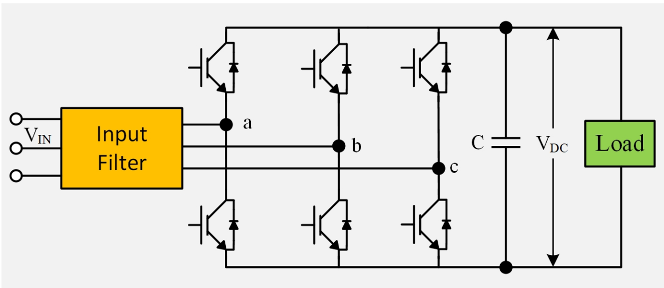


Figure 11: Active front-end converter.

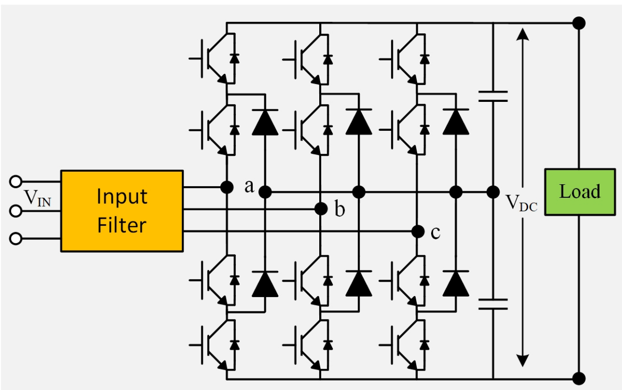


Figure 12: Three-level NPC [110]

In summary, as our power requirement is in MWs, hence, several modules need to be connected in parallel in order to provide LV and high power rectification.

3.4.2. DC-DC Conversion Stage

The DC-DC conversion stage is generally categorized into an isolated and non-isolated types. Non-isolated converters are preferably used in applications where the change in voltage is relatively small, isolation is not required, and efficiency is not considered as a major concern as well. Isolated converters, on the other hand, have a galvanic separation and facilitates to block noise, interference's, and produces a cleaner DC output. This type of converter topologies is preferred when the converters are grid-connected and isolation is recommended by regulatory authorities such as IEC 60950. In literature, there are plenty of isolated DC-DC converter topologies presented [20], some of them are mature for low-power applications only and are exhibited in this study. The overall categorization particularly suitable for low and high power charger and charging station are enlisted in Fig, 13.

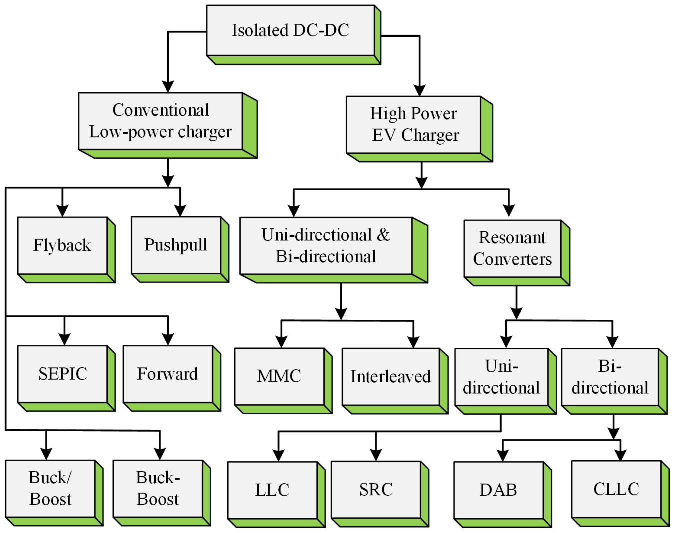
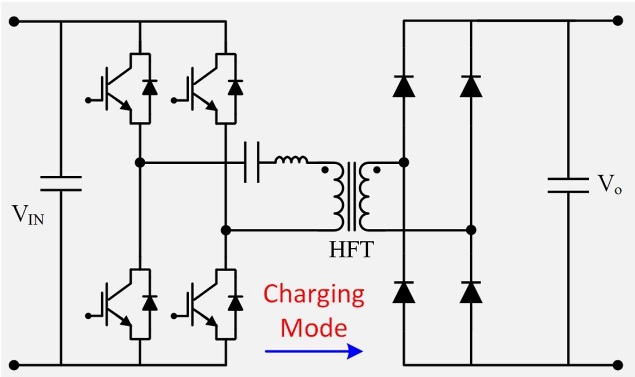


Figure 13: DC-DC conversion categorization and topologies.

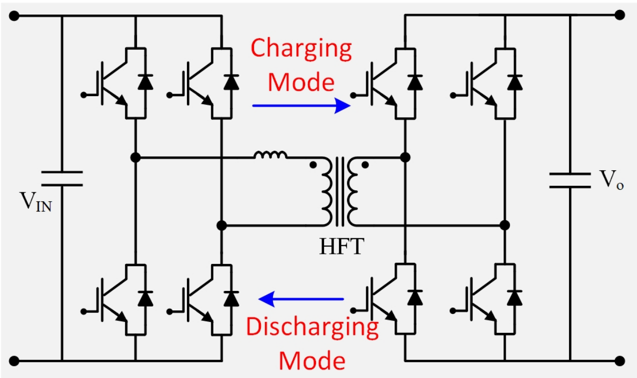
Among isolated DC-DC converter topologies, full-bridge DC-DC converter topologies are mostly used particularly for high power applications operating at high efficiency [112]. These type of topologies converts DC supply to an AC using IGBTs or MOSFETs and a high-frequency transformer to provide isolation. The last part is the rectification stage that is either done using switching devices or diodes, depending on the flow of power. If the power flow is uni-directional generally diodes are used whereas if the flow of power is bi-directional diodes are replaced with IGBTs or MOSFETs. The main drawback of the full-bridge topology is that it generally operates under hard switching conditions, which results in switching losses and hence results in the decrease of overall efficiency [113].

Another category of converters consists of a resonant tank (inductor and capacitor), which serves as a major part of the conversion process. This sort of DC-DC converter generally consists of a switching network (half bridge or full bridge), a resonant tank (L and C), and a rectifier unit (diode or active switches-based bridge). The resonant converters topologies as shown in Fig. 14 such as LLC [114] shown in Fig. 14 (a), dual active bridge (DAB) shown in Fig. 14 (b) [115], series resonant converter (SRC) [116], and CLLC shown in Fig. 14 (c) helps in providing zero voltage switching (ZVS), zero current switching (ZCS), high efficiency, and high power density. To minimize switching and conduction losses and to boost the efficiency, larger snubber capacitance is required that results in shrinking the load change.

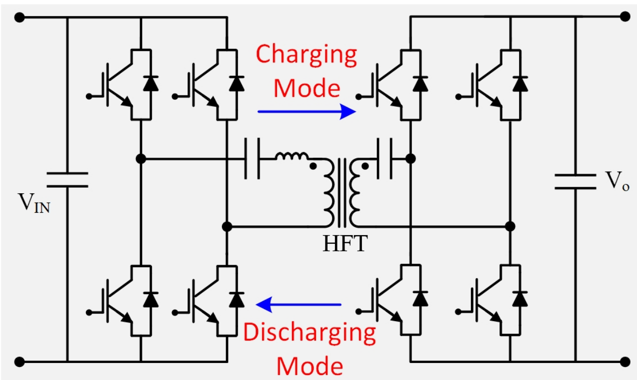
In conventional 2-level converters, the existence of high slopes of di/dt and stray inductances result in Electro-Magnetic Interference (EMI) issues. Further, conventional converters also suffer from high dv/dt during switching as the voltage across switching devices alter quickly from zero to full DC voltage that creates problem in parasitic capacitance. To cope with



(a) LLC converter (Uni-directional).



(b) DAB Converter (Bi-directional).



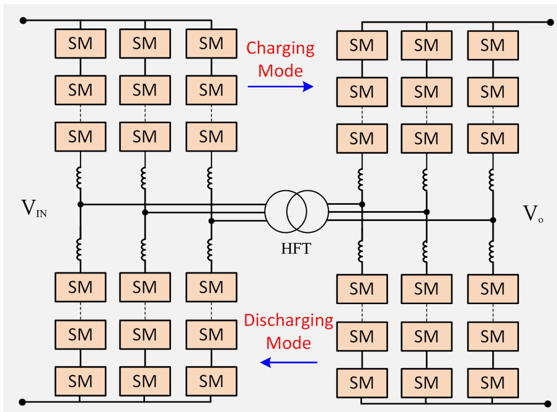
(c) CLLC converter (Bi-directional).

Figure 14: Resonant DC-DC converter topologies.

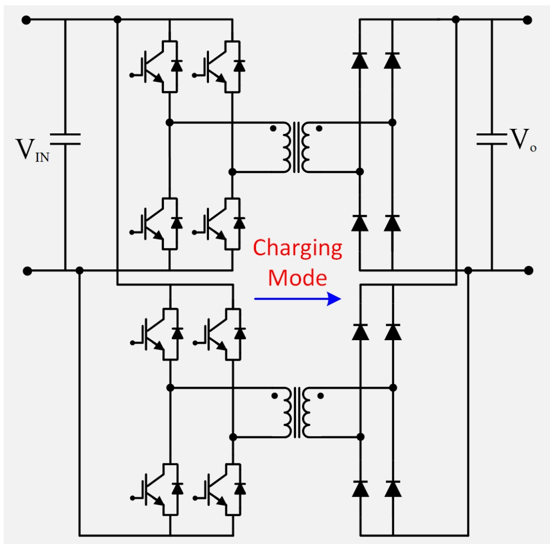
such challenges, modular multilevel converter (MMC)-based converters are used as shown in Fig. 15 (a). On contrary, MMC owing to have several sub-modules, the voltage stress on individual components is minimized and EMI also decreases. Each sub-module in an MMC consists of two or more switching devices (MOSFETs) and an energy storage element typically a capacitor, which is either placed in series or bypassed depending on the switching state of switching devices. The use of MMC further helps to minimize output voltage distortions without the requirement for high switching frequency or a need for any harmonic filters. This sort of topology is suitable for uni-directional or bi-directional SST-based charging stations.

Another approach used in the literature is the interleaved converter where several modules are connected in parallel to enhance power as shown in Fig. 15 (b) that is used for high power applications (EV chargers) such that it distributes low profile packaging characteristics and high power density [117]. It helps to distribute the power losses, thermal stresses of semiconductors, and magnetics, as lesser power is processed through single interleaved power stage [118]. Moreover, the ripple in the input and output current will also be minimized because of the ripple cancellation effect, which helps in decreasing the size of filters utilized in the input and output [119]. This type of topology is recommended for LV chargers/charging stations [120–122],

In summary, owing to build an LV and high power based charging station, several DC-DC converters required to be connected in parallel, hence, interleaved-based approach comprising of topologies such as LLC for uni-directional power flow is suitable whereas for bi-directional or V2G application parallel connection of several modules of DAB and CLLC topologies might be suitable. On the other hand, in the case of SST-based charging station bi-directional MMC-based solution is preferred.



(a) MMC bi-directional converter.

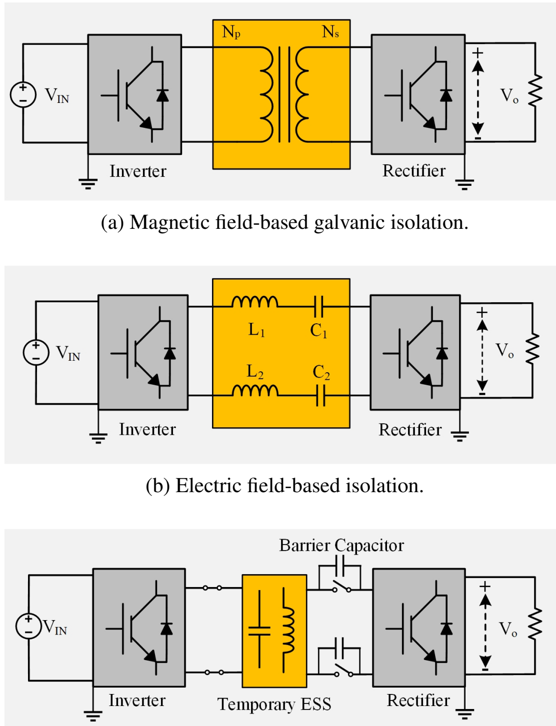


(b) Interleaved full-bridge uni-directional converter.

Figure 15: High power isolated DC-DC converter topologies.

3.5. Galvanic isolation stage

EVs can be charged either by wires or wireless ways, in the wireless approach energy is transferred by electromagnetic fields eliminating the use of plugs and wires, hence providing galvanic isolation naturally. On the other hand, in conductive-based EV charging, isolation is necessary between the grid and the charging infrastructure. A galvanic isolation barrier provides separate circuits at the barrier sides (it creates separated grounds), allowing the power (current) to be fully transferred through the barrier without having a common ground. Isolation in a DC-DC converter is generally provided using a high-frequency transformer such that to provide isolation between the input and output terminals. In the offline power supplies particularly charging stations for the EC and ES applications, isolation is mandatory as per the safety standards of UL2202 and IEC60950. Galvanic isolation in isolated DC-DC converters are categorized into a magnetic field-based (typically an HF transformer), electric field-based (LC resonant tank), semiconductor-based (pair of active switches). In the magnetic field isolation method, a high-frequency transformer is used which is separated either by a magnetic core or by air as shown in Fig. 16 (a). On the other hand, in the electric-field isolation method, pair of capacitors and inductors are used, which supplies power at a very high resonant frequency and hence blocking the line frequency as depicted in Fig. 16 (b). This sort of approach has been used in low-power applications such as LED driver [123], and EV chargers [124]. Currently, the semiconductor-based isolation method has been used in the literature for high power applications [125], [126]. It replaces the HF transformer with pair of switches as shown in Fig. 16 (c) such that energy is transferred in two modes. In the first mode, energy is stored in temporary energy storage while isolating from the load side whereas, in the second mode, energy is transferred from the temporary energy storage to the load while isolating from the input side.

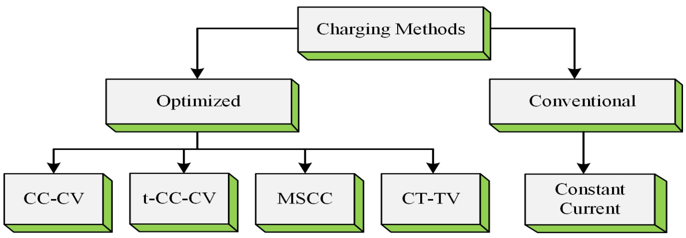


(a) Magnetic field-based galvanic isolation.

(b) Electric field-based isolation.

(c) Semiconductor-based galvanic isolation.

Figure 16: Galvanic isolation methods.



Note: CC-CV= Constant current-constant voltage; t-CC-CV= tickle constant current-constant voltage; MSCC= Multi-stage constant current; CT-CV= Constant temperature-constant voltage.

Figure 17: Charging methodologies.

3.6. Charging Methods

The charging of EVs can be categorized into slow, semi-fast, fast, and ultra-fast types where the key challenge is the charging time to charge onboard batteries, which generally takes several minutes to hours. In order to minimize the charging time comparable with the gasoline refueling time, several optimized approaches are reported in the literature as illustrated in Fig. 17. Among conventional methods, i.e., constant current (CC), a constant current is maintained during the whole charging process as illustrated in Fig. 18 (a), which relies on the SoC of the onboard battery packs. The advantage of this technique is that limited current is supplied during the whole process and charging current can be determined easily. The main drawback is that at any point if the SoC estimation algorithm fails, it might lead to overcharging or over-discharging of battery packs, which ultimately will shorter the battery life span.

The rate of charge of batteries is defined in terms of C-rate, which shows the rate at which the battery is being charged or discharged, where 1 C charging defines battery charging in 1 hour. Typically charging rate for charging lithium-ion batteries are between 0.5 to 3.2 C where a 3.2C/4C charging rate is required for fast charging [127] and up to 6C or greater (10C) for ultra-fast charging [128]-[129]. The increased C-rates, which are mandatory for ultra-fast charging result in an increase in temperature rise and ultimately having an impact on the lifetime if proper cooling is not provided. The list of maximum charging and discharging rates for EVs along with the battery chemistry is shown in the Table 6.

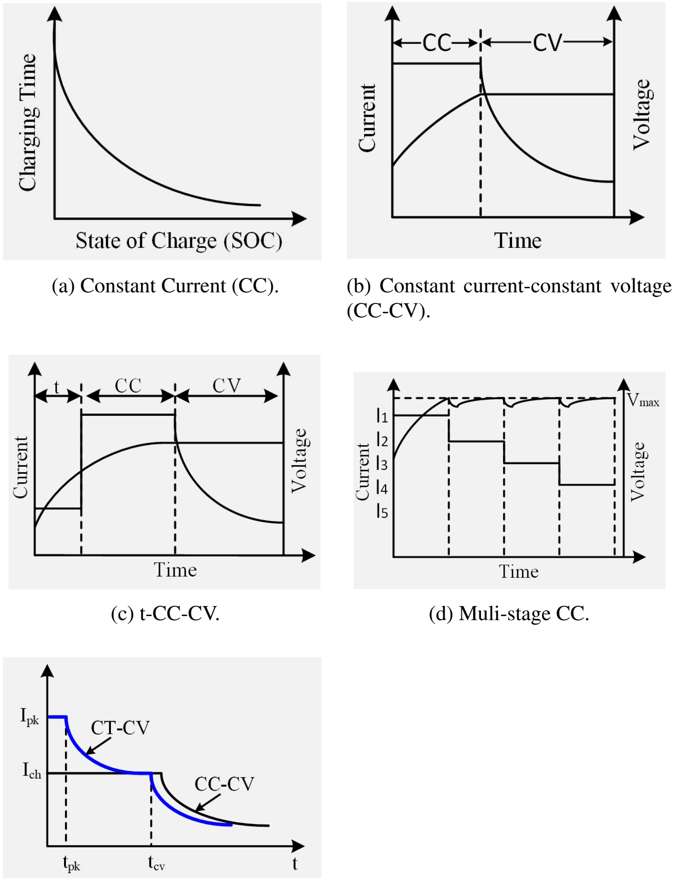
To overcome the disadvantages of CC, the constant current-constant voltage (CC-CV) method is utilized and is the most adopted method for charging lithium-ion batteries that are particularly used in the transportation sector. At the start, the CC stage is applied to the battery packs until the set voltage of the battery is achieved. As soon as preset voltage is attained, the CC phase is shifted to the CV phase as illustrated in Fig. 18 (b). The CC stage covers up to 85 % of the charging process for Li-ion

Table 6: List of commercial batteries equipped in EVs with their maximum charging and discharging rates.

Battery Company Manufacturer	Maximum C-rate (Charging)	Maximum C-rate (Dis-charging)	EV type	Cell chemistry	Ref
Hyperdrive	1.45C	1.17 C	The Pulse 63 (ES)	Lithium NMC	[130]
Corvus energy	3C	10C	Ampere Ferry (ES)	Lithium NMC	[131]
SuperB	1C	3C	Happiness Ferry (ES)	Lithium Iron Phosphate	[132]
Leclanché	1–2C	3C	Ellen Ferry (ES)	Lithium NMC	[133]

batteries [134]. The main drawback is that during CC mode, the voltage of the battery will increase abruptly which might result in higher polarization voltage. When the charging rate reaches a certain value (typically 0.02C), the charge is terminated and the battery is considered to be fully charged [135]. Secondly, the CV charging phase is considered quite time-consuming due to which ultra-fast charging might not be achieved. Another issue is that during the CC phase, a very high current is required to minimize the charging time that reduces the lifetime of the battery. To cope with these challenges and to increase the lifetime of the battery, usually, a trickle stage is added up before the CC, which is operated when the battery is discharged deeply as shown in Fig. 18 (c). The CC-CV charging method is implemented for fast charging stations as well as without the risk of over-charging. The multi-stage CC method, on the other hand, is generally used to minimize the charging time required in the CV phase [136]. A very high current is required in the start to raise the voltage level to the upper threshold limit [135]. As soon as it reaches the maximum voltage, it will switch to the next stage as depicted in Fig. 18 (d). The main challenge in this method is of choosing the appropriate charging current, for that, a few approaches in the literature have been utilized such as fuzzy logic controller [137], linear programming [138], ant colony approach [139], and consecutive orthogonal array [140]. The aforementioned techniques increase cell temperature and in order to cope with it, another technique utilized in the literature to charge lithium-ion batteries is constant temperature-constant voltage (CT-CV) as shown in Fig. 18 (e). This technique helps to achieve up to 20 % faster charging without having any impact on battery life and with a similar rise in temperature as in CC-CV method [141]. Some other techniques which are reported in literature includes 4C-1C-CV [142], boost-charging [143], pulse charging [144], sinusoidal ripple-current charge [145].

The battery degradation is strongly dependent on the type of charging algorithms implemented. Generically, degradation of the batteries is more influenced by high charging currents in comparison to discharging currents. In addition to it, the study in [146] depicts that higher currents not only degrade battery at higher SOC but also at extremely lower SOC as well. According to the study [147], at lower charging rate (0.5C), battery degrades in order of constant power > Multi-stage CC > CC. On the other hand, at a higher charging rate (1C) battery degrades with an increasing order Multi-stage CC > CC > constant power.



(a) Constant Current (CC).

(b) Constant current-constant voltage (CC-CV).

(c) t-CC-CV.

(d) Muli-stage CC.

(e) CT-CV.

Figure 18: Charging methodologies.

4. Vehicle-to-grid

The conventional fast-charging stations are uni-directional, which takes power from the grid to charge batteries of EVs. As, the recent electric power system utilizes LF transformers to step-up or step-down the voltage levels depending on the requirements, for instance, starting from the medium voltage (MV) to high voltage (HV) levels to transmit through transmission lines for longer distances and then back to MV and LV levels for distribution. The flow of power in this old-fashioned power system is uni-directional. Further, to minimize emissions from the energy sector, present grids are integrated with intermittent resources such as solar and wind urges to have cost-effective ways to tackle the peak loading times. Hence, to incorporate intermittent nature of RES, the V2G concept may help in this regard by supplying power during peak hours (peak shaving) and absorbing power during off-peak hours. This could be achieved if the flow of power in a conventional charging station be made bi-directional using the conventional LFT-based V2G approach as shown in Fig. 19 or the SST-based V2G approach as shown in Fig. 20. The conventional LFT-based V2G approach has a drawback in terms of huge footprints of LFT, bulky switch gear, and lack of controllability [155, 156], the comparison between both the approaches are summarized

Table 7: Comparison between the use of LFT vs SST.

Bi-directional Power Flow Techniques	Advantages	Disadvantages	Applications
Line frequency transformer (LFT)	• Uni-directional and Bi-directional power flow • Mostly adopted technique in uni-directional charging station • Extremely reliable • Relatively easy to control	• Large footprint of LFT • Weight and size of LFT • Bulky switch gear • Lower efficiency • Higher initial cost	• Distribution system • EV charger and charging station [148].
Solid state transformer (SST)	• Uni-directional and Bi-directional power flow. • Reduction in size and weight due to medium frequency transformer • Possibility of power factor correction • Flexibility to integrate renewable energy sources (RES) • Lower initial cost	• Higher efficiency • Shorter lifetime of medium frequency transformer • Restricted by power and voltage • Rating of the available power devices [149] • Complexity in control systems due to increased use of converters	• Railway traction [150], [151] • DC distribution system [152] • Microgrid applications [153] • EV charging station [19, 154]

in Table 7.

To minimize the size of the charging station particularly in urban areas where the price of land is very high SST based approach might be suitable. The rapid growth in the development of SST in the past two decades has opened doors to replace conventional LFT for some applications such as fast and ultra-fast EV charging stations, PV applications [157], and traction purposes [155]. As the wide band gap-based semiconductor devices such as Silicon carbide (SiC) and Gallium nitride (GaN) allow operation of these switching devices at a high switching frequency along with high temperature and voltage. Hence, using these switching devices at the grid side will increase the blocking voltage ability along with the parallel operation of several DC-DC converters further providing huge current remaining within the LVDC category. This SST-driven approach is not only beneficial for vehicle users but also for the charging station owners due to the higher efficiency, reduced size, and extremely fast charging capability [154].

Several studies and project based on this approach is implemented or being implemented for uni-directional power flow only. Among them, one of the SST-based uni-directional 50 kW chargers using SiC devices is implemented at North Carolina State University whose overall efficiency is 97.5 % compared to the conventional LF-based with an efficiency of 93 % [154]. Another key project relating to SST implementation at medium input voltage level (13.2 kV) and output voltage range (200-1000 V) with the power of 400 kW is being implemented by Delta electronics America [158]. In this project for the rectification stage, the NPC converter is implemented whereas, for the DC-DC isolated conversion stage, several modules of three-level LLC converter are utilized. To connect to EV, several modules of the interleaved buck converter are integrated to achieve a higher power level while remaining in the LV cate-

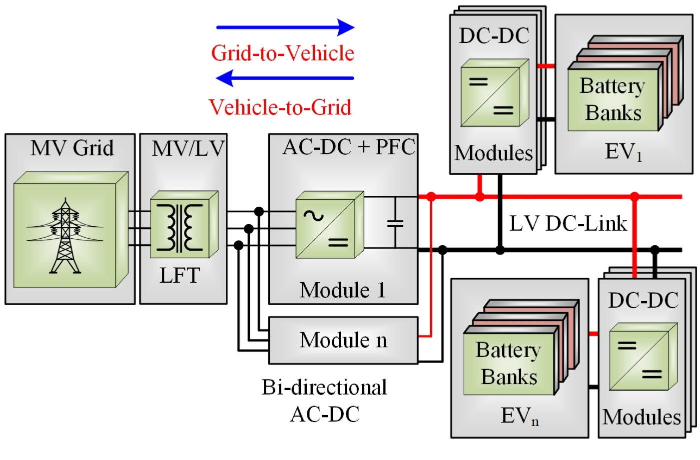


Figure 19: V2G – Conventional approach based on LFT.

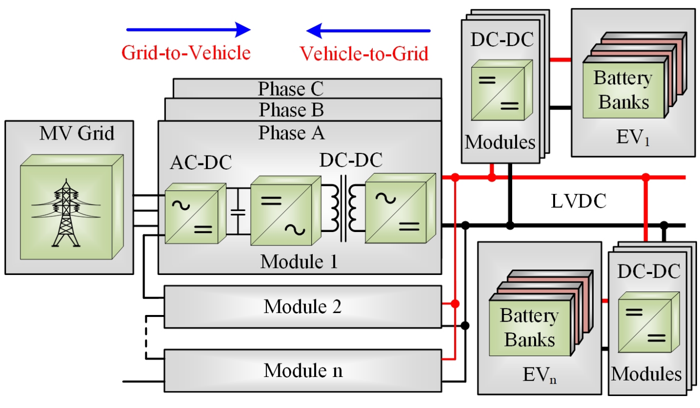


Figure 20: V2G – Modern approach based on SST.

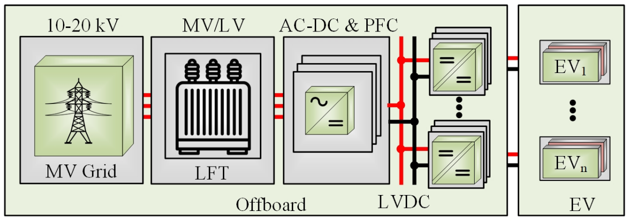
gory. For the V2G application, the study in [159] uses an active front-end converter to convert MV grid voltages along with a dual half-bridge for DC-DC isolated conversion. Further, battery packs with a non-isolated DC-DC converter are utilized between the rectification and DC-DC conversion stage to support the charging station.

Hence, for the V2G application owing to have reduced size and better controllability SST-based bi-directional charging stations could be a game-changer in the near future.

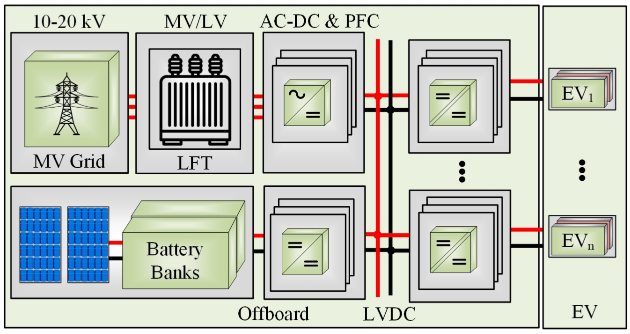
5. Possible Configurations of Charging Stations for Electric Vehicles

The possible configurations for high power and LV DC fast charging station are considered in this section, which is suitable for both uni-directional and bi-directional flow of power upon utilizing suitable power converters aforementioned in Section 3.4. The configurations presented here are based on the locality and condition of the local grid. As, charging stations for EVs vary from several kW to a few MWs range. Hence, for such high power requirements, MV dedicated lines need to be installed from the main grid to the charging station. The first two configurations refer to when LFT is used to step down the voltage level from MV to LV levels followed by the rectification stage and isolated DC-DC converting units. The first configuration as shown in Fig. 21 (a) is recommended where the local grid is strong enough. Such grids are high inertia grids such that voltages and frequency fluctuations in such a stronger grid maintain approximately constant under varying operating scenarios. On the other hand, if the grid is weaker, hence, upon variation in power demand there are noticeable voltage and frequency variations. The weaker grids are particularly found in the rural areas and smaller islands, hence to incorporate, stationary battery packs along with RES is installed to support the grid, this sort of configuration is shown in Fig. 21 (b). *MV Ampere* charging station is an example of this kind of configuration where 410 kWh stationary banks were installed to support weaker grid situation [160]. Similarly, integration of RES with EV charging infrastructure is frequently proposed in literature particularly RES-based seaport grid-connected microgrids [161]–[162], which can be used to support charging stations. ADS-TEC along with Porsche developed a 350 kW DC fast-charging prototype where compact-sized battery packs along with limited supply from the grid are considered to refrain from expensive grid extension [163].

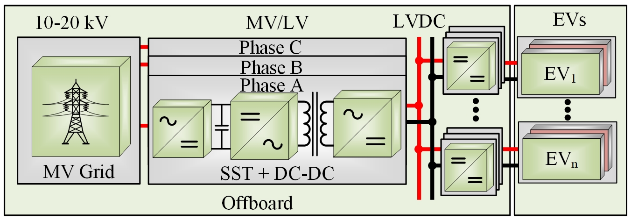
The concept of smarter cities equipped with highly intermittent RES-based microgrids is being built in several parts of the world, which requires large-scaled battery packs to absorb extra power and supply during low generation times. Therefore, instead of investing in stationary battery packs, EVs can be helpful to support the grid, which is referred to as V2G. For that SST-based switching devices may be a cost-effective approach along with lesser footprints such that to send power back to the grid, this sort of configuration is illustrated in Fig. 21 (c). As the requirement for an ES charging station is in MWs, hence there is an utmost need to have RES-based microgrids to support the local grid. The main issue occurs while installing a



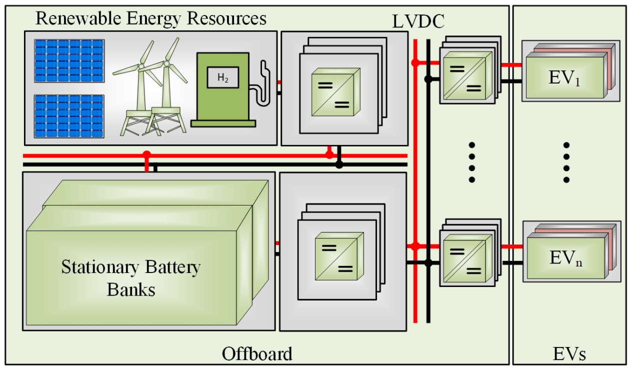
(a) Configuration 1: Charging station with DC-DC stage offboard.



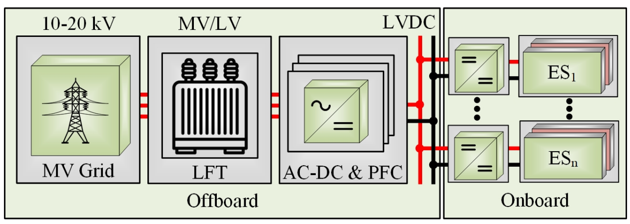
(b) Configuration 2: Charging station with DC-DC stage offboard with integration of battery packs and RES.



(c) Configuration 3: SST-based charging station.

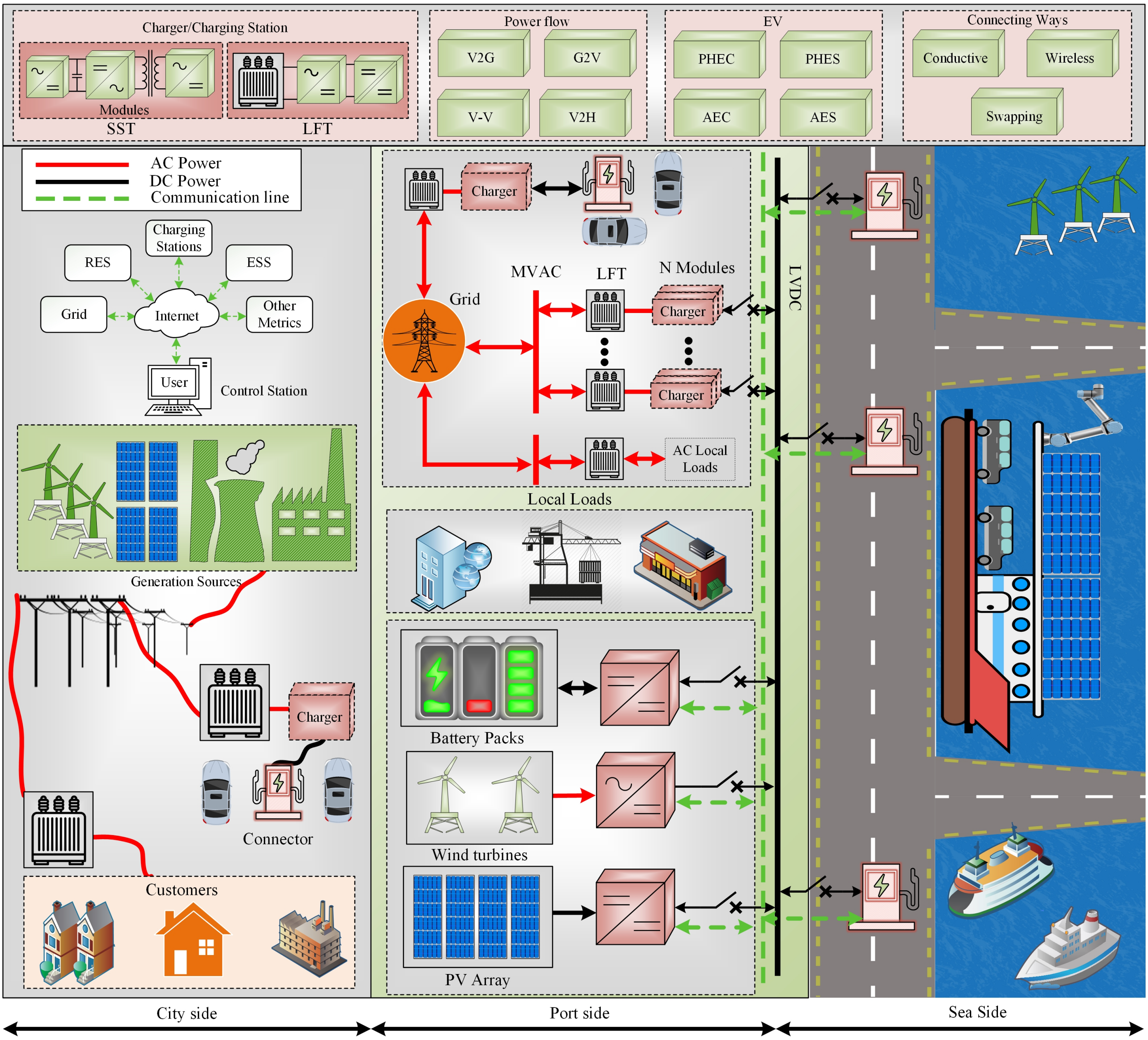


(d) Configuration 4: Mobile charging station with large sized battery packs.



(e) Configuration 5: Charging station with DC-DC stage onboard.

Figure 21: Possible configurations of EV charging station based on locality.



Note: V2G=Vehicle-to-grid; G2V=Grid-to-vehicle; V-V=Vehicle-to-vehicle; V2H=Vehicle-to-home

Figure 22: Integration of electric vehicles with the grid–Future perspective.

charging station in remote areas where access to the grid is an expensive solution. Hence, mobile charging stations based on stationary battery packs and/or RES can be utilized as an alternative as shown in Fig. 21 (d). For mobile charging stations, Porsche's high power charging truck (Taycan) is tested in the EU at varying temperature with 5000 operations. The power rating of 3.2 MW is capable to charge ten ECs simultaneously with a battery capacity of 2.1 MWh [164]. Volkswagen's mobile charging station equipped with 360 kWh battery packs justifies the practicality of this configuration. However, for ESs up till now, there is not any commercial mobile charging stations reported but recently a study in [165] proposes a ships-based mobile charging station for seaports that are not electrified. The last configuration shown in Fig. 21 (e) is suitable for ESs only where the DC-DC conversation stage is performed onbaord and *Ellen Ferry* charger is an example for such kind of configuration.

6. Challenges with possible solutions and future perspective

In near future, an increase in the integration of RES and EVs with existing grids is expected. Hence, the future power system could look like as shown in Fig. 22 where the bi-directional flow of power between EVs and with the grid could provide resiliency and stability. Ærø-Island is an example of such a type, which is equipped with emission-free resources such as wind power, solar, and biomass that covers more than 55% of islands requirement along with a grid connection from the mainland. Hence, in order to be self-sustaining stationary battery packs along with battery packs of EVs can be utilized. Another example is Vindø, the world's first energy island with an offshore wind capacity of up to 10 GW along with a storage facility that will be built in Denmark at the North sea by 2030. Currently, many developed and developing countries are installing offshore wind turbines such as the USA, China, Denmark. As they are much closer to the seaports as compared to the grid, there is a possibility of integrating these offshore wind turbines with seaport substations to support charging stations.

In summary, the main challenges are as follows:

- To build a charging station that is of LV range with very high power (MW range).
- The increased amount of EVs in the market requires a huge number of public charging stations to be built after every few km. As in current times, access to public charging stations is limited as if we compare with a number of gasoline stations available, which limit the use of EVs in a broader perspective.
- At present times, existing grids are integrated with a huge amount of RES and EVs, which are highly uncertain and intermittent in nature. To cope with this challenge, huge stationary battery packs can be installed, however, this is an expensive solution. On the other hand, V2G can be an alternative approach to provide stability, resiliency, and to improve the power quality of the grid but existing charging stations are uni-directional, which limits the use of V2G operation.
- Most of the batteries used for the transportation sector are Li-ion batteries. Although the pricing of these batteries has reduced a lot in the last decade but the cost of batteries, their lifetime, charge, and discharge rates are still major concerns. Further, the use of EVs is not considered totally as zero-emission despite of the fact they do not produce any local emissions during their operation. As production of EVs and their recycling involves higher emission factors in comparison with petrol car production [166]. Further, the amount of energy utilized in the production of batteries and their recycling adds up further emission factors. Hence, the benefits of minimal emissions achieved by utilizing EVs have moved towards battery production and its recycling, however, the overall Life Cycle Assessment (LCA) of EVs is still better than fossil fuel-based vehicles. [167]–[168].
- Building a charging station where the charging station spot is far from the grid or the existing grid is weaker and laying new transmission lines might not be a cost-effective solution. To cope with such a challenge, mobile charging stations can be built using RES (PV, Wind, fuel cell) and stationary battery packs can be one of the solutions.
- Forecasting the impact of power required by EVs on existing grid is quite challenging due to their uncertainty nature. As power requirements from EVs may overload grid and an increase in the generation will be required and if the resulting generation is from fossil fuels it may equally harm the environment.
- Another challenge is to minimize connection and charging time. At present times most of the existing charging stations are connected with EVs through bulky cables. To decrease charging time high power charging stations need to be built. Further, connection time can either be minimized by wireless power transfer ways along with battery swapping ways but safety concerns and design dissimilarity in ECs limit use of it.
- Modernized fast-charging stations are of high power and hence, a couple of LFTs are used to step down MV to LV levels. These LFT-based charging stations are bulky and have larger footprints. On the other hand, owing to the development of SiC and GaN devices, several modules of SST can be replaced with LFT, which will result in a reduced size of charging infrastructure.

7. Conclusion

This study reviews electric vehicles, charging infrastructure, and possible ways to build a high power and low voltage charger or charging station for electric vehicles. In summary, several types of electric cars and electric ships are reviewed along with their characteristics (similarities and dissimilarities). In order to build a charging infrastructure both for ECs and ESs, new dedicated medium voltage (10-20 kV) underground or overhead lines needs to be installed from the grid to the charging infrastructure. To step down medium voltage AC to low voltage AC levels either a low-frequency transformer can be utilized or modular solid-state transformers may be opted. The latter one is beneficial in a way that it has lesser footprints and the initial cost is low. To convert low voltage alternating current to low voltage direct current generally rectification based on H-bridge diodes with PFC is recommended for uni-directional power flow due to its lower cost and higher efficiency and for bi-directional flow of power, several modules of active front-end converters are employed. As currently, smart cities are being built, which are being integrated with more and more highly intermittent RES where the V2G concept might help to support and absorb the power from the grid or to provide ancillary services. Generally, magnetic field-based isolation (typically a transformer) is used but due to the leakage inductance of a MF transformer, a resonant tank (capacitor and inductor) needs to be integrated that adds up the complexity and the cost. An alternative approach is to use a pair of semi-conductor switches to provide an isolation between charging infrastructure and the vehicle, which ultimately is a cost-effective approach. The modern vehicle equipped with huge battery packs needs to be charged quickly and to minimize the charging time up to the time for filling the gasoline, interfacing robots or wireless-based charging is recommend in comparison with the old fashioned human-based connection approach. Further, for ESs (especially ferries) battery swapping could be one of the possible approaches and to charge the EVs, CC-CV or multi-stage CC approaches are preferred. Further, RES and stationary banks need to be integrated particularity in localities where the grid is weak to support the charging infrastructure.

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