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Review

Electric Vehicle Traction Drives and Charging Station Power Electronics: Current Status and Challenges

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Abstract: With the need for more environmentally friendly transportation and the wide deployment of electric and plug-in hybrid vehicles, electric vehicle (EV) charging stations have become a major issue for car manufacturers and a real challenge for researchers all over the world. Indeed, the high cost of battery energy storage, the limited EV autonomy and battery lifespan, the battery charging time, the deployment cost of a fast charging infrastructure, and the significant impact on the power grid are the origin of several research projects focused on advanced power electronics topologies and the optimization of the EV charging stations in terms of power transfer and geographical location. Three charging levels can be distinguished, which differ in terms of output power and charging time. The higher the level of charging, the faster the charging process, as more power is delivered to the vehicle at the expense of power quality issues and disturbances. Moreover, three types of charging systems can be distinguished, which are inductive recharging (contactless power transfer), conductive charging systems, and battery swapping. Additionally, EVs encompass fuel cell (FC) EVs, which uses hydrogen as primary energy resources, which is nowadays under extensive research activities in academia and industry. This review paper aims at presenting a state of the art review of major advances in power electronics architectures for EVs traction drives, and battery-based EVs charging stations. Specifically, the focus is made on light-duty electric vehicles drivetrain power electronics and charging stations specifications, the proposed power electronics solutions, the advantages and drawbacks of all these technologies, and perspectives for future research works in terms of smart EV charging and up-to-date solutions for power system disturbances mitigation.

Keywords: electric vehicles; fuel cell vehicles; EV charging stations; smart charging; power electronics; AC/DC charging stations; Fast/Ultra-fast charging; vehicle-to-grid; vehicle-to-home; green hydrogen



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1. Introduction

The increasing awareness of global warming and the advances in battery storage systems in power electronics [1–3] and electric motors technologies have paved the way for the massive deployment of hybrid vehicles, plug-in hybrid electric vehicles, and fuel cell (FC) vehicles [4,5]. As the number of electric vehicles (EVs) is significantly increasing, impacts on power grid performance and efficiency, such as overloading, reduced efficiency, power quality issues and disturbances, and voltage regulation, particularly at the distribution level, may significantly increase in the near future [6]. Hence, the rapid emergence of electric vehicles requires an advanced infrastructure of private and publicly accessible charging stations that provide efficient, reliable, and robust charging services while reducing grid impacts [7–11].

Passenger and light-duty electric vehicles are on the verge of going mainstream [12,13]. This is driven by the commitment to reduce environmental impacts and achieve fossil

fuel free transportation. Electric vehicles offer many advantages over traditional internal combustion engine (ICE) vehicles, such as fewer moving parts, higher efficiency, higher starting torque, reduced maintenance and operating costs, and the ability to be powered by locally produced renewable energy [14]. However, mass EV adoption is not without its challenges: EVs are generally more expensive than ICE vehicles; mining and conversion of lithium are expensive and are environmentally unfriendly processes; batteries weight and lifespan are critical [15]; and public charging infrastructure is in its infancy. In addition, unregulated mass charging of EVs can generate significant disturbances in the power grid [16–18]. On the customer side, unlike ICE vehicles that require a few seconds to a few minutes to refuel, electric cars require several tens of minutes to several hours to fully recharge, which implies a significant waiting time [19,20]. It is worth stressing that the autonomy of medium range EVs is still very limited and restricts their use to urban environment [21,22]. On the economic side, technological progress and cost reductions linked to the expansion of production capacity in manufacturing plants will lead to a decrease in the price of batteries, which represents the most constraining cost of the electric vehicle [23]. Indeed, in electrochemistry, battery autonomy is still increasing thanks to the improvement of the battery's energy density [24,25]. Regarding the electrical engineering and power electronics aspects, solutions concerning the reduction of the impact on the power grid [17,26] and the support to the grid by providing ancillary services during on-peak periods (vehicle-to-grid concept) [27–29] are still under progress, and this will represent the main track on which will be based the upcoming research works. Indeed, electric vehicles charging will have a considerable impact on the stability of the power grid. In addition, it will be necessary to meet the needs of a large and growing number of customers in terms of charging stations availability and charging requirements such as starting time, required power, and desired state of charge (SOC) [30,31].

Advances in batteries technology and fuel cells in motors drives and in power electronics have driven the rapid penetration of EVs in transportation sector. In EVs, power electronics converters control the power flow from the energy source (batteries and hydrogen tanks and fuel cell) to the wheels through an electrical motor. The classification of electric vehicles depends upon the combination of energy sources, energy storage devices, and power converters that drive the vehicle [2]. In battery electric vehicle (BEV), only battery pack is used as energy source, which can be combined with supercapacitors for dynamic performance enhancement [32]. Fuel cell associated with hydrogen tank and battery is operated in a fuel cell electric vehicle (FCEV) [33–35]. Battery associated with power electronics and motor drives and ICE are operated in hybrid electric vehicle and plug-in electric vehicle [36–38]. All these EVs present the advantage of reducing green house gas emissions and improving the efficiency of the energy conversion as compare to traditional ICE-based vehicles [39]. However, it presents some drawbacks that are related to lower driving range and long time to recharge batteries for BEV and security issues for FCEV.

Charging infrastructure is of paramount importance for the massive deployment of EV usage. Indeed, there is a need for EV charging stations parallel to gasoline stations especially in highways that have minimal impact on the electric utility distribution system [40–43]. These EV chargers should be reliable, robust, modular, cost competitive, and should comply with power quality standards [7]. EV charging stations can be broadly classified into three categories, which are conductive power transfer, inductive power transfer, and battery swap [6,44]. Conductive power transfer is subdivided into on-board, which are in compliance with AC charging and off-board chargers, which are used for DC charging. Moreover, EV charging stations comprise three charging levels depending on the charging powers and charging duration [45]. All EVs are equipped with a Level 1 on-board AC/DC charger that simply plugs into a standard AC power outlet. Level 2 is also an AC charger, which is faster compared to level 1 charger. This level is also based on the use of the AC/DC charger embedded in the EV but designed for higher powers. Finally, Level 3 is a DC fast charger with external power electronics to the EV. Charging levels and charging

times apply to EVs and plug-in hybrids, but not to traditional hybrids as they are charged by regeneration or by the engine, not by an external charger. EVs when connected to the charging infrastructure can be used to relief the grid during congestion periods by implementing vehicle-to-grid technology [46–48].

In this paper, a state of the art regarding the technologies and main characteristics of partially or fully electric vehicles are presented. The battery-based EVs charging methods (their types, infrastructures and standards) and the recent research activities on the power electronics architectures are discussed by enumerating their advantages and disadvantages [49]. Then, the required improvements for efficient and optimal EVs charging methods are highlighted. Techniques currently used in industrial applications to overcome the problems related to EVs charging stations integration into power grid are presented. Finally, a discussion is conducted on smart charging stations, more specifically charging stations with local energy production using available renewable resources associated with more recent advances in energy storage systems. Fuel cell-based electric vehicle with main challenges related to green hydrogen, that is considered as a flexible energy carrier, are briefly introduced. What this review can allow concluding is that the largest barrier nowadays towards mass-market EV adoption for is the charging problem for BEV and green hydrogen production for FCEV.

2. Light-Duty Electric Vehicle and Charging Stations Technologies

This section presents two aspects related to electric vehicles and charging stations infrastructure as follows:

- Departing from a mechanical study and WLTP driving cycle, presenting the requirements in terms of torque, power, and energy of a vehicle. Then, presenting all possible technologies of vehicles: ICE vehicles, hybrid vehicles, and electric vehicles.
- Presenting charging stations technologies for electric vehicles and refueling stations for fuel cell vehicles.

2.1. Power and Energy Requirements

To evaluate the power and energy requirements for light vehicles, Worldwide harmonized Light vehicles Test Procedures (WLTP) are used [50,51]. The purpose of these procedures is to ensure that the real-life conditions of use of vehicles and their current technologies are better taken into account during certification.

2.1.1. Worldwide Harmonized Light Vehicles Test Procedures

WLTP is a vehicle testing and certification standard that measures fuel consumption, electric range and CO₂ and pollutant emissions [52]. This test procedure mainly applies to passenger cars and light commercial vehicles while other procedures concern motorcycles and heavy vehicles. WLTP became effective in Europe in September 2017 for new models and in September 2018 for all new vehicles, replacing the new European driving cycle (NEDC), dating from 1973 and updated in 1996 [53,54]. These test procedures have also been adopted in China and Japan in recent years. Figure 1 provides WLTP cycles for which vehicles are classified into three main categories [55]. Each class includes several driving cycles, known as Worldwide harmonized Light vehicles Test Cycles (WLTC) designed to represent real-world use in city traffic, extra-urban traffic, on car roads and on highways. The duration of each cycle is the same for all classes, but the acceleration and speed curves are different. WLTC cycles are based on the following preliminary vehicle classification:

- **Class 1** concerns vehicles for which the ratio of rated power in W/kg ≤ 22
- **Class 2** is related to vehicles with ratio of rated power in W/kg > 22 but ≤ 34
- **Class 3** focuses on vehicles with ratio of rated power in W/kg > 34 . The majority of vehicles are included in class 3.

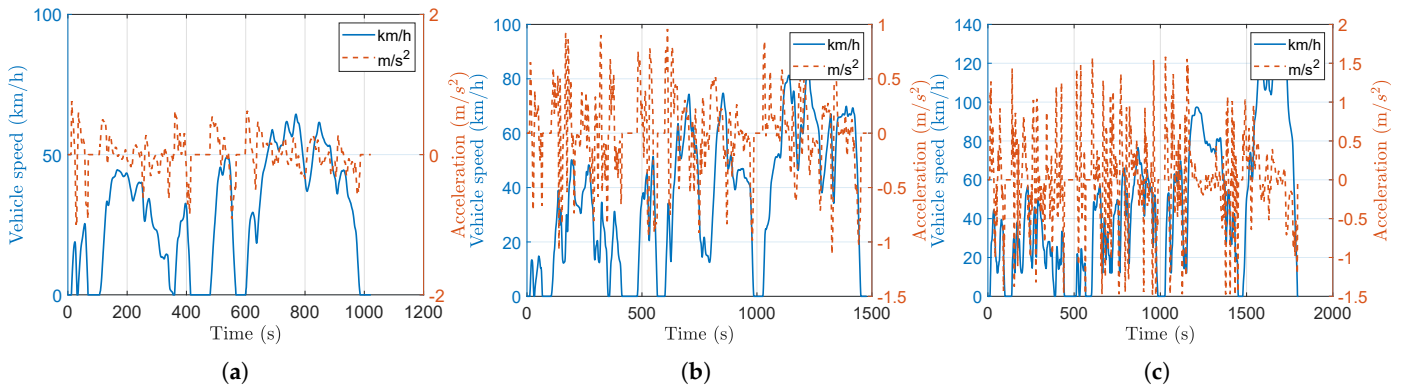


Figure 1. WLTP driving cycles for validation. (a) Class 1: Power-to-weight in W/unladen mass in kg ≤ 22 . (b) Class 2: Power-to-weight ratio in W/unladen mass in kg > 22 but ≤ 34 . (c) Class 3: Power-to-weight ratio in W/unladen mass in kg > 34 .

2.1.2. Numerical Study Results

Some simulations have been conducted for a standard class 3 vehicle, which power-to-weight ratio is greater than 34 W/kg to quantify the power and energy requirements in real world application [56,57]. The considered vehicle parameters are provided in Table 1. When a vehicle is moving, several resisting forces must be overcome, which are depicted in Figure 2:

- Aerodynamic force: $F_{aero} = \frac{1}{2}\rho C_x S_f V^2$;
- Rolling resistance force: $F_{rr} = f_{rr} M g \cos(\alpha)$;
- Slope resistance force: $F_{rc} = M g \sin(\alpha)$.

A straightforward computation leads to the following equations that model the vehicle dynamics:

$$\begin{cases} (J_{wheels} + M R^2) \frac{d\Omega}{dt} = C_m - C_r \\ C_r = \frac{1}{2}\rho C_x S_f R^3 \Omega^2 + M g (\sin(\alpha) + f_{rr} \cos(\alpha)) \end{cases} \quad (1)$$

where, C_r is the resisting torque that is applied to wheels and Ω is the rotational speed of the wheels.

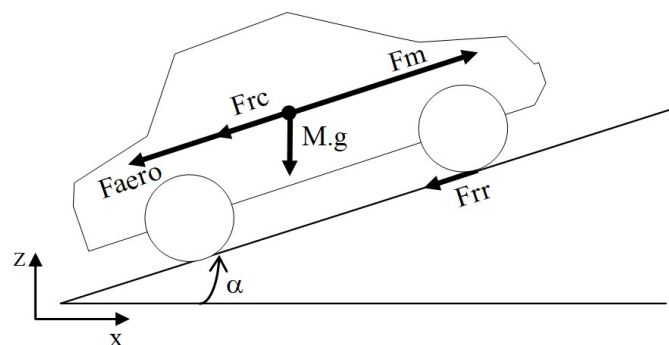


Figure 2. Forces affecting vehicles in motion.

Power requirements for achieving a WLTP driving cycle are depicted in Figure 3. These curves show that the required maximum power is around 85 kW, which is much greater than the average power. Moreover, the driving torque is about 1.5 kN.m, which is of paramount importance for motor drives sizing. Energy requirements are shown in Figure 4 for class 1, class 2, and class 3 vehicles, without considering the regenerative braking. It is interesting to mention that, for class 3 vehicles, the energy requirement is about 250 Wh/km. This means that, for 500 km range and considering that a 80% depth of discharge is required, the battery stored energy should be 156.25 kWh without taking

into consideration the energy required for supplying the auxiliary units (water circulating pump, control system, fuel circulating pump, ventilation fan, air circulating pump, etc.).

Table 1. Vehicle parameters.

Symbol	Parameter	Value
ρ	Air density	1.2 kg/cm ³
C_x	Air penetration coefficient	0.302
S_f	Vehicle cross-section	2.4 m ²
f_{rr}	Rolling resistance coefficient	0.012
g	gravity acceleration	10 m/s ²
α	Slope angle	
M	Vehicle weight	1500 kg
R	Radius of the drive wheel	0.35 m
J_w	Wheels momentum of inertia	$0.75 \times 4 \text{ kg} \cdot \text{m}^2$

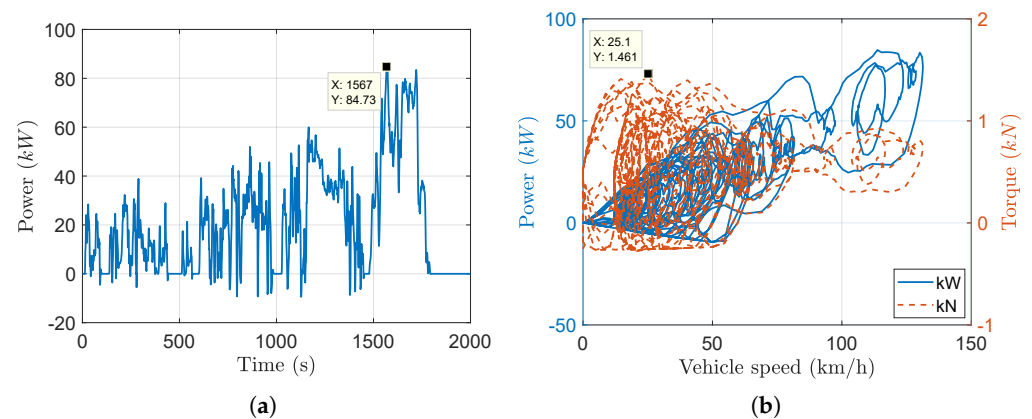


Figure 3. Simulation results for three class vehicles. (a) Class 3: Power versus time. (b) Class 3: Power versus vehicle speed.

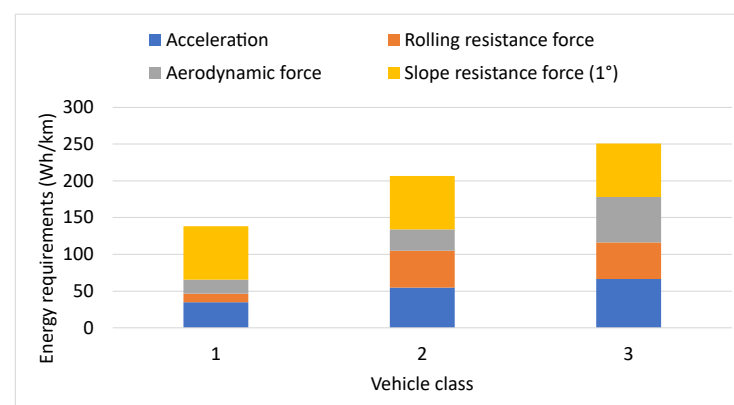


Figure 4. Energy requirements for standard vehicle (Table 1) using WLTP driving cycles.

Some solutions can be implemented to minimize the required energy in transportation as follows [58,59]:

- Vehicle mass reduction: the objective in automotive industry is to reduce weight by 30% with a cost limit of 500 € per 100 kg.
- Aerodynamics improvement:
 - No significant improvement of C_x (minimum of 0.26).

- Vehicle frontal area reduction.
- Total road load power reduction by improving tire technology.
- Evolution of road infrastructure: traffic management and pavement improvement.
- Eco-driving: driving as safely and smoothly as possible to reduce energy consumption and limit pollutant emissions.

2.2. Vehicles Technologies

Based on the power and energy requirements presented earlier several vehicles technologies can be considered. Indeed, vehicles can be classified based on the used motors as vehicles with 1 motor that include ICE vehicles, BEV and FCEV, or hybrid vehicles, which include both ICE and electrical motors [57,60]. Otherwise, it can be categorized based on the energy storage devices used: gasoline tank for ICE vehicles, batteries that can be associated with supercapacitors for BEV [61], and hydrogen tank and battery for FCEV vehicles [56]. EV classification is shown in Figure 5. Advantages and drawbacks of electric and ICE vehicles are provided in Table 2.

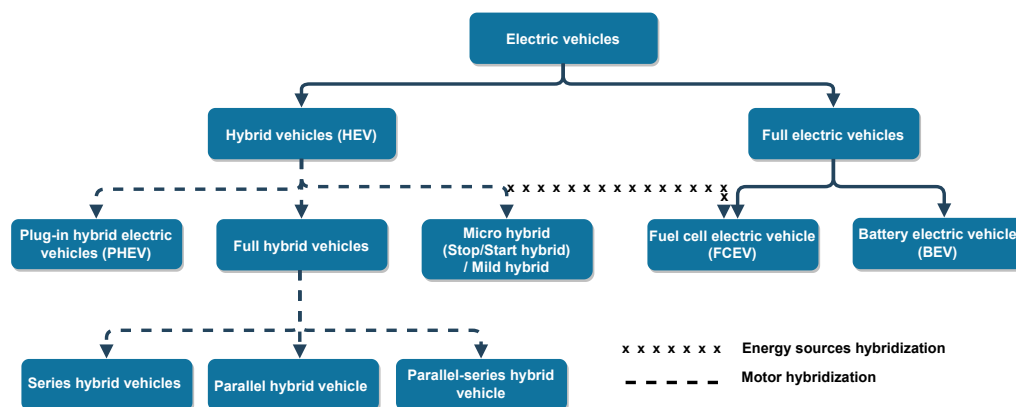


Figure 5. Electric vehicles classification.

Table 2. Comparison of ICE vehicles and electric vehicles.

	ICE Vehicles	Electric Vehicles
Advantages	<ul style="list-style-type: none"> • High energy density of the storage system (12 kWh/kg). • Energy distribution infrastructure. • Very low refueling time (60 L in less than 5 min representing a power of several MW). • Presence of a heat source to warm the vehicle interior. 	<ul style="list-style-type: none"> • High torque at zero speed. • No pollutants emissions. • High efficiency. • Suitable for urban use. • Simple mechanical principle.
Drawbacks	<ul style="list-style-type: none"> • Green house gas emissions • Sophisticated mechanical system • Low efficiency 	<ul style="list-style-type: none"> • Low energy density of the storage system (less than 200 Wh/kg) • High recharging time. • Lack of hydrogen distribution infrastructures and fast charging stations for BEV. • No heat source to warm the vehicle for BEV.

2.2.1. Internal Combustion Engine Vehicles

Internal combustion engine is a heat engine transforming chemical energy of fuel into kinetic energy, which is used to propel, move, or power the vehicle [62,63]. ICEs are

typically powered by fossil fuels like natural gas or petroleum products such as gasoline, diesel fuel, or fuel oil [64]. Renewable fuels like biodiesel and bioethanol are also used, which are commonly blended with fossil fuels [65,66]. Hydrogen, which is rarely used, is currently massively obtained from fossil fuels (gray hydrogen) and rarely from renewable energy resources (green hydrogen) [67]. For class 3 vehicles, energy consumption is about 250 Wh/km, which implies 25 kWh to achieve a range of 100 km. Assuming a thermal engine efficiency of 30%, the thermal energy required to drive 100 km is 83.33 kWh. As diesel has an energy density of 9.7 kWh/L, a class 3 vehicle consumes around 8.59 L and produces approximately 22.3 kg to drive 100 km (223 g per km). If a vehicle tank has a capacity of 70 L, the total range of this type of vehicle is 814 km. The power that this ICE must produce must be equal to 85 kW. Unfortunately, ICE presents the inconvenience of having a limited or no torque at low speed and a very limited torque band [68]. Manual transmission and a clutch or automatic transmission are usually used to overcome this issue at the expense of complex power transmission system [69].

2.2.2. Hybrid and Plug-In Hybrid Vehicles

Hybrid electric vehicle (HEV) is a vehicle which, in addition to its primary energy resource (chemical energy of the fuel), has a second form of reversible energy storage: hydraulic, pressure, kinetic, or electrochemical [70,71]. In general, HEV combines the electric motor associated with battery energy storage device with ICE to power the wheels. This way, ICE is operated in its maximum efficiency band and electric motor allows achieving acceleration stage [72]. Indeed, an electric motor is more efficient at producing torque and ICE is better for maintaining high speed. HEV comprises micro hybrid, mild hybrid, full hybrid, and plug-in hybrid [73,74]. Table 3 provides some characteristics depending on the hybridization level.

Table 3. Hybrid vehicles: level of hybridization.

Hybridization Level	Micro Hybrid (Stop/Start Hybrid)	Mild Hybrid	Full Hybrid/Plug-In Hybrid
Fuel consumption reduction in combined cycle	3 to 10%	15 to 25%	30 to 40%
Installed electrical power	2 to 6 kW	10 to 20 kW	20 to 60 kW
Battery voltage	12 V to 42 V	120 V to 150 V	200 V to 300 V

Three full hybrid vehicles configurations can be distinguished as depicted in Figure 6, which are series, parallel, and parallel-series vehicles [2]. The switching from ICE to electric motor and vice versa at adequate time and the regenerative braking yields to better efficiency of the whole system. In a series hybrid vehicle (Figure 6a), the ICE generally provides average power, while the power peaks are handled by the energy storage device [75,76]. The internal combustion engine, which is not directly coupled to the wheels, can be operated in an optimal operating range, which reduces consumption and pollution. The internal combustion engine automatically starts when there is only 30% charge left in the battery. The range in pure electric mode is about 60/70 km. The battery is charged from the main grid for plug-in electric, or while driving during the energy recovery phases: when going downhill, when slowing down by lifting the foot off the gas pedal, or when braking. In parallel hybrid configuration (Figure 6b), the combustion engine provides power to the wheels in the same way as in a conventional vehicle [77,78]. It is mechanically coupled to an electric motor that can assist it. According to the structure and the design of the vehicle, the mechanical coupling can be either torque addition coupling or speed addition mechanism [77,79,80]. Finally, the parallel-series hybrid vehicle (Figure 6c) combines the two previously presented principles [81,82]. This vehicle is composed of

two electric machines and a planetary gear that allow the mechanical coupling with the ICE [37].

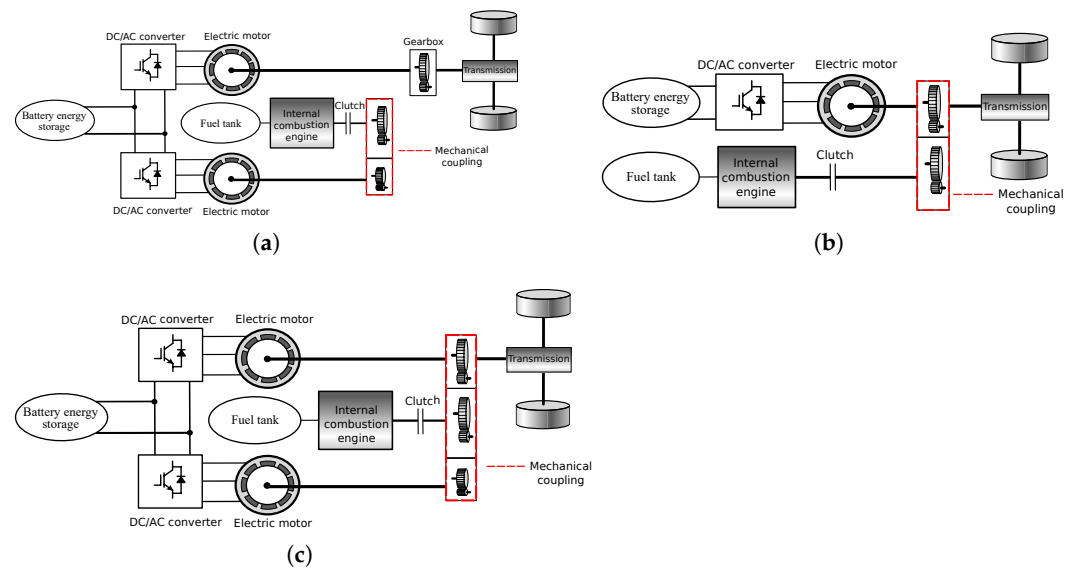


Figure 6. Full hybrid vehicles classification. (a) Series hybrid vehicle. (b) Parallel hybrid vehicle. (c) Parallel-series hybrid vehicle.

2.2.3. Battery Electric Vehicles

In BEV, battery energy storage system (BESS) provides the power required for the traction/propulsion [24,83]. The range of the EV depends upon the battery capacity and the driver behaviour. Nowadays, 360 V to 400 V DC voltage batteries are used with an extensive research to step up the voltage to 800 V [84,85]. Several electric motor technologies are used to propel EVs such as permanent magnet synchronous motors, induction motors, wound rotor synchronous motors, and internal permanent magnet synchronous reluctance motors (IPMSynRM) [86–88]. The typical BEV power conversion system is shown by Figure 7a. BEV can operate in two different operating modes: battery mode and regenerative braking mode. In battery mode, the power is transferred to the motor that drives the wheels through a boost DC/DC converter followed by DC/AC converter. In regenerative braking mode, EV kinetic energy is converted to electricity and stored in the battery.

With the regenerative braking mode, the energy consumed at the wheels is about 15 kWh per 100 km (except for highway driving). The efficiency of the transmission train is about 90%. Therefore, 16.7 kWh of electric energy is required to achieve 100 km range. If the same range is expected as in ICE vehicle, it is necessary to have a available energy of 145 kWh. Batteries can not be completely discharged, and a battery of 160 kWh is required. Batteries specific energy depends on the used technology. It varies from 75 Wh/kg for Lithium-Titanium-Oxide (LTO) batteries to around 250 Wh/kg for Lithium-Nickel-Manganese-Cobalt-Oxide (NMC) batteries. Considering a specific energy of about 150 Wh/kg, the total mass of the required battery must be 1100 kg. Unfortunately, this weight is huge and the implementation of this battery is not suited for various reasons such as battery cost, battery weight, and battery recharging time. The previous battery sizing is performed based on the electric vehicle range [89]. It is of paramount importance that chosen batteries allow supplying the required power while fulfilling the thermal constraints [90,91]. A thermal study is required to achieve an appropriate battery sizing based on power constraint or limit the required power and consequently the performance of the EV [92,93]. Another solution would be to combine two types of ESS: batteries for achieving the required autonomy and supercapacitors for power peaks delivery [94,95].

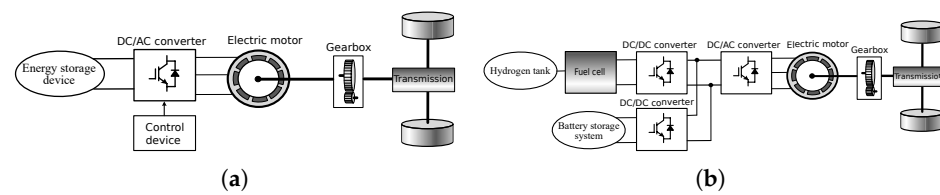


Figure 7. Electric motor vehicles. (a) Battery electric vehicles. (b) Fuel cell electric vehicles.

2.2.4. Fuel Cell Electric Vehicles

A fuel cell electric vehicle (FCEV) is an electric vehicle that uses a fuel cell in combination with a small battery or supercapacitor, to power its on board electric motor as depicted in Figure 7b [96–99]. The key component of the FCEV is the fuel cell, which generates electricity using oxygen from the air and compressed hydrogen stored in a special technology of tanks at 350 bars or 700 bars (10,000 PSI) [100–102]. FCEV are considered as zero-emissions vehicles that emit only water and heat. Low temperature fuel cell (80 °C) are available in the market, while high temperature fuel cell (160 °C) are under extensive investigations in academia and industry. Several types of fuel cells exist such as polymer electrolyte membrane fuel cells, direct methanol fuel cells, alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, solid oxide fuel cells, and reversible fuel cells [103–105]. Five modes of operation can be distinguished in FCEV. In fuel mode, a fuel cell is used to supply the motor in EV powertrain. In battery mode, a battery is used to propel the train individually. The use of both of fuel cell and battery is termed combined mode. In this mode, average power is provided by fuel cell and power peaks are supplied by battery. In split mode, fuel cell is used to drive the vehicle and to charge the battery. Finally, in regenerative mode, kinetic energy is used to charge the battery during vehicle braking.

Fuel cell vehicles present the advantages of longer range and short fueling times. Moreover, as long as energy used to produce hydrogen is sustainable, it can be truly a green fuel [106,107]. However, the efficiency of FCEV is only 38% as compared with BEV, which are from 80% to 95% efficient [108,109]. Moreover, despite some advances in the technology to generate hydrogen, the vast majority of it is a polluting gray hydrogen that requires energy-intensive processes that are largely fueled by natural gas and fossil fuels or lots of nuclear electricity. Finally, delivering hydrogen would require building a vast and expensive new infrastructure [110].

2.3. Charging Stations

With the rapid expansion of the electric vehicle market (electric and plug-in hybrid vehicles) and the increase of their battery capacity, a properly distributed recharging infrastructure with reliable and safe recharging possibilities is essential to meet users' needs and contribute to the deployment of electric mobility. EV charging technologies can be categorized into three main classes, namely, conductive charging, inductive charging, and battery swapping, as shown in Figure 8 and corresponding illustrations are provided in Figure 9.

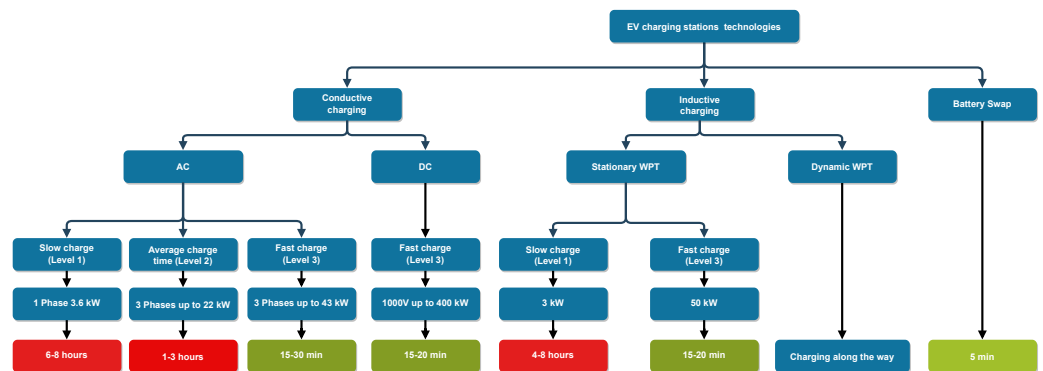


Figure 8. Charging stations classification.

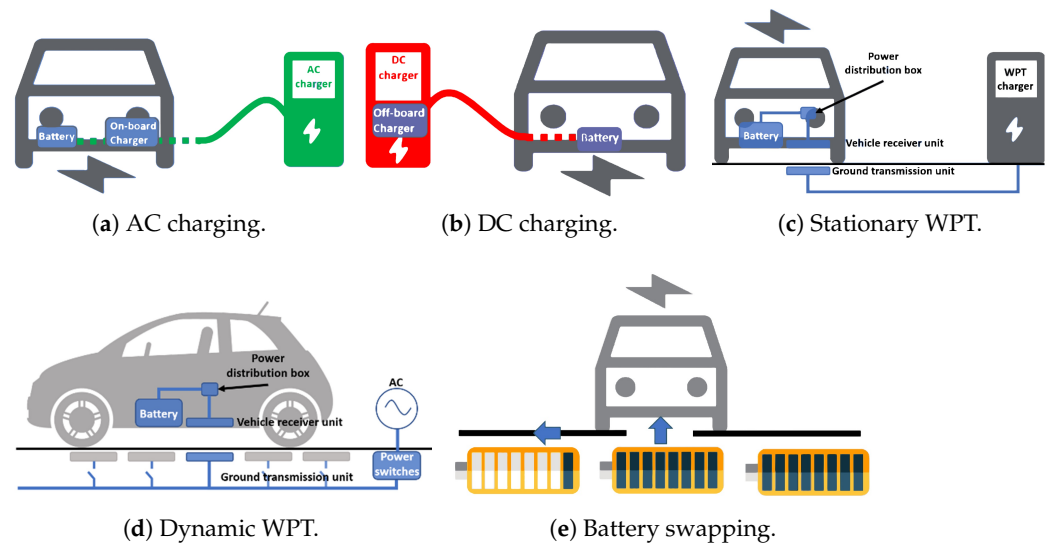











Figure 9. Charging stations classification illustrations.

2.3.1. Electric Vehicle Supply Equipment

Electric vehicle supply equipment (EVSE) supplies electricity to the electric vehicle batteries. EVSE includes electrical power conductors, charge ports, protection equipment, and software and communication devices and protocols that are used to provide electric power to recharge the EV batteries in an efficient and secure manner and to ensure communication between the EV and the charging station [111], on one hand, and manage the charging station and the electric grid interactions, on the other hand [112,113]. The types and standards of EVSE are given by Table 4. These standards and codes mainly define the interface between the EV and EVSE and the interface between the EV and power grid. The most common standards include SAE J1772 in north America and IEC 61851/62196 in Europe and emerging markets. These EVSE can be either AC or DC, as shown in Figure 8. AC charging uses power directly from the electric grid with the EVSE simply monitoring the flow of power and ensuring safe operating environment, as shown in Figure 10. The conversion from AC to DC power is performed on board to feed the battery. However, DC charging options convert the grid AC power to DC power off-board and directly supplies the EV battery, as depicted in Figure 10. This allows higher charging power levels compared to the AC charging. All chargers require simple pins for communications and controls, which ensure fault detection and overloading protection [114,115]. Modern vehicles and charger communications include vehicle communication, which monitors the flow of data throughout vehicles including state of charge, charger communication, which oversee the flow of data throughout EVSE, and finally, network communication, which oversee the flow of data throughout third-party data providers [114]. EVSE has specific requirements for power quality but has a wide range of permitted power output for different charging levels [45].

Table 4. Types and standards of charging connectors.

Connectors	Charging Modes	Symbols	Country	Pins	Voltage, Current, Power	Standards
Type 1/j1772	AC		USA Japan	3 power pins (L, N, PE)	1Φ 120 V, ≤16 A, 1.9 kW 1Φ 240 V, ≤80 A, 19.2 kW	SAE j1772 IEC 62196
Type 2/Mennekes	AC		EU China	5 power pins (L1, L2, L3, N, PE) 2 control signals—CP, PP (PWM for CP)	1Φ 230 V, ≤32 A, 7.4 kW 3Φ 400 V, 63 A, 43 kW	IEC 62196 GB/T 20234.2-2015
	DC		Tesla (EU)	3 power pins (DC+, DC−, PE) 7 control signals (comm. CAN)	400 V, ≤140 A, 56 kW	IEC 62196
CHAdeMO (JEV G105-1993)	AC		Japan	3 power pins (DC+, DC−, PE) 7 control signals (comm. CAN)	200–500 V, ≤400 A, 200 kW CHAdeMO 2.0: 1000 V, ≤400 A, 400 kW	IEC 61851-23, -24 IEC 62196-3 IEEE 2030.1.1TM-2015
CSS/Combo	DC		USA	3 AC pins 2 DC pins 2 control signals CP (PLC), PP	200–1000 V DC, ≤350 A, 350 kW	IEC 62196-1/2/3 IEC 61851-1/22 IEC 61851-1/23 ISO/IEC 15118 DIN SPEC 70121 SAE J2847/2
			EU	5 AC pins 2 DC pins 2 control signals CP (PLC), PP		
GB/T	DC		China	5 power pins (DC+, DC−, PE, 2 Aux. power pins BT) 4 control pins : 2 PP, 2 CAN	750/1000 V, ≤250 A, 237.5 kW	GB/T 20234
Tesla	AC		Tesla (Except EU)	3 power pins (DC+, DC−, E) 2 control signals CP, PP	1 Φ 240 V, ≤72 A, 17.2 kW	IEC 62196
	DC			3 power pins (L1, N, E) 2 control signals CP, PP	400 V, ≤650 A, 250 kW	

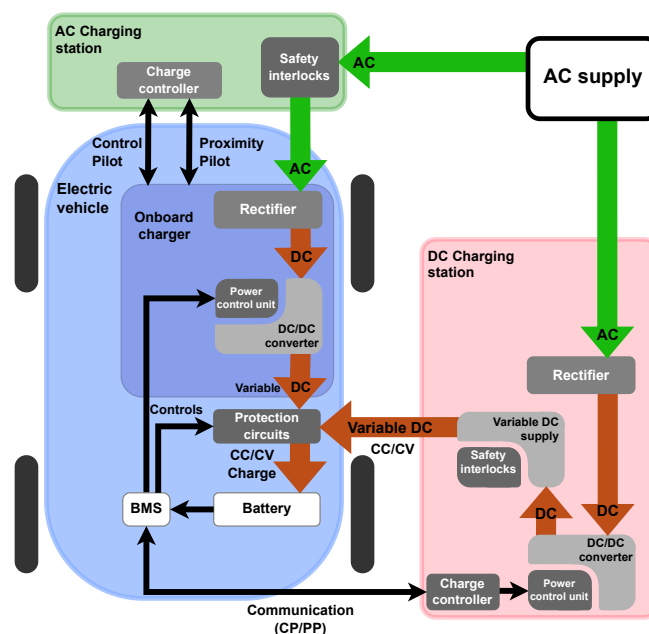


Figure 10. Electric vehicle supply equipment.

2.3.2. EV Charging Modes and Charging Stations Level

There exist three EV charging modes, which are conductive charging [45], inductive charging [116–118], and battery swapping [119,120]. These charging modes are briefly discussed in the following:

- **Conductive chargers:**

Conductive chargers can be either on-board or off-board. On-board chargers are AC chargers that are limited in terms of size and nominal power. The AC/DC conversion is performed within the vehicle, which may offer the possibility to use the traction energy conversion system for battery charging. Off-board chargers are DC chargers characterized by higher output power. Moreover, this configuration offers more flexibility in terms of the power that can be supplied. Conductive charging stations can be classified into three distinct levels. EVSEs are classified as Level 1, Level 2, and DC Fast Charger, which differs in terms of output power type and level. All vehicles can be connected to a Level 1 or Level 2 chargers [16,121]. However, some vehicles can not be charged at a level 3 charger because they exceed the limits set by the manufacturers, such as the limits related to the batteries charging rate.

- **Level 1 charger:** Level 1 charging is via an on-board low power EV charger (do not exceed 2 kW). These chargers plug into a standard 220 V outlet (120 V in north America) and can recharge an EV for a range of 200 km in 20 h. Standard electrical outlets are available everywhere; level 1 charging is usually performed at homes and in the parking bays of residential buildings.
- **Level 2 charger:** Level 2 chargers are generally AC chargers that are concerned with the following standards: type 1 (j1772), type 2 (mennekes), and AC Tesla charger. This level is based on the use of the EV's on-board AC/DC charger designed for higher power ratings. Level 2 charging requires a fixed charging station powered by a separate 208 V or 240 V branch circuit. It requires specific equipment and installation for their deployment at domestic and commercial level.
- **Level 3 charger:** Generally, DC chargers that are based on the use of the off-board EVSE offering a much higher power than level 1 and 2 and can charge an electric vehicle much faster (less than 1 h). These chargers are generally installed along highways. Level 3 should comply with the requirement of the following standards: type 2 DC (mennekes), CHAdeMO (JEV G105-1993), DC Tesla chargers, CCS combo, and GB/T.

- **Inductive chargers:**

The inductive charger is a contactless power transfer (WPT) system allowing battery charging based on electromagnetic waves [122–124]. This type of charging is available in two configurations:

- **Stationary charging [124]:** performed at a standstill in a parking space. This would eliminate the required terminals with charging triggering and payment being controlled via the electric vehicle multimedia system.
- **Dynamic charging [125]:** EV charging performed while driving thanks to a device integrated along the road.

Wireless charging will effectively solve the problem of the multitude of charging ports that vary in shape, size, and pins configuration depending on EV brand and country. In fact, with the use of this charging method, all the electric vehicles will be charged with the same infrastructure and will be exempted from the use of conventional cables. Additionally, thanks to the system ground integration, it avoids any risk of vandalism or ripping off by a distracted driver and also eliminates any risk of electrocution as there is no electrical contact.

Moreover, with dynamic inductive charging, it is possible to downsize the battery capacity, which will contribute to a considerable reduction in the EV cost. However, this charging method has some drawbacks. Indeed, the inductive charging method has a lower overall efficiency than the conductive charging method, as the power

conversion process using an air gap is less efficient than the direct power transfer using cables. Furthermore, inductive charging efficiency decreases due to the misalignment between the transmitter and the receiver coils.

- **Battery swapping [119,126]:**

Battery swapping works on the basis of changing the depleted battery and replacing it with an identical battery with a 100% charge. The process involves driving into a battery switch bay, and an automated process will position the vehicle, disconnect the current battery, and replace it with a fully charged battery. Depleted batteries are charged in the station for later use. The system operates under the business model that the EV user owns the vehicle, not the battery. The battery swapping remains the fastest method (equivalent to refueling time). However, this method is very difficult to implement as batteries must be standardized between several EV manufacturers. Additionally, users are more likely to reject the idea changing their batteries with others that may have poor health conditions. There are also significant cost and logistical issues, as enough extra batteries in switch bay are required to supply customers quickly.

3. Power Electronics for EV Charging Stations

EV charging requires either single-phase or three-phase charging stations that have unidirectional or bidirectional power flow capabilities. Moreover, EV charger can make use of traction powertrain equipment to achieve high power density and weight reduction in order to save space in the vehicle while increasing efficiency.

3.1. Specifications

Generally speaking, an electric vehicle charging station should comply with the following specifications and deliver a number of other functions, particularly durability, efficiency, and performance:

1. Implement a power factor correction: absorb a sinusoidal current free of harmonics with a power factor equal to 1.
2. Bidirectional power electronics topology that allow participating to the energy storage on the grid in order to implement a vehicle-to-grid or vehicle-to-home concept.
3. Bidirectional power electronics topology that allow participating to the energy storage on the grid in order to implement a vehicle-to-grid or vehicle-to-home-concept.
4. Using the traction inverter in the EV charging power electronics.
5. No additional filtering inductance by using traction motor windings.
6. Possibility of balancing battery elementary cells by implementing a part of battery management system functions.
7. Contactless power transfer.

3.2. Power Electronics Solutions

To meet these EV charging stations requirements, several power electronics solutions have been proposed and implemented by car manufacturers and energy providers. These solutions are briefly presented and discussed in the following subsections. The readers may refer to the following paper for more details on power electronics configurations [6].

3.2.1. Unidirectional Battery Charger

Unidirectional chargers have a diode bridge rectifier (DBR) associated with a filter stage and a DC/DC converter, as shown in Figure 11. The DBR can be either single-phase (Figure 11) or three-phase to increase the charging power. Moreover, a high frequency isolation transformer is used to ensure isolation during EV charging. This converter topology does not have the ability to use EV battery as energy resource and then inject power to the utility grid. However, it allows providing ancillary services, mainly voltage regulation, by supplying or absorbing reactive power from the main grid without EV battery discharging.

Unidirectional battery chargers offer a simple and easy-to-control solution to manage EV fleet and meet the requirements for safe, reliable, and cost-competitive EV charging solution. However, with the increasing penetration of EV in the transportation sector, it is intended to play a key role in the main grid regulation (mainly, frequency and voltage regulation), which can not be totally ensured using unidirectional EV chargers. Consequently, there is a need for bidirectional power flow topologies that allow EVs to act as a distributed energy storage on the power system [127,128].

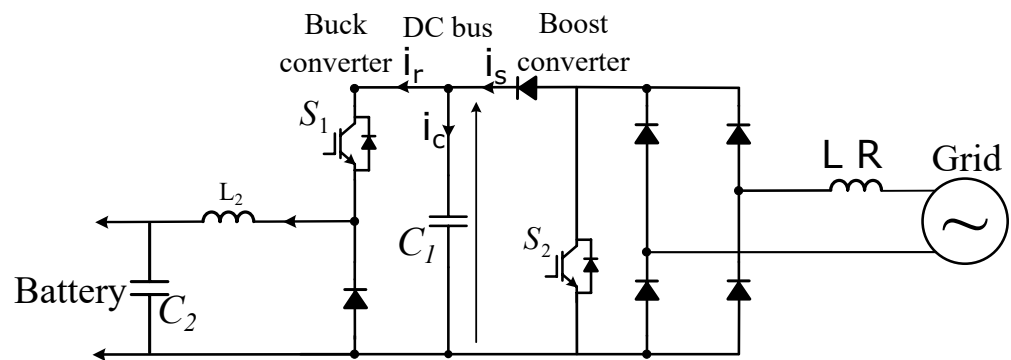


Figure 11. Unidirectional battery charger for EVs.

3.2.2. Bidirectional Battery Charger

Bidirectional EV chargers are composed of two stages, which are a single-phase or three-phase active front end (AFE) followed with a bidirectional DC/DC converter, as depicted in Figure 12. AFE is a bidirectional AC/DC converter that allow regulating the DC bus voltage and controlling quasi-sinusoidal grid currents, while ensuring a unity power factor (current phase angle control) or exchanging reactive power with the power grid. The second stage allows controlling the charging current of the battery. The DC/DC converter can be either isolated or non-isolated circuit configurations as discussed in [6]. This converters topology offers a bidirectional power exchange with the main grid to support the grid during congestion periods and behave as additional energy storage during off-peak periods.

Bidirectional charging has several advantages compared to unidirectional charging. During EV charging operation, it has been shown that the use of bidirectional charging can increase the benefits by at least 25% compared to standard unidirectional charging through the vehicle-to-grid (V2G) principle. In bidirectional charging, the use of the battery capacity of EVs can also contribute to ancillary services, such as maintaining frequency and voltage at the nominal levels and controlling congestion risks. Indeed, this distributed energy system allows can provide/absorb active power to maintain nominal grid frequency (global parameter) and supply/absorb reactive power to regulate voltage level (local parameter).

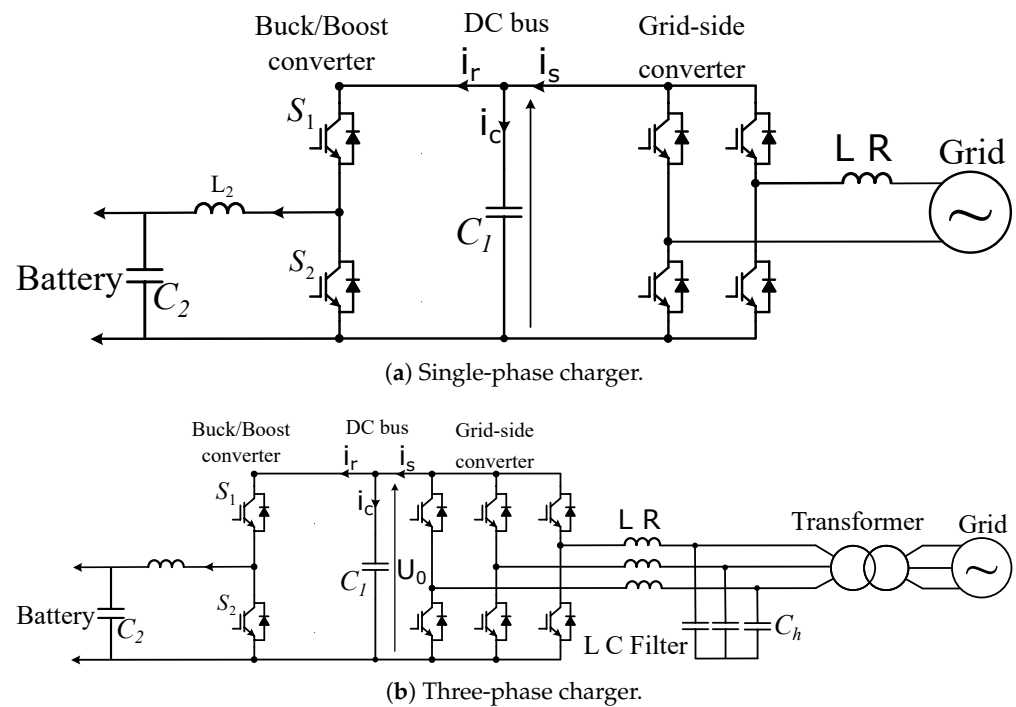


Figure 12. Bidirectional battery charger for EVs.

3.2.3. Integrated On-Board EV Charger

AC charging typically needs an on-board AC/DC power converter. Quite interestingly, the motor and the motor drive inverter, which converts the DC power from the battery into AC power for the motor, can also be used as the on-board charger for the battery [129]. Indeed, the existing devices of the drivetrain are reconfigured with minimum additional components to allow recharging. This eliminates the need for a separate AC/DC power converter for the on-board charger. Since the drivetrain power converter is usually high power (greater than 100 kW), this also means that the EV can reach quite high charging rates (greater than 22 kW). The challenge is to design the motor drive and its control to provide the dual functionality of EV charging when stationary and EV propulsion when in motion [130,131].

Integrated on-board EV charger is a bidirectional EV charger that uses a single inverter/rectifier for all operation modes of EV. This topology allows minimizing the number of power electronic devices since the same power switches are used both for EV traction/propulsion, braking, and battery recharging. This way the cost, size, and weight of EV charger are considerably reduced. A topology of such power conversion system is provided in Figure 13 in which the same converter is used for supplying the motor and recharging EV battery. In Figure 14, the on-board charger configuration uses the traction inverter as well as the motor windings. The motor windings of each phase are split into two equivalent parts and then reconnected in reverse to cancel the torque in battery charge mode. Motor winding acts as an inductor filter so that the line currents are smooth sinusoidal currents with low THD [132]. An excellent example of this implementation is the Renault ZOE EV, which provides 43 kW on-board AC fast fast charging. The Renault has claimed to use a junction box that helps in modifying the operation of the motor and motor drive components to be used as an on-board EV charger.

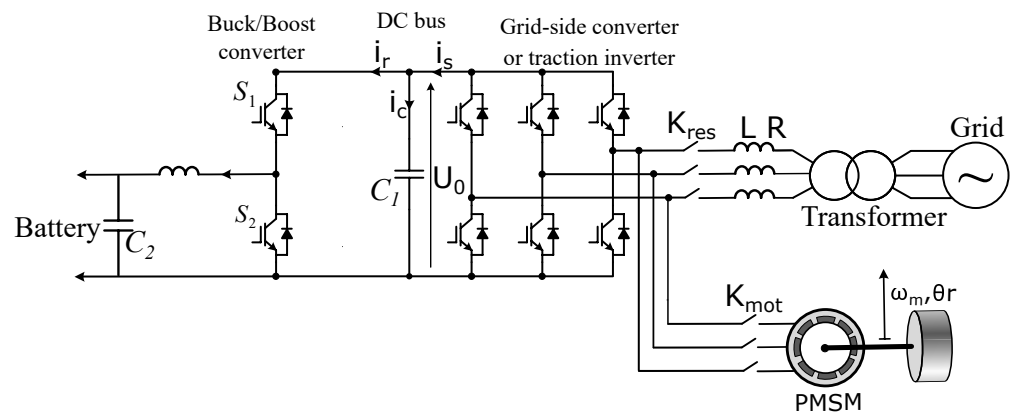


Figure 13. Bidirectional battery charger for EVs using traction inverter.

The main issue with these integrated on-board EV chargers is the produced motor torque due to the current flowing in the motor windings. One solution to control the torque is to use a mechanical brake during battery charging. Other solutions that depend on the motor type can be mentioned: In the case of AC motor with wound rotor, cutting off the excitation cancels the magnetic field of the rotor. Therefore, the interaction between the stator and rotor magnetic fields is canceled and the zero torque condition is maintained during charging. However, even if the excitation is switched off, reluctant torque may occur, causing the machine to vibrate or even rotate. In the case of a permanent magnet synchronous motor, since it has no starting torque, the stator windings of the three-phase machine can be connected to the grid without the risk of rotor rotation. However, vibrations may still occur. Moreover, the integrated on-board EV chargers present other drawbacks as follows:

- Need for a specially designed electrical machine;
- Difficulty in accessing the neutral point of motor windings;
- Reduced reliability due to the use of mechanical contactors.

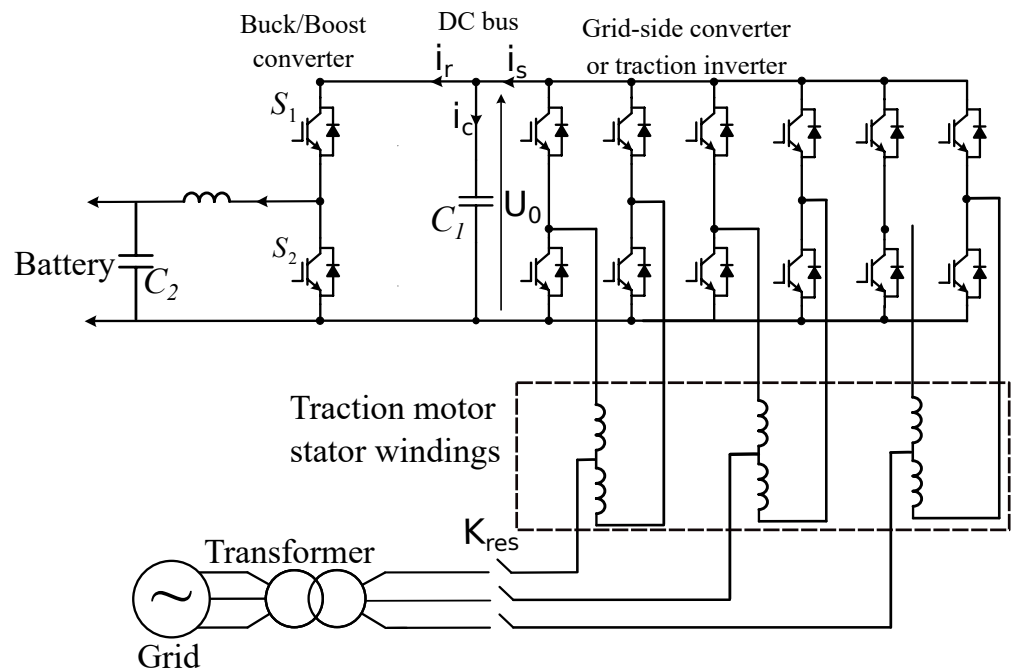


Figure 14. Bidirectional battery charger for EVs using traction inverter and motor windings.

3.2.4. Bidirectional Battery Charger Using Modular Multilevel Converters

This type of embedded chargers use modular multilevel converters (MMC), which are more attractive than two-level converters and neutral point clamp converters. MMC

is an advanced voltage source converter that has competitive advantages such as output power high quality, high modularity, simple scalability, fault tolerant capability, and low voltage and current rating demand for the power switches [133,134]. In recent years, the incorporation of wideband gap semiconductors (SiC and Gan) are investigated to implement the MMC application with further advantages of high-voltage and high-power operations, low power losses, high efficiency, improved reliability, and reduced module size and cooling system [135,136].

Multilevel cascaded H-bridge converter is the best suited for battery charging applications [137,138]. Converter topology using an MMC at battery cells level to achieve both the traction inverter and on-board battery charger is shown in Figure 15. In motor mode, power flows from the batteries to the motor through the cascaded inverters. Cascaded inverters can also be used as rectifiers in battery charging mode [139,140]. It is possible to use the motor windings as an inductor, but it is more appropriate to use small external inductors.

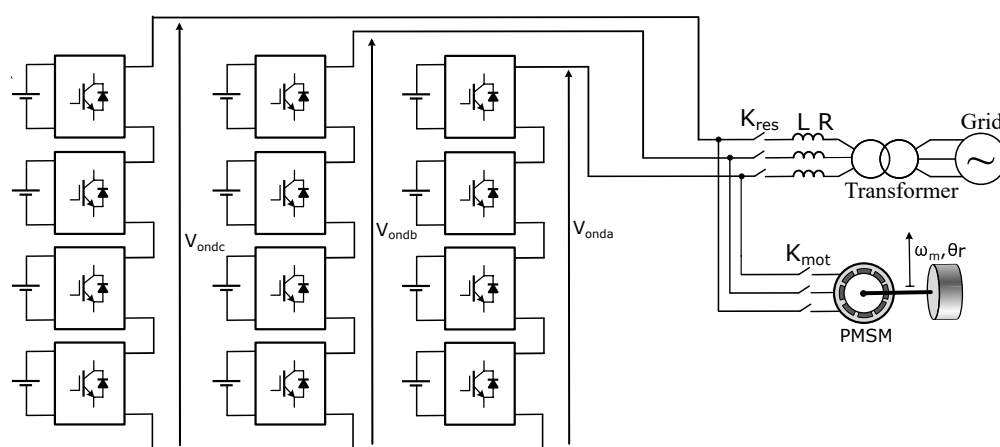


Figure 15. Bidirectional battery charger using multilevel modular converters.

3.2.5. Contactless Power Transfer-Based EV Charger

Inductive charging is the best alternative to conductive chargers due to the many advantages that this technology offers. In fact, this charging mode has the following advantages: accessibility, standardized charging, ease of exchanging of information with the vehicle [141], and safety for the user since there is no electrical contact and the heavy cables are eliminated. This can considerably reduce the weight of the vehicle and, thus, its energy consumption. Inductive charging is based on wireless power transfer principle [142,143], as depicted in Figure 16. In this configuration, the grid AC voltage is rectified using an AC/DC converter with a power factor correction (PFC) to ensure unity power factor and to adjust the rectified output voltage (which is usually around 400 V). A high frequency inverter is fed by the DC output voltage, producing a square voltage wave at a frequency of 85 kHz [144]. The high-frequency inverter is followed by an impedance matching network (IMN) eliminating the current harmonics produced and compensating for the reactive power due to the leakage inductance of the transmitting coil, this block is also known in the literature as the primary compensation stage. When the transmitter coil is fed with the filtered output voltage of the inverter, it produces a time-varying magnetic field that can be directed towards the receiver coil using ferrite cores allowing wireless power transfer from the ground assembly to the vehicle assembly. The time-varying magnetic field induces an AC voltage in the receiver coil at the same frequency as primary coil voltage. This voltage is applied to a secondary compensation stage (IMN) and then rectified. The rectifier can be a controlled rectifier or diode-based rectifier [145,146]. In bidirectional systems, a controlled rectifier is required to ensure a bidirectional power flow to implement the V2G concept [147–149]. Finally, a buck-boost DC/DC converter is used to control the current delivered to the battery.

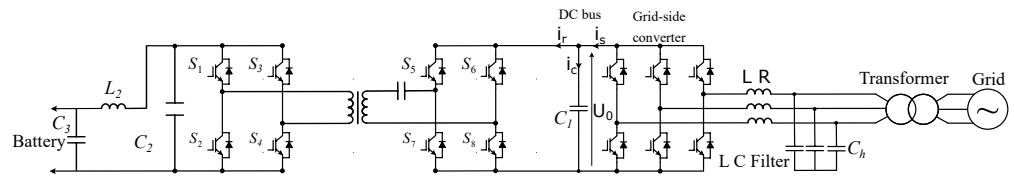


Figure 16. Contactless power transfer for EV charging.

3.3. Summary on EV Charging Stations Technical Requirements

EV charging modes varies according to several criteria related to efficiency, durability, performance, and cost. Several power electronics architectures have been investigated in academia and implemented in industry. With the evolution of the vehicle electrical system and the increase in charging power demand for different levels, new types of AC chargers whose operation is based on the use of traction inverter and EV motor windings are emerging. These types of chargers allow to provide high power and have a compact architecture and low cost. Moreover, inductive charging seems to be a very attractive technology for EV charging stations in the near future, especially for domestic applications. Table 5 recalls the EV chargers specifications presented in Section 3.1 and presents the compliance between these specifications and the presented EV chargers.

Table 5. Specifications and proposed power electronics topologies (Numbers 1 to 6 refer to EVs charging stations power electronics specifications presented in Section 3.1 and check mark means that the proposed power electronic topology complies with the corresponding specification).

Specifications	1	2	3	4	5	6
Unidirectional battery charger	✓					
Bidirectional battery charger	✓	✓				
Bidirectional battery charger using the motor drive inverter	✓	✓	✓			
Bidirectional battery charger using the motor drive inverter and electric machine winding	✓	✓	✓	✓		
Bidirectional battery charger using multilevel modular converters	✓	✓	✓	✓	✓	
Contactless power transfer-based battery charger	✓	✓				✓

4. Smart Charging and Grid Impact Mitigation

As the fleet of electric vehicles grows, the need for more electrical energy becomes crucial, especially during on-peak periods. The charging of electric vehicles will have a considerable impact on the stability of the utility grid. Additionally, it will be necessary to meet the demand of a large and growing number of customers in terms of availability of charging stations and charging requirements (start time, power, and desired SOC) [150]. In the following EV chargers impact on power systems is discussed. Then, three charging strategies are presented and critically analyzed, which are non controllable EV charging, dual pricing EV charging, and smart EV charging. This critical review highlights the relevance of adaptive control and smart energy management of charging stations that may integrate distributed energy resources (DER) and energy storage systems (ESS).

4.1. Charging Strategies

As a result of governments incentives in several countries to opt for green mobility, a significant annual increase in EVs sales is expected in the upcoming years. The uncoordinated and random charging activities of a large number of EVs could put a lot of stress on the distribution system, resulting in several types of technical and economical problems. These issues include sub-optimal generation dispatch, huge voltage fluctuations, degradation of system efficiency and economy, and an increase in the probability of power outages due to grid congestion.

4.1.1. Dumb and Dual Pricing EV Charging

Dumb charging implies that EV owners start battery charging as soon as the vehicle is plugged into a charging port, assuming that electricity cost is the same throughout the day [151–153]. Unlike dumb charging, in dual pricing charging, users charge their vehicles based on the price of electricity. Current pricing models vary according to the time-of-use (TOU) that the utility has set for different time slots [154,155]. These are generally simple rules, such as day and night tariffs, which are intended to control peak demand. Currently, due to the low EV penetration in the transportation sector, no specific charging strategy is performed (uncontrolled charging) or a passive strategy is implemented. Among the passive strategies, the most common is off-peak charging, which provides an economic incentive to charge electric vehicles during the night. However, this solution has the disadvantage of abruptly increasing power demand because all vehicle charging processes would start almost simultaneously. Therefore, as electric mobility increases, it will be mandatory to develop smart charging strategies to relief power transmission and distribution systems and ensure economical benefits for EV owners, aggregators, and grid operators [156].

In [157], in order to evaluate the effectiveness of the dual charging strategy, the authors conducted a test on a 1% sample of the Berlin population, i.e., 16,000 drivers with specific daily trips (home-work-home and home-study-home) to eliminate any irregularities. They divided the city of Berlin into four parts (HUB1 to HUB4), each of which incorporates a basic load curve that corresponds to a typical urban area (residential, industrial or commercial) with maximum allowed powers of 9 MW, 4.4 MW, 8 MW, and 8.2 MW, respectively. The maximum available battery capacity of each EV is assumed to be 10 kWh. According to the results obtained for the dumb charging strategy, the energy consumption shows typical peaks in the morning (when arriving at work) and in the evening (when returning home). For the dual-pricing strategy, it has been noticed that peak power demands are still present despite the change in overpricing time because users are influenced by the electricity price. This means that, although users are indeed sensitive to the price signal, this strategy only shifts the peak consumption without smoothing it over time. The adoption of a smart charging process is therefore a critical requirement to avoid increasing peak power demand.

4.1.2. Smart Charging Stations

Smart charging refers to any technology that optimizes the charging or discharging of an electric vehicle by managing the vehicle's charging power in an efficient, flexible, and cost-effective manner [158,159]. Smart charging helps to mitigate issues related to grid congestion by reshaping the power demand curve to fill charging valleys and suppressing power peaks, as shown in Figure 17 [156,160]. It also optimizes the integration of renewable energies that are generally intermittent, thus reducing energy costs related to charging while contributing to a more sustainable transportation [161–163]. Additionally, to make benefit of the excess renewable energy, a charging station can be equipped with an energy storage system [164,165]. The most common energy storage technologies are: electrochemical storage (batteries), chemical storage (hydrogen production and storage), and mechanical storage (flywheels). These ESS offer many advantages such as energy storage during off-peak periods or during high renewable energy production. They can operate as backup generators during power outages or during islanded mode [166].

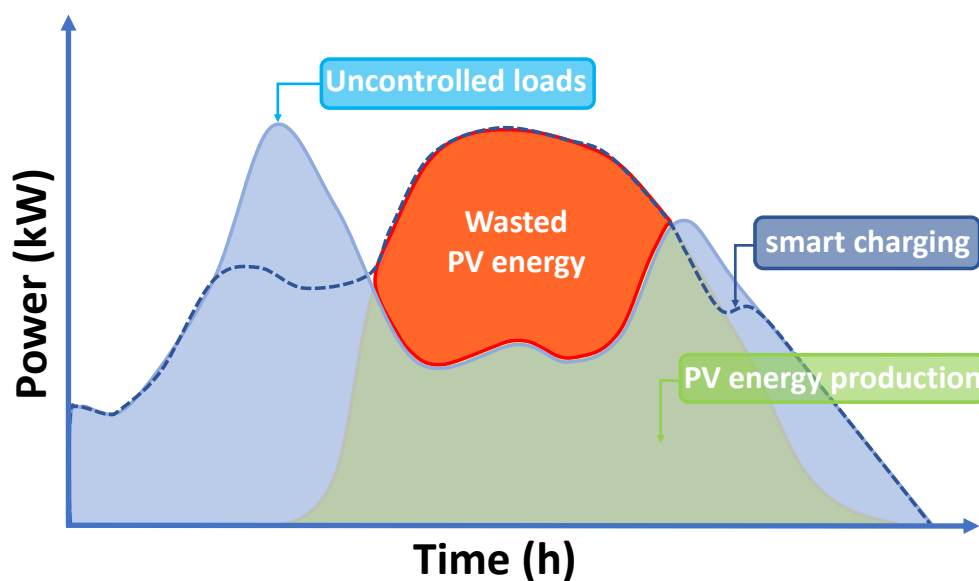


Figure 17. Consumption profile of EVs fleet during a working day with and without smart charging considering renewable energy integration.

Managing the charging process in terms of time scheduling and power profile will not only limit potential challenges, but also open up new opportunities. This can be achieved through the use of vehicle-to-grid (V2G) [167]. The use of charging capacity from electric vehicles can contribute in ancillary services, including maintaining frequency and voltage at the required levels, controlling congestion risks, and managing demand/production balance [168]. The use of V2G also supports the integration of more intermittent renewable energy generation (RES) [169]. This technology is all the more promising as electric vehicles are parked in most of the time. Connected to the grid, EVs are available to provide energy to the grid and be recharged before driving again. However, the implementation of V2G concept presents several challenges. Indeed, the energy management system must be able to communicate with the operators/electricity providers and the EVs fleet to provide the required amount of energy to meet ancillary services demand while respecting the charging requirements of the customer [170,171]. It is of paramount importance to note that with this method EV battery degradation is accelerated due to high number of charge/discharge cycles [172]. It is therefore necessary to optimally schedule V2G taking into consideration the technical and economical aspects. Furthermore, it is crucial to have an automated and standardized information exchange between the vehicles and the grip operators. In this regard, different communication protocols are used: ISO/IEC 15,118 is related to the communication between an electric vehicle and the charging station, while IEC 61,850 is related to the communication between the charging station and the energy provider .

There are several barriers that make these energy management systems for charging stations difficult to implement, including [173,174]:

- Charging infrastructure high cost, including the information and communication technologies.
- Smart charging requires electric vehicles to be parked for long periods of time so that the system can control and schedule the power flow efficiently. This type of condition is relevant in specific locations such as workplace stations and commercial charging stations and is not suited for highways where customers are not expected to stay for long periods of time.

4.2. EV Chargers Impact on Power System and Mitigation Methods

The level 1 EV charger has the advantage of having a minimum impact the utility grid. However, level 2 and level 3 chargers increase power demand locally, which may have a great impact of the grid stability. Moreover, since non-linear power electronics are

considerably involved, EV chargers induce power quality (PQ) disturbances. These PQ issues include increased losses in distribution transformers, harmonic distortion, frequency and voltage deviation, and excess thermal stress on cables, switchgear protective devices, and transformers [7,175]. These disturbances can be mitigated by using high PQ chargers and smart chargers [176–178]. Additionally, EV chargers cause grid losses increase since the transmission line currents RMS value and harmonic content increase

To overcome these issues, several measures can be implemented. Indeed, coordinated EV charging should relieve the power system and reduce the voltage and frequency deviation [179]. A decentralized smart metering can be incorporated in order to guarantee the supply demand balance. Furthermore, to reduce line currents harmonics, high frequency PWM techniques are required, and MMC and matrix converters can be used [180]. Finally, the use of renewable energy resources (RES) and energy storage devices at charging station level can significantly mitigate the impact of EV charging on the power grid [181–183]. An example of the use of PV and hybrid energy storage system composed of batteries and flywheel for optimal energy management in EV charging station is shown in Figure 18 and is investigated in [184]. Major future EV charging future advances include:

- Development of high-voltage (up to 1000 V DC) off-board chargers to decrease charging time and reduce line currents and, consequently, to reduce thermal stress on distribution system components.
- Optimal and coordinated EV charging to relieve the utility grid and the implementation of V2G and V2V concepts, which may allow reducing grid congestion and lower EV owners EV charging bill.
- Development of high efficiency WPT chargers.
- Use of wide-bandgap semiconductors, which are characterized by higher power density, higher efficiency and lower thermal stress.
- Deployment of hydrogen for renewable energy storage and its massive usage in the transportation sector. This aspect is extensively discussed in the literature [185] and is shown in Figure 19.

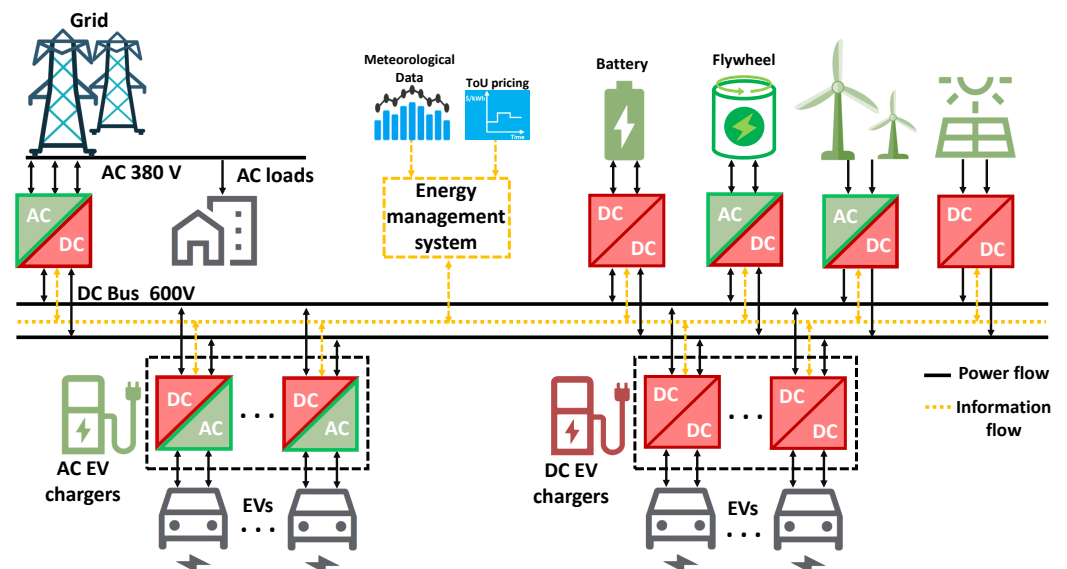


Figure 18. Smart charging station composed of renewables and ESS.

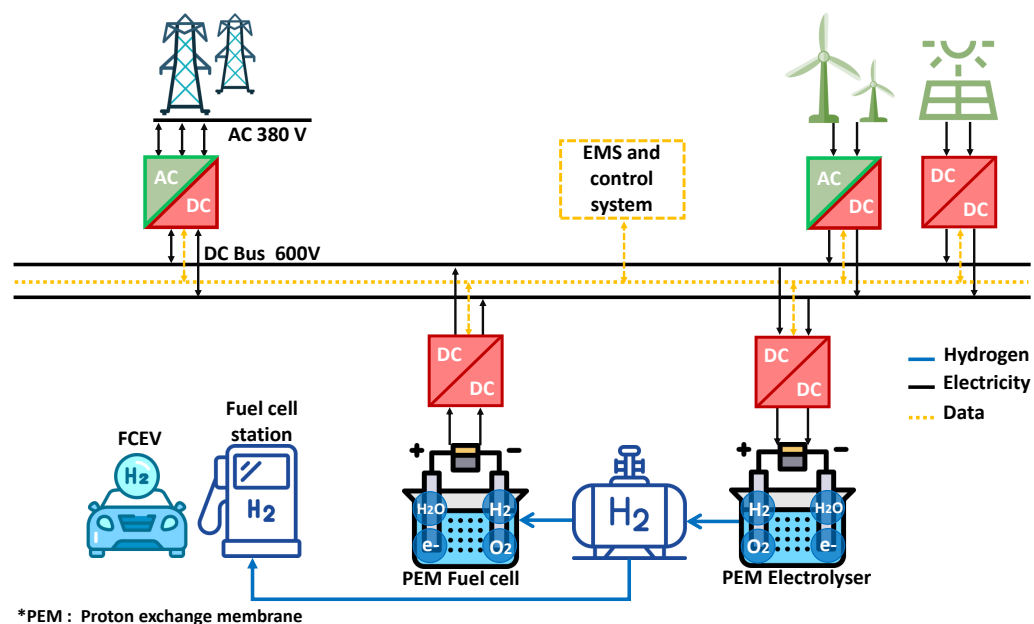


Figure 19. Green hydrogen production, storage, and usage.

5. Conclusions

This paper has reviewed the current status of electric vehicle technologies including HEV, PHEV, BEV, and FCEV and the associated power electronics and energy conversion system components. WLTP driving cycles have been used to determine the power and energy requirements for a specific vehicle. Then, conventional ICE vehicles, hybrid, and full electric vehicles are presented and discussed. Based on the specifications for EV chargers, different on-board and off-board battery chargers have been briefly presented and discussed. Specifically, integrated on-board chargers offer the possibility to optimize the use of traction/propulsion power converters and motor windings, but suffers from a long time to fully recharge EV batteries. On the other hand, off-board chargers are high power chargers that require few minutes to recharge the EV batteries up to 80% state of charge (SOC). Unfortunately, the massive usage of such equipment could have a negative impact on the utility grid and may cause PQ disturbances. To overcome this issues, one solution relies on the integration of distributed energy resources and energy storage systems on the charging stations level. Moreover, coordinated and well-planned EV fleets charging is required to mitigate the impact on the distribution grid without upgrading the utility grid. Finally, the implementation of V2G and V2V technologies are required to take benefit of such distributed energy storage systems.

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Abbreviations

The following abbreviations are used in this manuscript:

EV	Electric vehicle
FC	Fuel cell
ICE	Internal combustion engine
SOC	State of charge
WLTP	Worldwide harmonized Light vehicles Test Procedures
WLTC	Worldwide harmonized Light vehicles Test Cycles
BEV	Battery electric vehicle
FCEV	Fuel cell electric vehicle
WPT	Wireless power transfer
PHEV	Plug-in hybrid vehicle
BESS	Battery energy storage system
IPMSynRM	Internal permanent magnet synchronous reluctance motor
EVSE	Electric vehicle supply equipment
BMS	Battery management system
PQ	Power quality
AFE	Active front end
DBR	Diode bridge rectifier
V2G	Vehicle-to-grid
V2V	Vehicle-to-vehicle
PEI	Power electronic interface
THD	Total harmonic distortion
MMC	Modular multilevel converters
WBG	Wide-band-gap semiconductors
SiC	Silicon Carbide
GaN	Gallium Nitride
PFC	Power factor correction
IMN	Impedance matching network
DER	Distributed energy resources
ESS	Energy storage systems
RMS	Root mean square
PWM	Pulse width modulation
RES	Renewable energy resources
PV	Photovoltaic
IPT	Inductive power transfer
SOC	State of charge
TOU	Time-of-use
LTO	Lithium-Titanium-Oxide
NMC	Lithium-Nickel-Manganese-Cobalt-Oxide

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