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A Technological Review on Fast Chargers for Electric Vehicles: Standards, Architectures, Power Converter Topologies, Fast Charging Techniques, Impacts and Future Research Directions

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ABSTRACT

The escalating concerns about petroleum resources depletion and ecological issues have accelerated the technological evolution of electric mobility. Electric vehicles (EVs) promise to revolutionize future transportation by reducing fossil fuel dependence, improving air quality, integrating with renewable energies, and enhancing energy efficiency, especially when smart grids have become omnipresent. However, range anxiety and long charging times remain substantial barriers to widespread EV adoption. This review underscores the critical role of fast-charging technology in overcoming these barriers. Fast chargers (FCs) alleviate long charging times by delivering higher charging power in shorter durations, like refueling at gas stations, resulting in promoting consumer interest. Besides, the presence of a fast-charging infrastructure along travel routes is essential to provide quick access to charging points, minimizing range anxiety. The successful FC deployment necessitates careful consideration of appropriate power electronic interfaces to avoid grid issues, including voltage fluctuations, frequency deviations, and power quality disturbances through the implementation of advanced control mechanisms like voltage regulation and power factor correction. Hence, a substantial portion of research efforts has been directed towards the advancement of FCs utilizing silicon carbide (SiC) and gallium nitride (GaN) technologies. This focus highlights breakthroughs in power electronics, facilitating faster charging rates. Besides, adequate cooling is essential for FCs to prevent semiconductor component damage. The review contributes to the thorough examination of pertinent information regarding FCs, encompassing standards, architectures, power converter topologies, compatible battery chemistries, fast-charging techniques, and cooling systems. It also explores the multifaceted impacts of fast-charging on AC-grid and traction batteries, focusing on advanced solutions for grid stability, battery lifespan, and environmental sustainability, including smart grid technologies, battery management systems, and shifting towards renewable energy resources. Finally, the future research trends towards fast-charging are presented. This review provides a unique perspective on the current state of fast-charging infrastructure by synthesizing information from various sources, serving as a valuable one-stop source for researchers interested in this topic.

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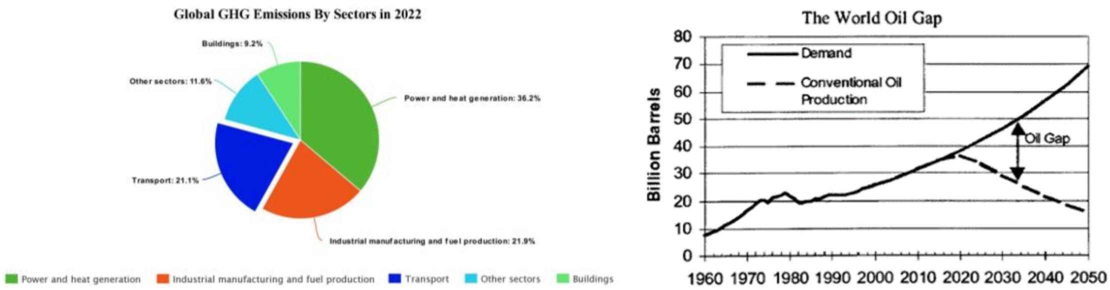
1. Introduction

Transportation has been a pivotal element of both personal and business activities for centuries, firmly establishing its status as an indispensable part of our daily existence. Nevertheless, the transportation sector, encompassing road transportation, non-road transportation, aviation, and inland waterways, bears responsibility for approximately a quarter of worldwide greenhouse gas (GHG) emissions. This places it among the most significant contributors to GHG emissions, as depicted in Fig. 1(a) [1]. Specifically, road transportation is responsible for approximately 75% of the overall emissions, with internal combustion engine vehicles (ICEVs) being widely criticized for their significant role in generating harmful emissions into the atmosphere [2]. All existing ICEVs rely primarily on different types of fossil fuels like gasoline, diesel, or natural gas to operate them. The fuel-burning reaction occurs inside the ICE during vehicle operation, and various emissions are released to the air as byproducts via the exhaust system. These emitted pollutants are made up of several types of harmful gases like sulfur oxides (SO_x), nitrogen oxides (NO_x) and carbon oxides (CO_x) that contaminate the atmosphere, creating natural disasters such as sea levels rise, climatic variability and ozone layer depletion [3]. Moreover, inhaling the particulate matter present in the emitted gases poses a substantial health hazard to humans, as some of these particles are carcinogenic [4]. Hence, one of the primary challenges confronting the world today is mitigating the adverse effects associated with the transportation sector on the environment and human health due to these toxic emissions [5].

Lately, electric vehicles (EVs) have gained significant popularity because of their potential to decrease global air pollution, safeguard human health, and provide various other compelling factors that contribute to their renewed viability as a practical product in the automotive market. The Electric Power Research Institute (EPRI) claims that even in contrast to more efficient ICEVs, the widespread use of EVs would considerably reduce GHG emissions [6]. The world faces a pressing issue stemming from its reliance on oil resources, which could run out in the near future. The concurrent rise in the use of ICEVs amidst dwindling global oil supplies raises the specter of a potential global economic crisis that is probably greater than the one experienced in the last years as the number of ICEVs is increasing in line with lower availability of world oil [7], [8]. Fig. 1(b) highlights the difference between fuel demand and global oil production that becomes evident after the year 2020 [9]. Hence, it is expected that world oil supply through 2040 will further increase by 30% on the basis of 2011 due to predicted energy demand [10]. Transportation sector is responsible for 30% of the world energy used and 60% of the oil used, while road transportation is alone responsible for 80% of the energy used [11].



(a) (b)

Fig. 1. (a) Worldwide GHG emissions associated to each sector according to the joint research centre (JRC) report 2023 [1], (b) world oil demand by 2050 [9]

In this context, EVs stand as a highly promising technology poised to bring about a transformation in the transportation and energy sectors. They offer a range of benefits, including emission-free operation, quiet operation, minimal maintenance, high energy efficiency, and suitable propulsion characteristics [12], [13], [14]. Moreover, several emerging technologies are proposed within the automotive industry that has the potential to bring good opportunities for the rapid development of new EV markets. One of the latest technologies is autonomous or self-driving which makes the use of EVs more convenient and intelligent [15], [16]. Hence, many industries are transitioning towards greater automation together with the electrification of the energy and transportation sectors. Six phases of autonomous EV development are defined by National Highway Traffic Safety Administration, where L0 is no automated driving, L1 is driver assisted driving; L2 is semi-automated driving, L3 is highly automated driving, L4 is the fully automated driving and L5 is the driverless phase where human will be just passenger [17]. The development of EVs with high levels of automation is receiving more research attention and funding from the automotive industry as well as other technical industries. This is the main reason that the EV has to be autonomous, to bring more perks in terms of cost reduction, safety, service level, and above all environment benefits [18], [19]. Autonomous or self-driving EV is the next generation vehicle, which can drive itself without any human interaction, employing sophisticated sensors (ultrasonic, GPS, radar, LiDAR, cameras, etc.) and control schemes, as shown in Fig. 2 [15], [20]. It can decide the traveling route, identify environmental changes, and adapt the speed and position of the vehicle in order to maintain lane control and safe following distance on the road and to reach the desired destination. The expanded deployment of such vehicles will also facilitate the establishment of wireless charging (a fully autonomous EV should also charge without any human interference) [21], [22]. In fact, at the 2022 Beijing Winter Olympics, autonomous vehicles including shuttle buses, freight trucks and road sweepers were tested, proving that the advancement of the communication infrastructure enables the utilization of self-driving EVs [23].

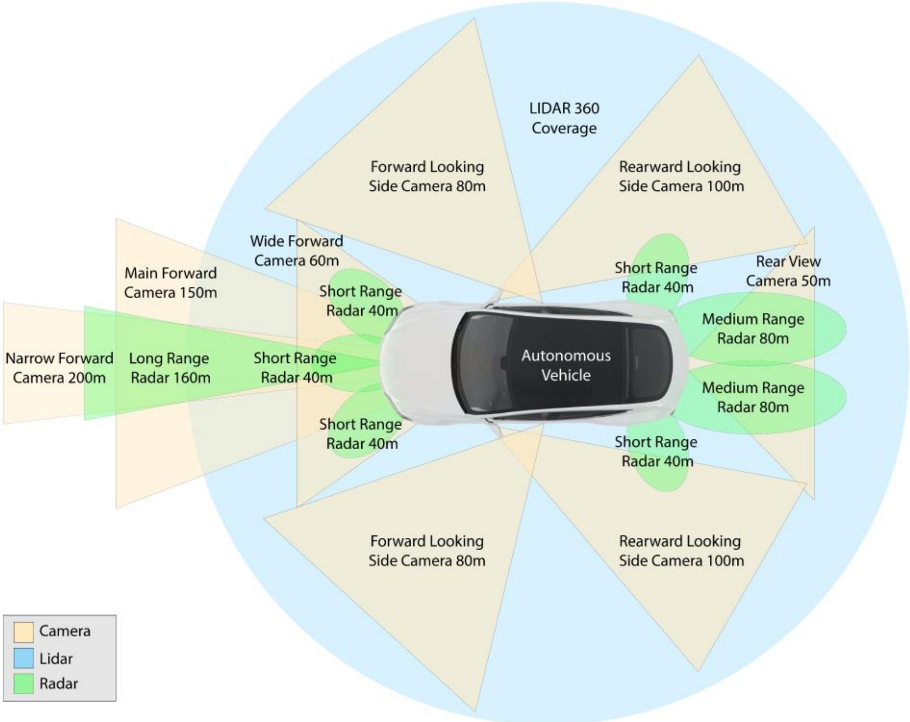
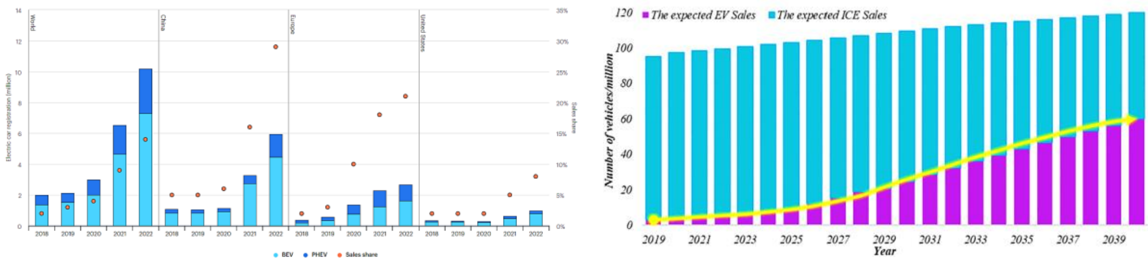


Fig. 2. Various sensors for environment perception in autonomous EVs [15], [20]

Hence, numerous countries worldwide are transitioning to EVs as the preferred alternative to traditional ICEVs [24]. The EV world sales are gradually increasing according to international energy agency (IEA) report, as illustrated in Fig. 3(a) [25]. It is clear that EV markets are seeing exponential growth as sales exceeded 10 million in 2022. A total of 14% of all new vehicles sold were electric in 2022, up from around 9% in 2021 and less than 5% in 2020. Three markets dominated global sales. China was the frontrunner once again, accounting for around 60% of global EV sales. More than half of the EVs on roads worldwide are now in China and the country has already exceeded its 2025 target for new energy vehicle sales. In Europe, the second largest market, EV sales increased by over 15% in 2022, meaning that more than one in every five vehicles sold was electric. EV sales in the United States – the third largest market – increased 55% in 2022, reaching a sales share of 8%. Actually, EV sales are expected to continue strongly through 2023. Over 2.3 million EVs were sold in the first quarter, about 25% more than in the same period last year. Based on current trends, the global sales of EVs can be roughly expected in the next 16 years, as illustrated in Fig. 3(b) [26].

Nonetheless, to make this transition, EVs face certain limitations that need to be addressed. Range anxiety, the availability of charging infrastructure, and the comparatively longer charging time when compared to refueling conventional ICEVs are often cited as the key obstacles that impede the wider adoption of EVs in the market [27], [28]. Typically, EVs may cover 100-250 km per one charge and consume energy of 15-20 kWh per 100 km [29], [30], whereas the top-tier vehicles with larger batteries can achieve a longer driving range of 300-500 km [2], [31]. Drivers must be aware of the driving range because recharging EV isn't easy like coming to a nearby gas station [32]. Since the battery packs act as a fuel tank in EVs, EVs become dependent on their stored energy. Therefore, the driving range relies directly on the battery packs capacity [33], [34]. For instance, Renault Zoe carries a 22-kWh battery with an energy consumption of 14.6 kWh per 100 km, resulting in an autonomy of approximately 140-210 km per single charge [35]. While Nissan Leaf is currently with a 62-kWh battery which provides consumers with an autonomy of 360 km [31]. Once battery is depleted, charging it requires long time in comparison to refueling an ICEV that vary from 15 minutes to 8 hours based on the last distance traveled by the vehicle [36], [37]. The charging time mainly relies on charging infrastructure, charger configuration and operating voltage levels [28].



(a) (b)

Fig. 3. (a) EV global market sales [25], (b) EV global expected sales rate during the next 16 years [26]

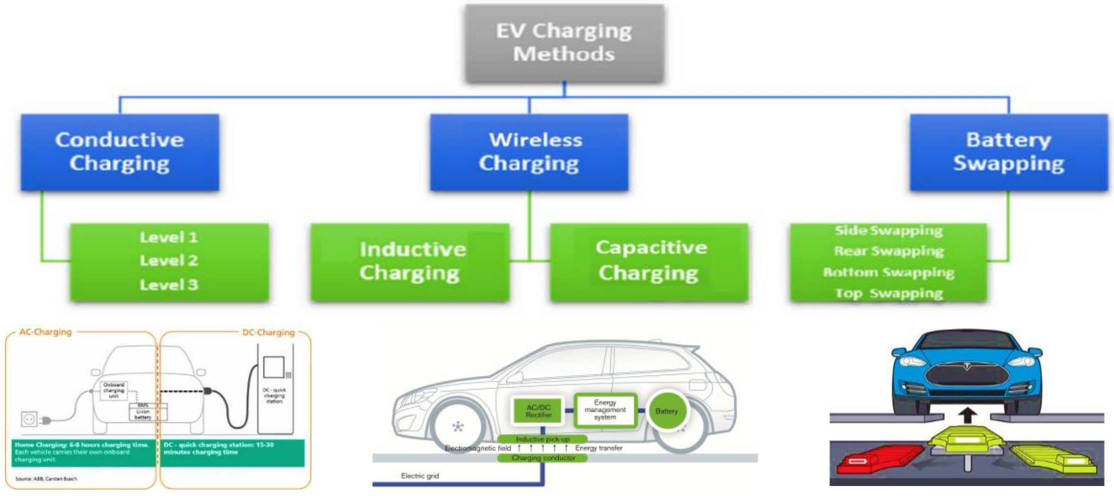
Hence, to encourage the extensive adoption of EVs in the future, it is imperative to incorporate fast-charging options into EV designs. This is particularly vital, given that refueling an ICEV typically takes 2 to 5 minutes, in contrast to an EV that relies on residential or public charging options, which can take several hours to cover a similar distance on a single charge [38]. Reducing the time required to recharge EV batteries and establishing a robust fast-charging station infrastructure are vital aspects for improving customer satisfaction and alleviating users' concerns related to range anxiety [39]. If fast-charging technology can bring EV recharge times in line with the typical refueling duration of ICEVs and fast-charging stations become as commonplace as traditional gas stations, not only in urban areas but also along highways, it would significantly boost the adoption and popularity of EVs [38], [40]. Nowadays, a significant step has been taken by EV manufacturers regarding narrowing the difference between EVs and ICEVs, compelling the advancement of appropriate chargers that can accommodate grid-compliant fast-charging [41]. This approach holds promise for addressing some of the enunciated issues and making EVs more competitive. However, the implementation of fast-charging technology poses substantial challenges, including issues related to infrastructure development, battery durability, and the standardization of charging protocols [42], [43]. These challenges underscore the intricate balance required to maximize the benefits of fast-charging while overcoming the technical and logistical hurdles associated with its widespread adoption.

The fast-charging technology is expected to recharge the battery in a matter of minutes like a gasoline station. In stark contrast, most EVs on the market take 2–6 h to recharge that causes a quite poor vehicle experience [44], [45]. Shortening charging time can bring great convenience to our lifestyle. According to the United States Advanced Battery Consortium (USABC), fast-charging is to obtain 80% of state of charge (SOC) of battery within 15 min, which means the battery pack can be charged to 80% of SOC at 4C rate (1C-rate refers to the current to drain all the capacity in 1 h) or higher [46]. Tesla Model 3, the current leader in the EV industry, uses its own supercharger to charge to 80% in 27 min. Porsche Taycan needs 23 min to charge from 5% to 80%, which still fails to meet the requirement of fast-charging.

In general, EV charging can be achieved through three methods, each based on how power is transferred: conductive charging, wireless charging, and battery swapping charging [47]. Fig. 4 provides a detailed illustration of the EV charging methods. The primary approach for battery charging is conductive charging, which involves creating a direct physical electrical link between the power supply network and the EV charging system [21], [48], as shown in Fig. 4(a). The charging circuitry and its control components can either be integrated within the vehicle itself or situated externally to the vehicle. EVs typically receive power from electric vehicle supply equipment (EVSE), often referred to as EV charging stations. These charging stations can be divided into three categories: residential stations, public stations, and fast-charging stations. Residential charging stations, commonly found in residential neighborhoods, enable EV recharging during periods when electricity demand is lower, often at night, to take advantage of lower energy costs and reduce demand during peak hours. Public charging stations are situated at frequently visited locations, such as public buildings, shopping centers, and corporate parking lots. Often, electric utility companies manage these stations and include payment systems for the convenience of users. Fast-charging stations are typically found at rest areas along highways. These stations are equipped with control and protection mechanisms that enable them to provide higher voltages and currents from the electric grid, facilitating rapid charging of EVs [49]. The conductive charging method is efficient thanks to its direct connection, lightweight design, ability for bidirectional power flow, and overall simplicity [50]. However, there have been safety-related concerns brought up. The cable linking the plug and the vehicle, particularly in public spaces and parking structures, could present a safety hazard by possibly causing tripping incidents for pedestrians or vehicle owners [51]. Given the high voltage and current carried by the line, it is crucial for EVSE to be designed in such a way that it automatically halts power flow if the cord connector is improperly connected.

On the other hand, wireless or contactless charging doesn't use any wires between the EV and the charging infrastructure, thus eliminating the need for charging cords [52], as shown in Fig. 4(b). It uses primary (transmitter) and secondary (receiver) coils to transfer power based on the principle of electromagnetic induction [53]. The road's surface houses the primary coil, while the secondary coil is positioned within the EV [54]. The concept looks appealing since the infrastructure, lying beneath the road surface, is concealed and inconspicuous [55]. This streamlines the charging process and minimizes the hazard of any possible harm during the operation of electrical equipment under all-weather conditions. Wireless charging systems typically exhibit lower efficiency and power density in comparison to conductive charging systems [56], [57]. However, a commercial inductive charger has the capability to provide high power with an efficiency reaching up to 86% [58]. Furthermore, the electromagnetic emissions from the charger could potentially impact the vehicle's electronics, necessitating an enhancement in vehicles' resistance to such emissions [59].

The last charging method is the battery swapping method, also recognized as "battery exchange". This method involves the direct replacement of a depleted battery with a fully charged one for a fee at some special stations, called battery swapping stations (BSSs) [60], as shown in Fig. 4(c). The BSS primarily consists of a distribution transformer, AC-DC converters, battery chargers, vehicle batteries, charging racks, robotic arms, a control system, a maintenance system, and other equipment essential for the charging and swapping of batteries. A key benefit of this method is that drivers aren't required to leave the vehicle; they can swiftly replace the discharged battery without getting out. However, there are some technical barriers, including the substantial expenses incurred due to the procurement of numerous batteries, the infrastructure expenditures involved with establishing BSSs, the necessity for standardization of vehicles and batteries, and the potential danger of battery degradation [61]. The charging methods including conductive charging, wireless charging, and battery swapping charging are summarized in Table 1 [57], [62].



(a) (b) (c)

Fig. 4. Different EV charging methods: (a) Conductive charging, (b) Wireless charging, and (c) Battery swapping

Table 1. Summary of charging methods [57], [62]

Aspect	Conductive Charging	Wireless Charging	Battery Swapping
Efficiency	High	Moderate to high	Moderate
Infrastructure Requirements	Extensive charging station infrastructure needed for widespread adoption	Infrastructure required, but less extensive compared to conductive charging	Specialized swapping stations with battery inventory
Practicality	Commonly used, well-established infrastructure	Emerging technology, infrastructure needs growth	Limited adoption, infrastructure challenges
Charging Time	Fast charging possible	Generally slower than conductive charging	Fast swapping, but requires availability of fully charged batteries
Flexibility	Flexible charging locations with widespread charging stations	Limited by proximity to charging pads, requiring specific parking positions	Limited by availability of swapping stations and battery compatibility
Cost	Relatively lower upfront cost, user pays per kWh	Higher upfront installation costs, technology is evolving and can be expensive	High initial investment in swapping infrastructure
User Experience	Familiar and easy to use	Convenience of wireless charging without physical connection	Fast and convenient for those with access to swapping stations
Advantages	Well-established infrastructure, Lower cost compared to wireless	No need for direct connection, Seamless integration with infrastructure	Quick turnaround, No need for charging infrastructure
Limitations	Limited charging speed, Physical wear and tear on connectors, Limited scalability	Efficiency loss over distance, Initial cost of installation, Slower charging	Standardization challenges, Limited availability of compatible batteries

This review focuses on recent research efforts dedicated to the advancements in fast-charging technology for EVs and their potential contributions to the field. By synthesizing information from various sources, this review offers a unique perspective on the current state of fast-charging infrastructure, highlighting technological breakthroughs, challenges, and opportunities. The pivotal contribution of this review lies in its thorough examination and presentation of pertinent information regarding FCs, encompassing various standards, architectures, power converter topologies, compatible battery chemistries, fast-charging techniques, and cooling systems. It also provides detailed insights into the multifaceted impacts of integrating fast-charging with AC grids and traction batteries, such as grid stability, battery lifespan, and environmental sustainability. Furthermore, the future research trends towards fast-charging technology are presented. This review will provide a consolidated and insightful overview that will serve as a valuable resource for researchers, industry professionals, and policymakers navigating the dynamic and rapidly evolving field of EV fast charging infrastructure.

The review is arranged as follows: After the brief introduction, Section 2 gives an overview of the fast-charging concept in plug-in EVs, including the conductive charging levels, the international standards for fast-charging, and the different charging systems. Then, Section 3 outlines the high-power battery technologies compatible with fast-charging technology. Section 4 discusses the different fast-charging techniques used with EV batteries. Section 5 introduces the different fast charger (FC) architectures, analyzes the possible power converter topologies in each conversion stage according to the selected architectures, and discusses some industrial FC designs. Further, Section 6 summarizes cooling systems for power electronic converters in FCs. Section 7 points out the major impacts of fast-charging on grid stability and batteries lifespan. Section 8 summarizes the efforts in EV battery recycling to achieve sustainability. Section 9 presents the future research trends towards fast-charging technology. Finally, conclusions are provided in Section 10.

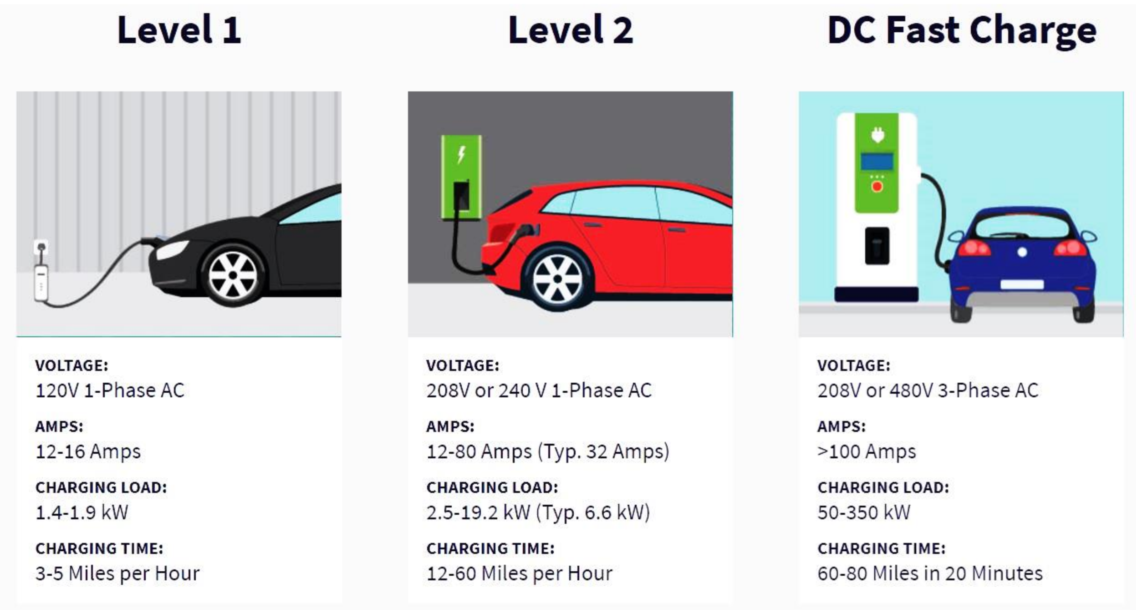
2. Fast Charging Concept in Plug-in EVs

2.1. Conductive Charging Levels

Charging levels for conductive charging can be segmented according to the power rating they use [63]. The Society of Automotive Engineers (SAE) outlines the conductive charging method for EVs within the scope of the SAE J1772 Standard [64]. The SAE J1772 standard categorizes conductive charging into three distinct levels [65]. Fig. 5 shows a detailed depiction of the conductive charging levels. With level 1 charging, the EV is connected to a 1-phase 120 V_{AC} grid for about 8 to 12 hours to attain a full charge [66]. The power capacity for level 1 charging can reach a maximum of 1.92 kW, as shown in Fig. 5(a). It is the most common solution because it matches the voltage levels typically available in residential and private places, and it doesn't require the creation of new charging infrastructure. During level 2 charging, the vehicle's batteries are recharged with a maximum power capacity of 19.2 kW, as shown in Fig. 5(b). This process occurs while the vehicle is connected to a 1-phase 240 V_{AC} grid for a duration of 4 to 6 hours. It is the prevailing approach employed at private and public locations exclusively designated for EV charging. There might be a requirement to set up specialized equipment and connections for both residential and public charging units. Level 1 and 2 charging, with their relatively lower power capacities, are suitable for overnight charging, especially for slow and gradual replenishment. The limitations in power ratings at these levels have driven the development of fast-charging technology. DC fast-charging, which falls under level 3 charging, is characterized by its requirement for an external charger. The increased adoption of level 3 (DC fast-charging) has been driven by its ability to address range anxiety and cater to a more time-sensitive charging experience [67]. Level 3 charging significantly reduces the time required for charging EVs, making it a more attractive option for drivers who need a quick recharge. This feature has played a crucial role in enhancing the overall convenience and acceptance of EVs, contributing to the growth of the EV market [68]. Typically, level 3 charging delivers power at 50 kW, but in recent developments, it has achieved a maximum power capacity of 350 kW with a 3-phase 480 V_{AC} grid connection, as shown in Fig. 5(c). In level 3 charging, there is a direct connection of high-current DC voltage to the EV battery pack. When it comes to fast-charging, the power source usually completes charging the vehicle battery up to a capacity of 80% within 30 minutes or less [69]. This technology is utilized in commercial charging stations, functioning in a manner similar to how gas stations serve ICEVs. Level 3 charging requires a dedicated network and rigorous safety protocols [70]. Once the vehicle is connected to the charging station, it communicates its desired charging current level through communication protocols. The specific protocol used can vary based on the type of connector in use.

2.2. International Standards for Fast Charging

The proliferation of FCs has occurred on a global scale. This growth has prompted the creation of various standards by different standardization bodies, depending on the power levels available in each respective country [71]. These standards are issued by countries with some of the largest EV populations worldwide, including the United States, the European Union, and China [72]. To be more specific, the SAE-J1772 standard is utilized for EV charging in North America and the Pacific region. In contrast, China follows the GB/T 20234.3 standard, while Europe has adopted the IEC 62196-3 standard. To ensure compatibility, each standard uses its own standardized coupler for fast-charging, such as CHArge de MOve (CHAdeMO), Combined Charging System (CSS), Tesla, and GB/T [73]. Every type of fast-charging coupler imposes limitations on the maximum output voltage and current. These international standards for fast-charging are essential contributors to interoperability and the development of a global charging infrastructure for EVs [74], [75]. They establish a common ground by defining specifications for charging protocols, connectors, and power levels that manufacturers worldwide adhere to. This universal framework ensures that EVs from different manufacturers can seamlessly connect and charge at any compatible charging station globally [76]. Without such standards, there would be a risk of fragmented charging ecosystems, where diverse proprietary technologies might hinder cross-compatibility. The adherence to international standards fosters a cooperative environment, encouraging the creation of a cohesive and accessible charging network that transcends geographical and brand-specific barriers. This, in turn, supports the widespread adoption of EVs by providing users with a reliable and consistent charging experience, thus promoting the growth of a sustainable global electric mobility infrastructure. Table 2 provides a description of the various standards governing fast-charging technology, encompassing both existing standards and those currently in development [73], [77].



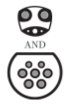
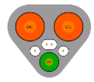
(a) (b) (c)

Fig. 5. Conductive charging levels according to SAE J1772 standard: (a) Level 1, (b) Level 2, and (c) Level 3 (DC fast-charging)

The CHAdeMO protocol, which originated in Japan, is among the most widely embraced fast-charging standards. This protocol facilitates fast-charging at a range of power levels between 62.5 kW and 400 kW [78]. The CSS, a fast-charging protocol for EVs, is endorsed by a German organization known as CharIN e.V. This protocol employs Combo 1 and Combo 2 connectors and can handle charging rates of up to 350 kW [79]. Tesla has created a proprietary fast-charging protocol specifically designed for Tesla Superchargers. This protocol is capable of delivering a charging power of up to

250 kW [80]. The GB/T protocol is specifically tailored for the Chinese market. As a result, a new standard tentatively named “ChaoJi” has arisen through collaboration with China, aimed at ensuring that it remains compatible with the existing GB/T standard. The objective is to attain a charging capacity of up to 900 kW. Additionally, there is a collaborative effort between ChaoJi and CCS to guarantee the compatibility of ChaoJi with the CCS standard [81]. CharIN has officially introduced the Megawatt Charging System (MCS), specifically designed for electric trucks and buses. This connector can handle power levels of up to 4.5 MW.

Table 2. Different standards governing DC fast-charging systems in EVs [73], [77]

Standard	CHAdeMo	GB/T	CCS Combo 1	CCS Combo 2	Tesla	ChaoJi	MCS
Compatible Standards	IEEE 2030.1.1 IEC 62196-3	GB/T 20234.3 IEC 62196-3	SAE J1772 IEC 62196-3	IEC 62196-3	N/A	CHAdeMo and GB/T	N/A
Region	North America Japan Europe	China	North America Japan	Europe	North America	Universal	-
Connector Inlet							
Maximum Current (A)	400	250	400	400	631	600	3000
Maximum Voltage (V)	1000	750	600	900	500	1500	1500
Maximum Power (kW)	400	185	200	350	250	900	455.000

2.3. Charging Systems for Plug-in EVs

The EV charging infrastructure comprises three primary components: a customer information system, an operating system, and a charging system. Among these components, the charging system holds the utmost importance as the most critical and indispensable element of the entire charging infrastructure. The conductive charging system consists of two primary options for battery charging: on-board charging and off-board charging, determined by the charger's position in relation to the vehicle [82]. Therefore, two primary categories of EV battery chargers exist: the on-board charger, sometimes referred to as a slow charger, is situated inside the vehicle. It enables low-power transfer for battery charging when the EV is parked and connected to a charging point. Conversely, the off-board charger, also referred to as an FC or ultra-FC, is positioned external to the EV and supplies high power directly to the EV's batteries.

The on-board charger is limited in its power capacity, typically up to level 1 or level 2. These limitations are primarily due to factors such as weight, space, and cost considerations. As a result, it is well-suited for nighttime charging using a standard household AC utility outlet or for daytime charging at workplaces or shopping centers. In particular, the FC, also recognized as a level 3 charger, can be installed at dedicated locations to provide fast-charging services. Fig. 6 presents a basic illustration of on-board and off-board EV charging systems [73], [82]. In this review, off-board chargers are classified as FCs, which typically provide power levels equal to or exceeding 50 kW. Table 3 illustrates various state-of-the-art DC FCs from multiple manufacturers [77], [83], [84]. As depicted in Table 3, these chargers utilize the connectors and standards mentioned earlier. In addition, the power levels vary to cater to a broader range of customers' needs. These charging systems are characterized by many technical specifications, such as voltage, current, rated power, and charging efficiency. Voltage is a critical parameter in charging systems because it determines the potential difference that drives the flow of electric current. Higher voltage generally allows for faster charging, but it must align with the specifications and capabilities of the EV battery. Current represents the rate at which electric charge flows into the EV battery. It's an essential parameter in understanding how quickly the battery is being charged. Charging systems need to provide the appropriate current according to the battery's specifications. The power rating of a charging system indicates how quickly it can deliver energy to the EV battery. A higher power rating allows for faster charging times, but it's also influenced by the limits of the EV's battery and the charging infrastructure. Finally, high efficiency is crucial in charging systems to minimize energy losses during the charging process. Lower efficiency results in more energy being converted into heat, which is not only inefficient but can also lead to issues such as overheating. Efficient charging systems are desirable for conserving energy and ensuring optimal operation.

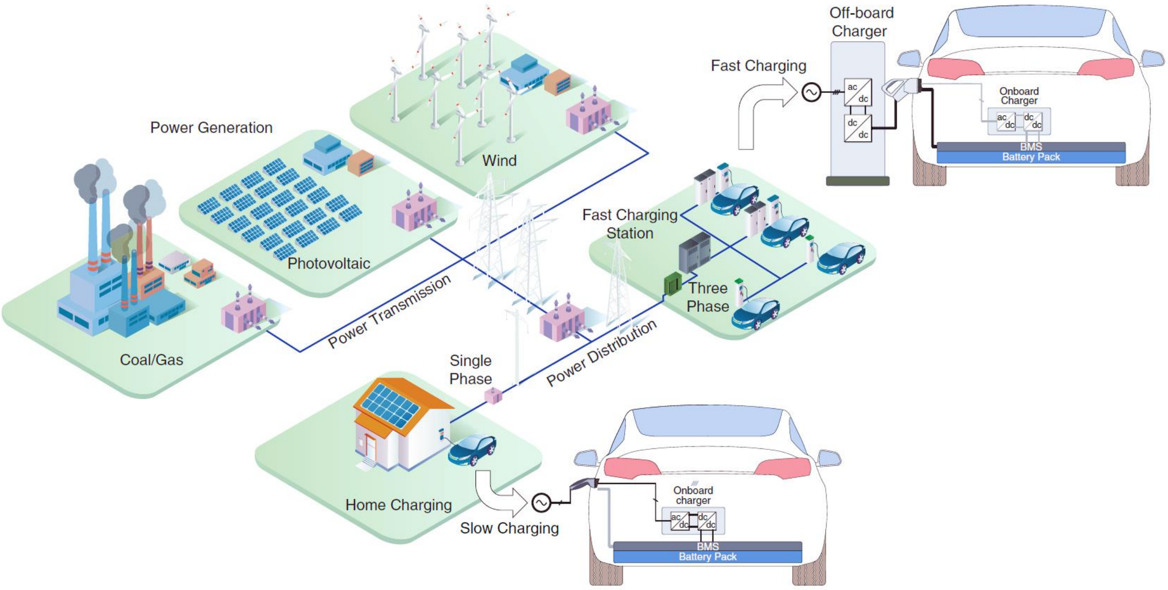


Fig. 6. On/off-board conductive charging systems [73], [82]

Recently, bi-directional EV charging systems have emerged as a pioneering technology with the ability to revolutionize the electric mobility and energy sectors. The increasing prominence of bi-directional charging systems, exemplified by Vehicle-to-Grid (V2G) and Vehicle-to-Home (V2H) technologies, is transforming the landscape of EVs, as shown in Fig. 7 [85], [86]. These innovative systems not only facilitate conventional charging from the grid but also enable EVs to act as dynamic energy hubs, capable of discharging surplus energy back to the grid or powering homes during peak demand periods [86], [87]. This bi-directional functionality not only enhances the overall efficiency of EVs but also plays a pivotal role in grid management, offering a flexible and decentralized approach to energy distribution [88]. As a result, these technologies hold immense promise for optimizing energy usage, bolstering grid resilience, and contributing to a more sustainable and responsive energy infrastructure [89].

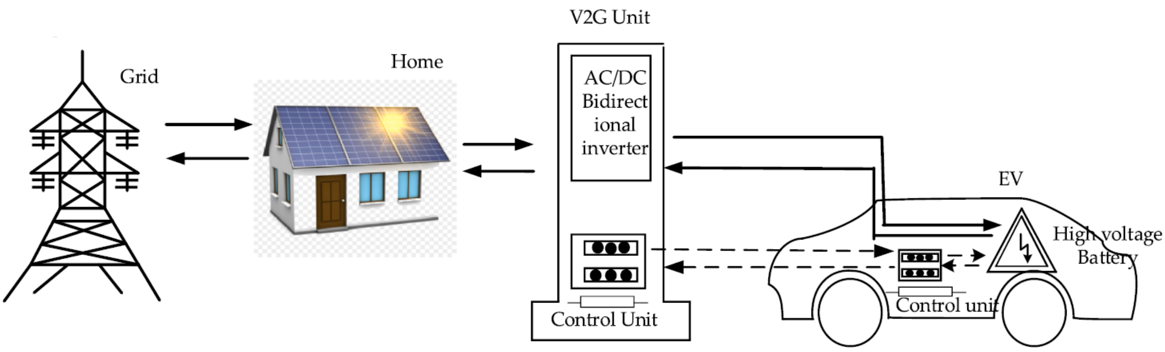


Fig. 7. Bi-directional EV charging systems with V2G and V2H technologies [85], [86]

Table 3. Commercial DC FCs on the market [77], [83], [84]

Manufacturer Model	ABB Terra 53	PHIHONG Integrated Type	EVTEC espresso & charge	Tesla Supercharger	Tritium Veefil-RT	ABB Terra HP
Power	50-kW	120-kW	150-kW	135-kW	50-kW	350-kW
Supported protocols	CCS Type 1 CHAdeMO 1.0	GB/T	SAE Combo-1 CHAdeMO 1.0	Supercharger	CCS Type 1 & 2 CHAdeMO 1.0	SAE Combo-1 CHAdeMO 1.2
Input voltage (V_{AC})	480	380 ± 15% 480 ± 15%	400 ± 10%	380-480	380-480	400 ± 10%
Output DC voltage (V_{DC})	200-500 50-500	200-750	170-500	50-410	200-500 50-500	150-920
Output current (A)	120	240	300	330	125	375
Efficiency (%)	94	93.5	93	91	> 92	95
Time to add 200 miles (min)	72	30	24	27	72	10

3. Current and Future Battery Types for Fast Charging

The maximum charging power is constrained by battery technology. Additionally, customers often desire batteries with high energy capacity to meet the demand for extended driving ranges. Fast-charging depends on batteries with elevated energy density, permitting more energy storage in a compact and lightweight form. Moreover, batteries should exhibit high charging efficiency, an extended life cycle, robust power handling capabilities, and efficient thermal management systems to be well-suited for fast-charging. They should feature sturdy cell designs, reliable chemical compositions, and efficient safety measures. Lithium-ion batteries are the favored choice for energy storage in contemporary EVs. They offer several advantages, including high energy density, extended lifespan, high specific power and energy, rapid charging capability, low self-discharge rate, recyclability, and a lightweight design [90], [91]. Additionally, they don't experience potential memory effects and don't contain any hazardous metals such as lead, mercury, or cadmium [92]. The primary drawback of lithium-ion batteries is their costly manufacturing, primarily because of the specialized packaging needed for these batteries [93]. There are numerous variations of lithium-ion batteries currently in use in today's EVs, and many more are under development. These lithium-ion batteries are mainly categorized based on the types of cathode materials, which include Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Lithium Titanate Oxide (LTO), Lithium Iron Phosphate (LFP), Lithium Nickel Manganese Cobalt Oxide (NMC), and Lithium Nickel Cobalt Aluminum Oxide (NCA) batteries [90], [94], [95]. These batteries possess unique characteristics, including cell voltage, life cycle, energy density, and cost, which stem from variances in their internal architecture and the specific materials used in the construction of their cathodes and anodes. Fig. 8 provides a qualitative comparison between different lithium-ion batteries based on specific power, specific energy, performance, safety, longevity, and cost [96]. Batteries like LMO and LFP have high energy density; however, they aren't well-suited for fast-charging because of their relatively slow charging rates. While batteries characterized by high power density, such as NCA and NMC, are the preferred choice for fast-charging applications. As depicted in Fig. 8, the LTO battery offers excellent specific power, making it particularly well-suited for fast-charging. However, it is more expensive in comparison to other lithium-ion batteries. In general, lithium-ion batteries exhibit a compromise between energy density and the duration required for recharging. Table 4 provides a list of some commercial batteries that can be charged at 4C (in 15 minutes) while maintaining an acceptable energy density (i.e., greater than 150 Wh/kg) [97].

Silicon anodes have garnered considerable interest as prospective substitutes for conventional graphite anodes in lithium-ion batteries due to their inherent advantages [98], [99]. Silicon's ability to store a higher amount of lithium presents a significant boon, promising to elevate energy density levels in batteries. This enhanced energy storage capacity could translate into batteries with prolonged usage durations and increased overall efficiency [100]. The potential shift from graphite to silicon anodes holds the promise of revolutionizing the battery technology landscape by delivering more powerful and longer-lasting energy storage solutions [101]. The higher energy density of silicon anodes also offers the prospect of creating lighter and more compact battery systems, a crucial factor in various applications, ranging from consumer electronics to EVs. As researchers continue to explore ways to address challenges associated with silicon's expansion and contraction, the advantages of higher lithium storage capacity underscore the transformative potential of silicon anodes in advancing the performance and capabilities of lithium-ion batteries [102], [103]. Besides, integrating graphene or other nanomaterials into battery design has shown promise in improving electrical conductivity and overall performance [104]. These materials can enhance the charge/discharge rates and extend the battery's lifespan [105].

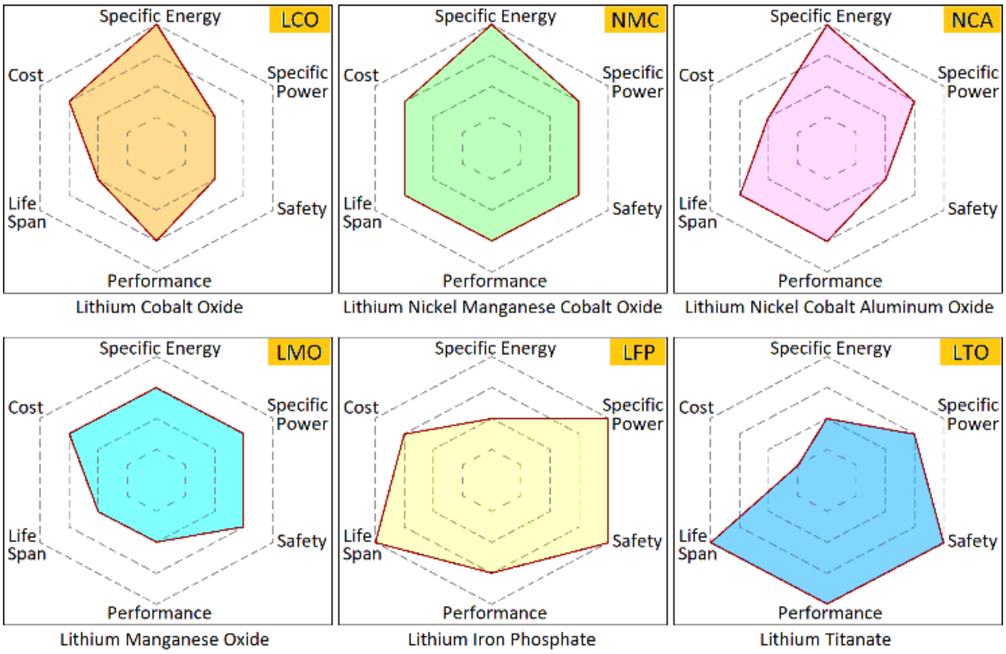


Fig. 8. Specifications of different lithium-ion batteries utilized in existing EVs [96]

Table 4. Commercial batteries compatible with fast-charging [97]

Company	Material of anode/cathode	Charging rate (Max.)	Energy density
CATL	Graphite/NMC	4C	215 Wh/kg
Enevate	Si/NMC	9C	350 Wh/kg
Microvast	PC/LMO	4C	190 Wh/kg
Kokam	Graphite/NMC	4C	152 Wh/kg

Note: PC: Porous Carbon, C: Battery Capacity

In addition to the previously mentioned lithium-ion batteries, there are different high-voltage battery options well-suited for fast-charging, including solid-state batteries and lithium-sulfur (Li-S) batteries. The emergence of these alternatives holds great promise for transforming the landscape of energy storage and EVs. Solid-state batteries represent a developing technology with the potential to enable efficient fast-charging. These batteries utilize solid electrolytes rather than liquid electrolytes, providing increased energy density, enhanced safety, and the prospect of rapid charging rates. Moreover, the potential for higher energy density translates to increased storage capacity and longer-lasting charges. Solid-state batteries can be engineered to operate at high voltages, enabling them to support fast-charging capabilities. Li-S batteries, on the other hand, represent a cutting-edge battery technology, offering superior energy density as well as reduced size and weight compared to traditional lithium-ion batteries [106]. Despite being in the developmental phase, Li-S batteries offer promising attributes for the future of efficient and swift charging solutions. These attributes stem from their capability to support high-voltage operations and facilitate rapid charging rates. Additionally, the shift away from cobalt, a material with ethical and environmental concerns, aligns with the industry's pursuit of sustainable and eco-friendly solutions.

Reference [107] provides a comprehensive review of batteries used for electric mobility. The comparative assessment of both emerging and current battery technologies has led to the conclusion that numerous batteries aren't well-suited for fast-charging. Lead-acid batteries and Nickel-Cadmium (Ni-Cd) batteries aren't regarded as appropriate for fast-charging because of their restricted energy density and charging capabilities. While batteries such as Sodium-Sulphur (Na-S) and Nickel-Metal Hydride (Ni-MH) offer high energy density, they aren't typically regarded as ideal for fast-charging. Their operational temperature range and intricate design characteristics result in their diminished suitability for accommodating rapid charging in EVs. Batteries such as Zinc-Bromine (Zn-Br) and Aluminum-Air (Al-air) batteries offer substantial theoretical energy levels but are infrequently employed in EVs. Their limited applicability for fast-charging stems from issues associated with rechargeability and their relatively short lifespan.

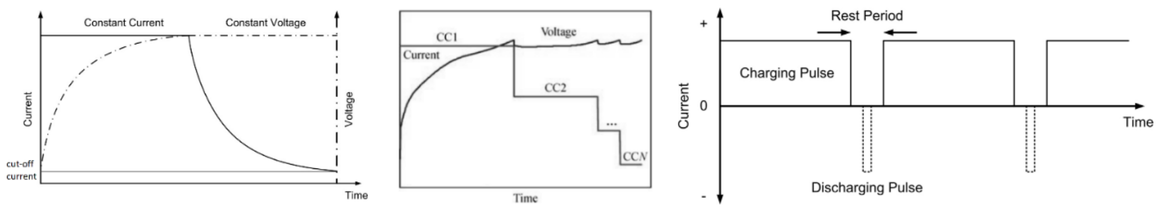
4. Fast Charging Techniques

Charging a battery seems like a straightforward process, but achieving fast-charging can introduce certain challenges. These challenges revolve around the battery life cycle, effective heat dissipation, proper battery ventilation, and the effectiveness of the charging circuit [108]. The essence of fast-charging lies in efficiently transferring energy to the battery at significantly high power levels without causing any harm to the battery. These power levels are not solely determined by the battery type and its chemical characteristics but are also influenced by the choice of the appropriate charging technique. Battery charging technique refers to the shapes and magnitudes of the currents and voltages to be used during charging. Over the years, various charging techniques have been developed to reduce charging time, enhance charging efficiency, minimize performance degradation, and ensure safe fast-charging [109]. The conventional charging techniques encompass constant current (CC), constant power (CP), constant voltage (CV), trickle current (TC), and taper charging. In order to address the shortcomings of conventional charging techniques and enable faster and safer charging of EV batteries, advanced charging techniques have been developed. These advanced techniques often incorporate a combination of the conventional approaches, resulting in techniques like constant current-constant voltage (CC-CV) charging, multi-stage constant-current (MCC) charging, pulse charging, and negative pulse charging, all of which are employed for rapid battery charging [110], [111].

A hybrid charging technique known as CC-CV has been introduced by combining CC charging with CV charging, as illustrated in Fig. 9(a) [111]. Generally, many commercial battery FCs employ the CC-CV charging technique [58], [112]. The CC-CV charging technique consists of two main phases: the initial phase is characterized by CC charging, and the subsequent phase involves CV charging. Initially, a predetermined constant current, usually specified by the cell manufacturer, is supplied to the battery. This phase primarily focuses on charging most of the battery's capacity. Once the battery voltage or the SOC approaches a predetermined threshold, known as the cut-off voltage, the charging mode switches from CC to CV. This shift limits the current level to safeguard the battery from the risk of overcharging and potential damage. Then, the battery undergoes a charging phase in which the current is gradually reduced while maintaining a constant charging voltage. The CV phase will continue until the current decreases to a predetermined value, typically 0.1C or 0.05C, or until a specified capacity level is attained [113]. Despite the use of the CV mode to complete the charging of the remaining battery capacity, the charging process typically requires a similar amount of time, or in some cases, may even extend beyond the duration needed in the CC mode. This is because it necessitates a reduction in charging current to guarantee that the battery is thoroughly topped off [114]. The benefits of the CC-CV technique encompass regulating the charging current flowing into the battery, keeping the charging voltage within limits, controlling the power being supplied, efficiently utilizing the battery controller, safeguarding the battery against over-voltage conditions, minimizing thermal stress, and facilitating fast-charging [72], [115].

MCC is another widely used fast-charging technique, as illustrated in Fig. 9(b) [108]. The key distinction between MCC and CC-CV charging techniques is that in MCC charging, the battery undergoes a sequence of multiple monotonically charging currents throughout the entire charging process [116]. The sequence of charging currents in this technique needs to be progressively decreased and structured as several constant current stages ($I_{CC1}>I_{CC2}>\ldots>I_{CCN}$). When the terminal voltage reaches a predefined voltage threshold while it is in one of the constant current stages, the charging process will transition to the next constant current stage, where the charging current is further reduced [117]. This reduction in charging current will persist until the battery's terminal voltage approaches the final predefined voltage threshold, during which the current will be at its lowest level. When applying the same initial charging current, this technique generally results in a slightly longer charging time in comparison to the CC-CV technique.

Pulse-charging has been investigated as a battery fast-charging technique in certain studies [72], [118]. This charging technique performs battery charging by delivering charging current in a pulsating or intermittent manner, as opposed to a continuous flow of current [119]. The charging rate, determined by the average current, can be managed by adjusting the pulse width in the pulse-charging technique. An intriguing aspect of this charging technique is the inclusion of a brief intermission lasting 20-30 milliseconds between charging pulses, which plays a crucial role in stabilizing the chemical processes occurring within the battery [120]. The rest interval facilitates the harmonization of chemical reactions with the charging procedure, thereby helping to minimize the formation of gas at the electrode surface [121], [122]. On the other hand, negative pulse-charging complements pulse-charging as a technique. This technique involves introducing a brief discharging pulse during the pulse-charging resting interval to depolarize the battery and eliminate any gas bubbles that could have developed on the electrode surfaces while the battery was undergoing pulse-charging [123]. Fig. 9(c) provides an overview of the typical operations involved in pulse-charging and negative pulse-charging [111]. Table 5 gives a brief comparison of the fast-charging techniques mentioned above by stating their advantages and disadvantages [108], [110].



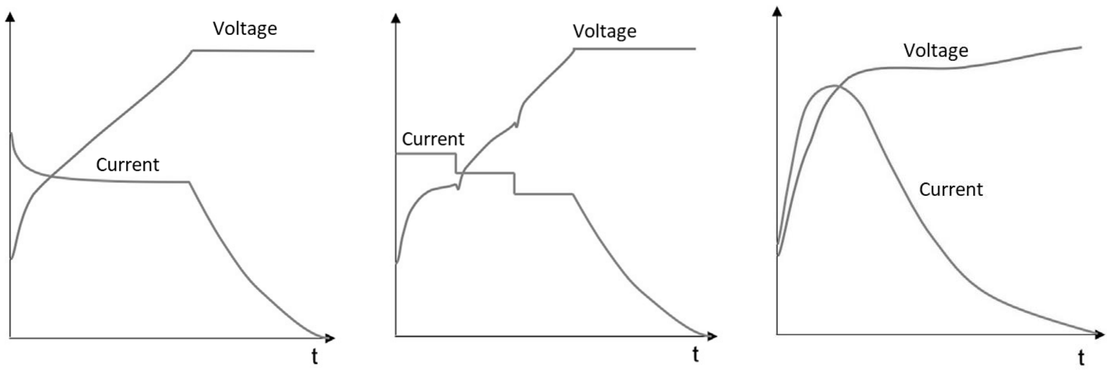
(a) (b) (c)

Fig. 9. Charging profiles of common fast-charging techniques: (a) CC-CV, (b) MCC, and (c) pulse-charging and negative pulse-charging [108], [111]

Numerous innovative fast-charging techniques have been developed, building upon CC-CV, MSCC, and pulse-charging principles. These techniques aim to enhance battery charge acceptance, reduce charging durations, improve efficiency, and boost capacity. Examples include constant power-constant voltage (CP-CV), multi-stage constant current-constant voltage (MCC-CV), and variable current profile (VCP) [109], [110], [124]. In CP-CV technique, the battery is charged using constant power until the battery voltage reaches its upper limit voltage in the initial stage of charging. Subsequently, the charging technique is switched to constant voltage charging, as illustrated in Fig. 10(a), which depicts the schematic diagram of the CP-CV charging technique [109], [110]. Combining both constant power and constant voltage elements in a charging technique may involve a dynamic adjustment between the two based on the state of the battery and other factors. This could optimize the charging process for efficiency, speed, and battery health [125]. Besides, MCC-CV is an advanced fast-charging technique designed to enhance the efficiency and speed of EV charging. This technique employs multiple steps for current control, allowing for a more precise regulation of charging parameters, as shown in Fig. 10(b) [109], [110]. By dynamically adjusting the voltage and current levels across multiple channels, MCC-CV aims to optimize the charging process, minimize energy losses, and reduce charging times for EVs [126]. This innovative approach ensures a more reliable and efficient fast-charging experience, addressing the growing demand for faster and more convenient charging solutions in the EV industry [127]. Finally, the VCP is a strategy based on impedance evolution with SOC, coupled with a current decaying profile to accommodate the polarization variations with SOC, as shown in Fig. 10(c) [109], [110]. The charging parameters are derived from equivalent circuit modelling and algorithm optimization, showing better charging efficiency and cycle life than standard charging [128], [129]. In this type of techniques, the main problem is that complex charging profiles are difficult to implement in practical chargers [130].

Table 5. Comparison of fast-charging techniques in EVs [108], [110]

Fast-charging technique	Advantages	Disadvantages
CC-CV	• Easy to implement. • Needs simple requirements.	• Long charging time. • Low efficiency. • The CV charging stage can cause severe degradation.
MCC	• Minimize the charging time. • Reduce heat generation. • Avoid lithium plating. • Avoid overcharging.	• Requires full estimation of all the internal equivalent parameters of the electric circuit.
Pulse Charging	• Reduces lithium plating. • Increases charging efficiency. • Increases lifetime. • Used in charging at low temperatures.	• Need a complex controller to manage the pulses.



(a) (b) (c)

Fig. 10. Schematic representation of innovative techniques proposed for fast charging. a) CP-CV, b) MCC-CV, c) Boost charging with a CC-CV-CC-CV, and d) VCP [109], [110].

For controlling the voltage and current profiles of the charger output during the charging process, the EV must be equipped with a Battery Management System (BMS). As presented in Fig. 11, this system monitors the voltage of each cell and the temperature, and it gives current and voltage references to the EV FC controller [131].

5. Different Power Electronic Topologies of Fast Charger

The battery FC essentially operates as an off-grid power supply. It draws electricity from the 3-phase AC grid and delivers it to the traction battery. To become a viable solution, an EV battery FC must meet the grid standard code requirements for total harmonic distortion (THD) and power factor (PF) while also employing an appropriate charging technique from the battery side [132]. Additionally, to realize V2G functionality, the FC should be bidirectional to facilitate regenerative operations [133]. This means that it has the capability to not only charge the vehicle's battery but also return power to the grid when needed. Furthermore, it should guarantee full galvanic isolation from the grid to comply with existing safety regulations such as the IEC EN 61851-23 standard [59]. Hence, the power electronic interfaces within the FC need to be constructed to ensure distortion-free performance, high PF, high power capacity, and galvanic isolation concerning the grid [134]. Additionally, given the substantial power transfer involved, it is imperative that the power converters operate with extremely high efficiency.

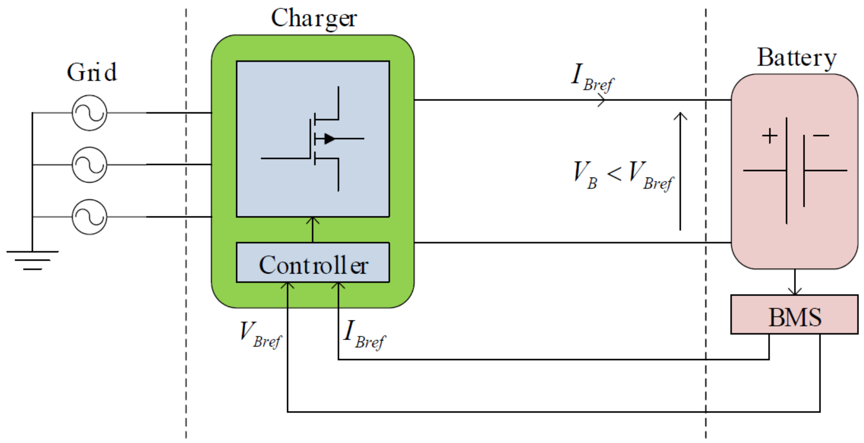


Fig. 11. fast charging system with BMS [131]

In general, a battery FC is a power converter made up of several stages in series that regulate the charging process. Fig. 12 illustrates the general block diagram of FC. This general structure mainly comprises two power conversion stages. The input stage encompasses an AC-DC power converter along with an input electromagnetic interference (EMI) filter, functioning as an active front end (AFE) for grid connection, while the output stage includes a DC-DC power converter at the back end, serving as an interface to the batteries. The input stage is used to perform AC-DC conversion, reduce THD caused during charging, and guarantee the PF close to unity according to recent power quality regulations, such as IEC 61000-3 in Europe and IEEE 519 in the United States [73], [135]. These regulations restrict the harmonic contents of current taken from the electric grid through AC-DC converters. While The output stage is specifically engineered to provide the necessary control over current and voltage for charging EV batteries. Additionally, it ensures that the fluctuation in the charging current remains within a safe operating range for the battery. These functions are essential to maintaining power quality and meeting the specific requirements for battery charging.

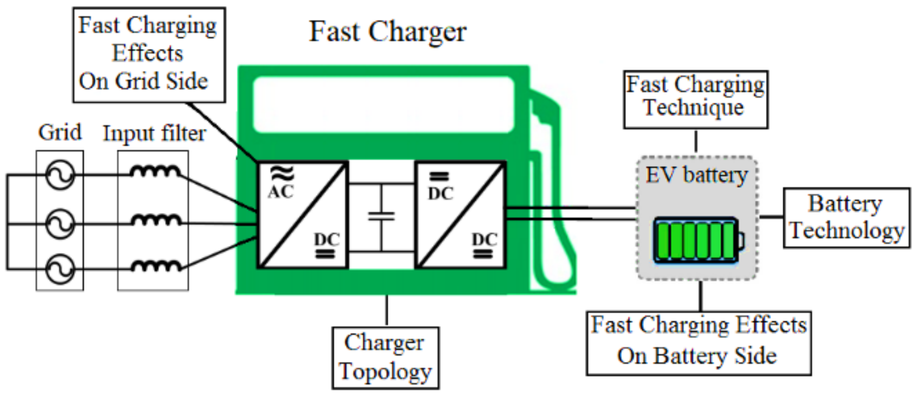


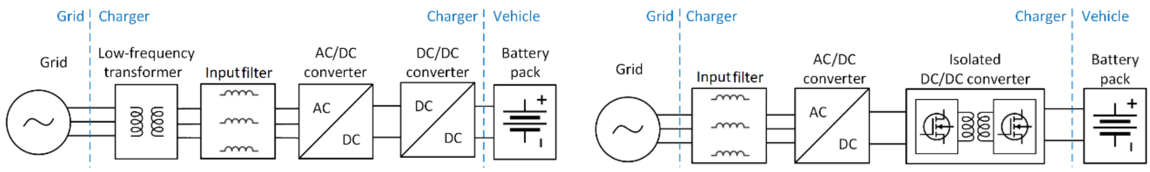
Fig. 12. General block diagram of FC

5.1. FC Architectures

Two different FC two-stage architectures, each employing the basic arrangement, are introduced [136]. The first architecture achieves galvanic isolation at the grid side by incorporating a low-frequency (LF) transformer prior to the input stage, followed by a non-isolated DC-DC converter.

Alternatively, the second architecture utilizes an isolated DC-DC converter in the output stage, integrated with a high-frequency (HF) transformer to provide galvanic isolation. Fig. 13 shows the different FC architectures [137]. The power conversion system of the first architecture comprises four key components: a LF transformer that offers galvanic isolation between the FC and the electric grid, an input filter designed to decrease current THD, ensuring compliance with IEEE and IEC standards, a 3-phase AC-DC converter responsible for controlling DC-bus voltage and grid PF, and a non-isolated DC-DC converter that manages the DC output by regulating both current and voltage to match the battery charging profile. This architecture is illustrated in Fig. 13(a) [137]. The key benefit of this architecture lies in the employment of a conventional LF line transformer, which is a relatively straightforward component that doesn't require a complex design process. Moreover, the incorporation of transformer-less DC-DC converters offers flexibility in choosing the configuration. Additionally, when necessary, multiple DC-DC converters can be interleaved to diminish the ripple in the output current, consequently reducing the size of the DC-DC converter output filter [134], [138]. Conversely, the necessity for larger magnetic materials results in an expansion of both the dimensions and weight of the LF transformer.

Alternatively, the second architecture consists of three primary components: an input filter, a 3-phase AC-DC converter, and an isolated DC-DC converter, which not only offers galvanic isolation but also regulates the battery's DC output, as depicted in Fig. 13(b) [137]. This architecture enables a decrease in the dimensions and weight of the charging system because of the high operating switching frequency of the transformer, resulting in a significantly increased power density of the system. Additionally, the HF transformer effectively shapes the output current, resulting in a decrease in the size of the DC-DC converter output filter. Nevertheless, this architecture requires the parallel interconnection of multiple DC-DC converters to minimize output ripple and align with the current charging profile, thus reducing the current carried by the switching devices. Additionally, the use of a transformer entails a more intricate design and higher costs compared to the LF solution, as it may necessitate specialized magnetic cores, such as amorphous alloys or nanocrystalline materials [139]. The choice of FC architecture largely hinges on the components and control strategies utilized to ensure its effective operation. As a result, this section provides an in-depth discussion of power converters, which have the potential to be used for EV fast-charging.



(a) (b)

Fig. 13. FC architectures: (a) FC with a LF isolation transformer, (b) FC with a HF isolation transformer [137]

5.2. Grid-Tied AC-DC Power Converters

Grid-tied AC-DC power converters, commonly referred to as rectifiers, serve as an intermediary that connects the electrical grid to a controlled DC-bus [140]. These converters need to meet several important performance criteria. They must ensure that the power they deliver to both the AC and DC sides of the system is of high quality [141]. This means the electrical power should be stable, reliable, and free from distortions that can affect the performance of connected devices or systems. Additionally, these converters must achieve a high PF on the AC side. A high PF is crucial because it helps to reduce the potential for harmful effects on the grid, such as excessive currents or voltage fluctuations [142]. Furthermore, these converters should be capable of regulating the output voltage within specified limits, ensuring that the voltage provided to the DC-bus remains constant and within the desired range. Finally, it's essential for these converters to be designed with simplicity and efficiency in mind, keeping their complexity to a minimum to enhance their overall performance and reliability. The ideal scenario for the power converter is to be cost-effective, which implies having a minimal number of active switches and placing less stress on both passive and active components [143]. This entails designing the converter in a way that minimizes the need for costly components and ensures the efficient use of available resources. An overview of 3-phase rectifier topologies is given in Fig. 14 [137], [142]. These converters can be classified into two categories: bidirectional and unidirectional AC-DC converters [144]. Unidirectional rectifiers are designed solely to extract power from the grid for EV battery charging. Conversely, bidirectional rectifiers have the ability to transmit power from the vehicle back to the grid when required [145]. Fig. 15 depicts a selection of common grid-tied AC-DC converters that are well-suited for fast-charging [77], [146].

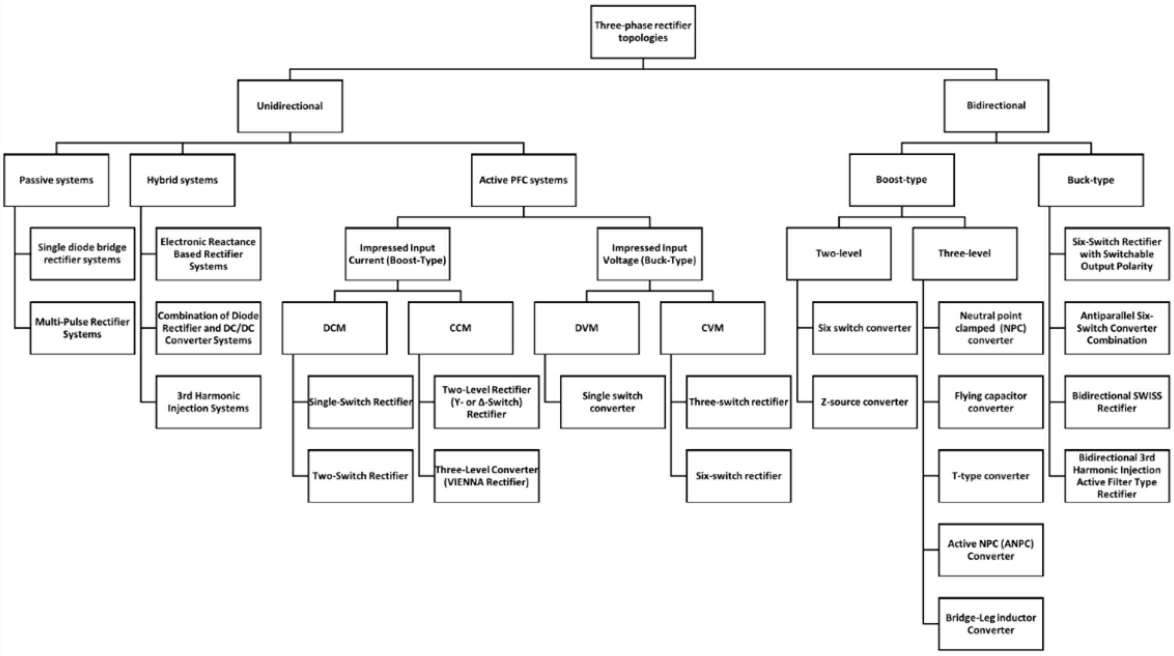


Fig. 14. Overview of 3-phase rectifier topologies [137], [142]

5.2.1. Bidirectional AC-DC Converters

The commonly employed grid-tied AC-DC converter is the 3-phase active pulse width modulation (PWM) converter, which utilizes six IGBTs, lacks diodes, and incorporates an L-filter, as illustrated in Fig. 15(a) [77]. This type of two-level converter is of the boost variety, and it produces an output voltage that exceeds the input phase voltage. The PWM converter produces minimal THD of input currents, operates bidirectionally, allows controllable PF, and has a DC-link voltage regulation with a capacitor filter of small size [147], [148]. The uncomplicated design, robust control strategies, and the presence of affordable switching devices possessing adequate voltage and current capacities have led to the widespread adoption of this converter in FCs [77], [149]. Nonetheless, this rectifier necessitates larger input inductors in terms of volume and has a restricted maximum switching frequency when contrasted with three-level converters [150].

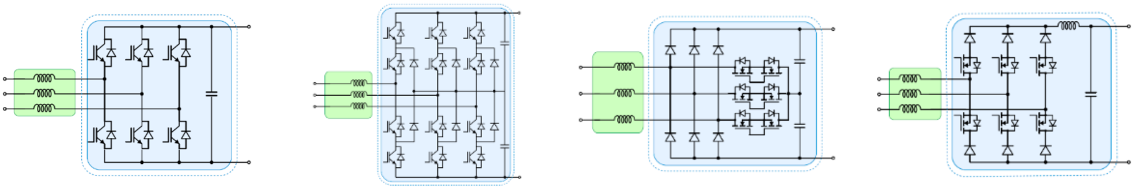
The neutral point-clamped (NPC) converter is another example of a bidirectional converter that features twelve IGBTs, six diodes, and an L-filter, as depicted in Fig. 15(b) [146]. The three-level converter supports bidirectional power flow and allows the use of components with lower voltage ratings, leading to decreased switching losses at a reasonable cost [137], [151]. Another benefit of utilizing the NPC converter is its capability to establish a bipolar DC-bus [152]. This feature allows for the connection of two DC-DC converters in configurations like series-series or series-parallel, effectively boosting the output power of the charging system [153]. Nonetheless, this topology necessitates a larger quantity of power semiconductor components, leading to increased costs. Additionally, employing extra switches results in reduced THD on the AC side, adding complexity to the control system [154].

5.2.2. Unidirectional AC/DC Converters

The Vienna AC-DC converter, as depicted in Fig. 15(c), is a widely utilized converter that incorporates six IGBTs, six diodes, and an L-filter [146]. In scenarios where unidirectional power flow suffices, the Vienna AC-DC converter offers a three-level arrangement that has fewer switching devices [155]. Despite retaining the benefits of three-level converters, the Vienna AC-DC converter also inherits the typical challenges associated with three-level converters, such as the requirement for maintaining balance in DC-link capacitor voltages [156], [157]. A significant drawback of the Vienna rectifier is its one-way power flow and the restricted range of control it offers over the PF.

When the output voltage is less than the input line-to-line voltage, a unidirectional AC-DC converter with buck-type characteristics is utilized. This converter, as shown in Fig. 15(d), consists of an L-filter, six IGBTs, and six diodes, with an extra inductor on the DC side [77]. Compared to boost-type converters, this converter offers several advantages, including built-in short-circuit protection, ease of control, and a reduced output voltage [158]. However, it operates in one direction only and has limitations in providing a wide range of PF control at the AC side [159], [160].

In summary, of the four converters mentioned, the PWM and NPC rectifiers are capable of handling power flow in both directions, while the Vienna and Buck-type rectifiers allow power flow in one direction only. The NPC and Vienna rectifiers have the advantage of producing lower THD on the AC side, but this comes at the cost of a more intricate control system compared to the buck-type and PWM rectifiers. Additionally, the NPC and PWM rectifiers provide a broader control range for PF compared to the Buck-type and Vienna rectifiers. A summary of their characteristics is provided in Table 6 [77], [84], [161].



(a) (b) (c) (d)

Fig. 15. AC-DC converters for FCs: (a) PWM rectifier, (b) NPC rectifier, (c) Vienna rectifier, and (d) Buck-type rectifier [77], [146]

Table 6. Comparison of various AC-DC converters for FCs [77], [84], [161]

Converter	Switches/Diodes	PF Range	Control Complexity	Bidirectional	THD
PWM rectifier	6 / 0	Wide	Low	Yes	Low
NPC rectifier	12 / 6	Wide	Moderate	Yes	Very Low
Vienna rectifier	6 / 6	Limited	Moderate	No	Very Low
Buck-type rectifier	6 / 6	Limited	Low	No	Low

5.3. DC-DC Power Converters

After the grid-tied AC-DC converters, the back-end DC-DC converters act as a link connecting the DC-link with the EV battery. These converters have the task of charging the EV battery using a designated charging technique, all while maintaining the battery's safety through communication with the BMS. The choice of an appropriate DC-DC converter is contingent on various considerations. These considerations encompass the voltage difference between the DC-side of the grid-tied rectifier and the battery, the converter's capacity to handle current, the extent of current fluctuations experienced by the battery, cost, efficiency, harmonic performance, and the need for isolation [143], [162]. The categorization of back-end DC-DC converters depends on whether there is physical isolation (galvanic isolation) between the supply and the output circuit. This isolation determines whether a converter falls into the isolated or non-isolated category. Isolated DC-DC converters have the option to employ any of the subsequent arrangements: phase-shift full-bridge (PSFB), LLC, dual-active bridge (DAB), or CLLC. Conversely, non-isolated arrangements encompass the buck converter,

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interleaved buck converter, unidirectional three-level buck converter, bidirectional three-level buck converter, or three-level flying capacitor converter. Table 7 summarizes the primary features and drawbacks of both isolated and non-isolated DC-DC converters [77], [146].

Table 7. Comparison of various isolated and non-isolated DC-DC converters for FCs [77], [146].

Converter	Type	Switches/ Diodes	Bidirectional	Main advantages and drawbacks
PSFB converter	Isolated	4 / 4	No	• Easy-to-implement control system, broad range of output voltages. • Significant switching losses in primary output diodes and switching devices; duty-cycle loss; challenging to achieve ZVS under light loads.
LLC converter	Isolated	4 / 4	No	• ZVS on primary side and ZCS on secondary side; Low reactive current. • Restricted controllability; challenging to achieve high efficiency and ZVS over a broad operating range.
DAB converter	Isolated	8 / 0	Yes	• Broad attainable output range. • Trade-off between reactive power and ZVS condition; inherent reactive current.
CLLC converter	Isolated	8 / 0	Yes	• Low reactive current; broad ZVS range. • Restricted controllability under wide output range.
Buck converter	Non-isolated	1 / 1	No	• Easy-to-implement control system. • Limited current and voltage capability. • Large output inductor.
Interleaved buck converter	Non-isolated	3 / 3	No	• Augmented current capacity; low current ripple; easy-to-implement control system; satisfied scalability. • Restricted voltage capability.
Buck-boost converter	Non-isolated	2 / 0	Yes	• Easy-to-implement control system. • Limited current and voltage capability.
Interleaved buck-boost converter	Non-isolated	6 / 0	Yes	• Augmented current capacity; low current ripple; easy-to-implement control system; satisfied scalability. • Restricted voltage capability.
Three-level buck converter	Non-isolated	4 / 0	No/Yes	• Increased voltage capability; reduced current ripple. • Not for interleaving because of circulating current.
Flying capacitor converter	Non-isolated	4 / 0	Yes	• Increased voltage capability; satisfied scalability. • Difficult short-circuit protection.

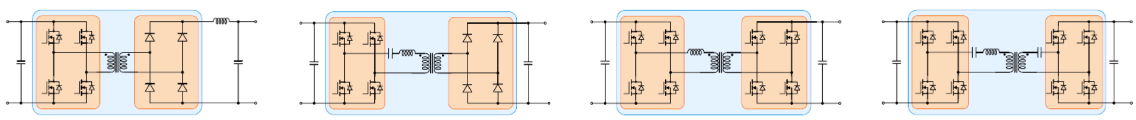
5.3.1. Isolated DC/DC Converters

Due to the requirement that the EV battery should never be connected to the ground, it is essential to have galvanic isolation to maintain a separation between the battery and the grid. This is crucial to ensure that the safety and protection systems of the battery remain unaffected by the charging system. One way to accomplish this is by employing a galvanically isolated DC-DC converter that incorporates a transformer. Fig. 16 illustrates the isolated DC-DC converters appropriate for FCs [77], [146]. In cases where unidirectional power flow is sufficient, the PSFB converter, as depicted in Fig. 16(a), is a viable topology [77]. This topology typically features an H-Bridge of switching devices situated on the transformer's primary side and is often accompanied by a diode bridge on the secondary side, which is linked to the EV battery [146]. As a result of this design, the converter is capable of facilitating power transfer in only one direction [163]. When the converter is in phase-shift PWM control, its switching devices can achieve zero-voltage switching (ZVS) during the turn-on phase or zero-current switching (ZCS) during the turn-off phase. Therefore, the PSFB converter is capable of providing a high output voltage and substantial power rating [164]. The primary drawbacks of this topology include losses during the turn-off of the switching devices, substantial losses in the output diodes, and the occurrence of significant ringing across the output diodes [77]. This ringing is caused by a combination of factors, such as the LCL resonance of the transformer's leakage inductance, the parasitic capacitance of the reverse-biased diodes, and the output inductor. In order to reduce ringing and mitigate voltage spikes, it's possible to implement active or passive snubber circuits [165]. However, this comes at the expense of decreased system efficiency.

Another unidirectional isolated DC-DC converter is the LLC resonant converter, as depicted in Fig. 16(b) [146]. The LLC resonant converter features an LLC tank comprising a resonant inductor, a resonant capacitor, and the HF transformer magnetization inductance. The converter output voltage is controlled by adjusting the switching frequency, which in turn modifies the impedance ratio between the resonant circuit and the effective load. This converter offers exceptional efficiency and high-power density, making it a popular choice for fast-charging [166]. Soft-switching methods can be implemented, involving either ZVS during turn-on or ZCS during turn-off. Nevertheless, it has limitations in regulating power efficiently at light loads, and maintaining the ZVS condition across a wide operating range can be challenging, which can impact efficiency.

If a situation necessitates power to flow in both directions, the DAB converter, as illustrated in Fig. 16(c), is a highly suitable option for EV charging systems [77]. It stands out for its exceptional power density, high efficiency, the ability to both step-up and step-down voltage, low stress on electronic components, reduced need for filter elements, and minimal sensitivity to component variations [167]. The DAB converter offers a solution for power control by modifying the phase difference between primary and secondary voltages and leveraging the transformer's leakage inductance to facilitate power transfer. Because of its uncomplicated structure and ZVS operation, it has gained popularity in numerous applications requiring isolated bidirectional DC-DC conversion [168]. Nevertheless, managing the eight power switches in this topology involves a more intricate control process, and its non-resonant operation may result in slightly reduced efficiency, particularly when operating at lower power levels [146], [169].

A different version of bidirectional DC-DC converters is the CLLC converter, as depicted in Fig. 16(d) [146]. The CLLC converter boasts a symmetrical circuit, delivering consistent voltage gain characteristics for power flow in both directions. This symmetry simplifies control processes and aids in managing power. Additionally, this converter allocates two resonant capacitors on the transformer sides, reducing the voltage stress experienced by these capacitors in comparison to the LLC converter [170]. However, much like the LLC converter, the CLLC converter encounters analogous design trade-offs, including challenges related to the ZVS condition and efficiency reduction over a broad range of power and voltage operations. Controlling the CLLC converter can also be intricate, primarily due to the consistent relationship between voltage gain and frequency within certain frequency ranges [77].



(a) (b) (c) (d)

Fig. 16. Isolated DC-DC converters for FCs: (a) PSFB converter, (b) LLC converter, (c) DAB converter, and (d) CLLC converter [77], [146]

5.3.2. Non-isolated DC/DC Converters

When the FC utilizes the existing isolation from a preceding power conversion stage, like the LF transformer before the input stage, it allows for the substitution of a non-isolated DC-DC converter in place of an isolated one. This non-isolated converter can still provide a floating power supply to the EV battery. Fig. 17 illustrates the isolated DC-DC converters suitable for FCs [77], [171]. In numerous scenarios, the voltage level of the EV battery is lower than that of the rectifier's output voltage. To address this, the use of the buck converter, as depicted in Fig. 17(a), may be applied to reduce the

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input voltage, thereby simplifying the charging process [171]. This is the most straightforward non-isolated topology for battery interfacing. However, it's worth noting that if a low current ripple is necessary, the filtering inductor of the buck converter will need to be relatively large. In addition to a single-phase converter, there's an option to use a multi-phase interleaved DC-DC buck converter, as depicted in Fig. 17(b), which combines two or more phase legs. This topology enables the sharing of the output current across three phases, resulting in decreased requirements for filter inductors and the need for small switching devices [77]. The 3-phase interleaved DC-DC buck converter boasts a straightforward design, good performance, and scalability to high power [49], [172]. Moreover, the converter generally exhibits high efficiency due to its base frequency being multiplied by three. This leads to a higher system frequency, improved transient response, reduced current ripple, and smaller output filters. However, it's essential to note that with an increase in the number of phases, there is a corresponding increase in the switching devices, costs, control system complexity, and power density [73], [173].

If there's a need for bidirectional power flow to exchange power between the EV battery and the grid, the buck-boost converters, as depicted in Fig. 17(c) and Fig. 17(d), are suitable for charging purposes [77]. Another topology known for its superior harmonic performance is the three-level buck converter, along with its bidirectional counterpart, as depicted in Fig. 17(e) and Fig. 17(f) [171]. This design minimizes current fluctuations, enabling the use of smaller inductors to conform to the required current ripple criteria [174]. Another three-level topology is the flying capacitor converter, as depicted in Fig. 17(g) [77]. This converter has the advantage of using smaller inductors and enabling easy power rating expansion through the parallel and interleaved connection of multiple phase legs. However, it presents challenges in designing short-circuit protection because of the inclusion of the flying capacitor. Additionally, the switching commutation loop involving the upper and lower devices is larger, which can lead to undesired voltage overshoot during switching [175].

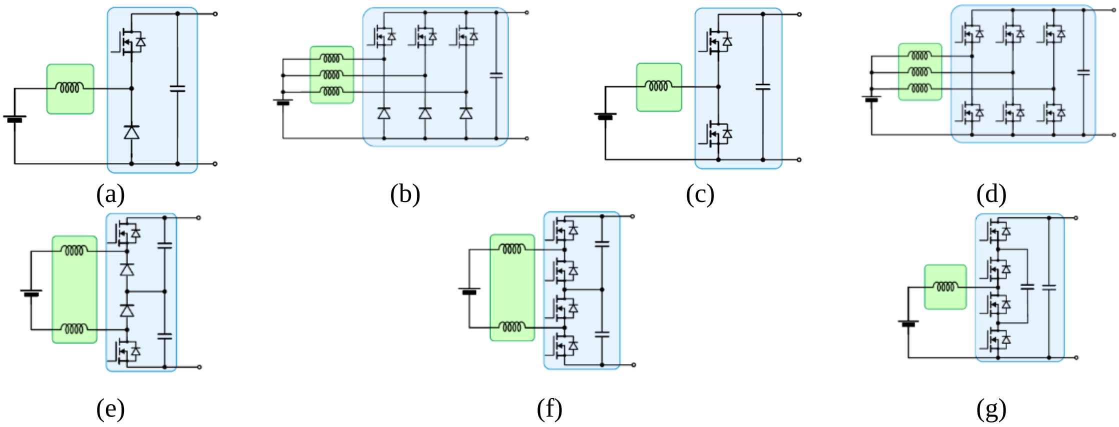

Fig. 17. Non-isolated DC-DC converters for FCs: a) Buck converter, (b) 3-phase interleaved buck converter, (c) Buck-boost converter, (d) 3-phase interleaved buck-boost converter, (e) Unidirectional three-level buck converter, (f) Bidirectional three-level buck converter, and (g) Three-level flying capacitor converter [77], [171].

5.4. Evaluation of Emerging Switching Technology for Power Converters

The most failure-prone devices are the semiconductor switching devices for power electronic converters. This is because of their high thermal stress property. Many of these failures are time-dependent dielectric breakdowns [176]. Hence, the efficiency and reliability of these switching components are crucial for the performance of the entire FC system [177]. With the emergence of new and improved devices, such as Wide Band-Gap (WBG) semiconductor switches, the FC performance can be improved substantially [178], [179]. The WBG devices can withstand higher junction temperatures, block higher voltages, and operate under higher switching frequencies. Moreover, switching and conduction losses are lower in WBG devices [180]. Such properties are illustrated in

Fig. 18 [181]. WBG active switches allow FCs to operate at even higher power levels. The efficiency of WBG chargers is reaching as high as 98.5% [182], [183].

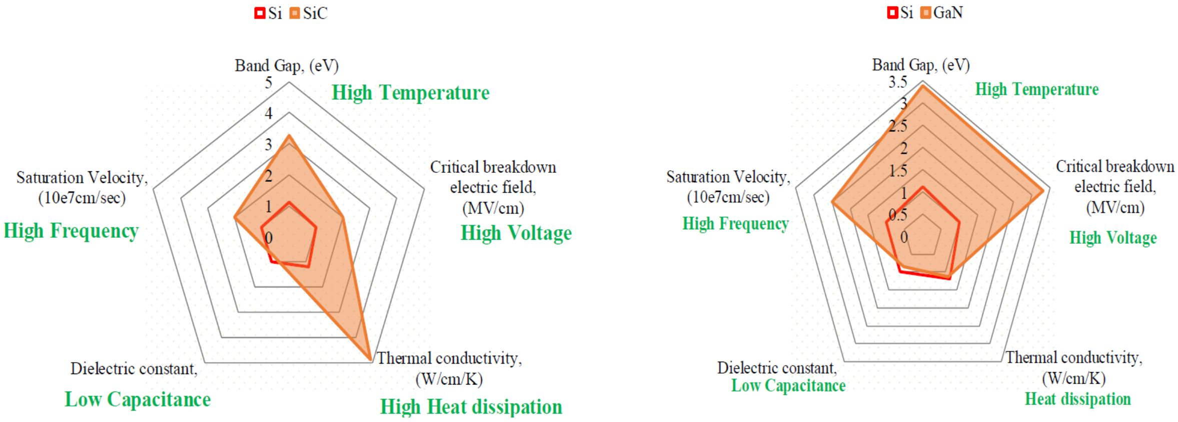

Fig. 18. Comparison between WBG devices (Silicon carbide (SiC) and Gallium Nitride (GaN)) with respect to Silicon (Si) [181]

Nowadays, SiC and GaN are the types of WBG devices commonly used in EVs. Si, SiC, and GaN semiconductor materials have fundamental differences in their material properties, such as bandgap, critical field, carrier mobility, electron saturation velocity, and thermal conductivity [184], which makes them suitable for different applications. As shown in Fig. 19 [137], Si is still the mainstream technology. For higher power and frequency applications, SiC devices are used. GaN devices are used in higher frequency but lower-power applications [185]. The FCs are outside the power level that GaN can support at this time. Therefore, Si and SiC are suitable choices for the design of high-power FCs. The Si IGBTs tend to have higher power ratings compared to metal–oxide–semiconductor field-effect transistors (MOSFETs). However, they are much slower, meaning they cannot operate at higher switching frequencies. Higher switching frequencies are essential in decreasing filter component sizes. Moreover, the SiC devices can block voltages above 10 kV [186], which makes them a suitable choice for DC FCs connected to the medium voltage grid. A 350 kW SiC-based DC charger at 4.16 kV AC is presented in [187]. While [188] proposes a SiC-based FC connecting to a 2.4 kV AC. The current ratings of commercially available discreet SiC devices can reach up to 100 A for SiC Diodes and MOSFETs and 160 A for SiC Bipolar Junction Transistors (BJTs) [186]. SiC power modules that consist of several devices in parallel can be used for higher current applications.

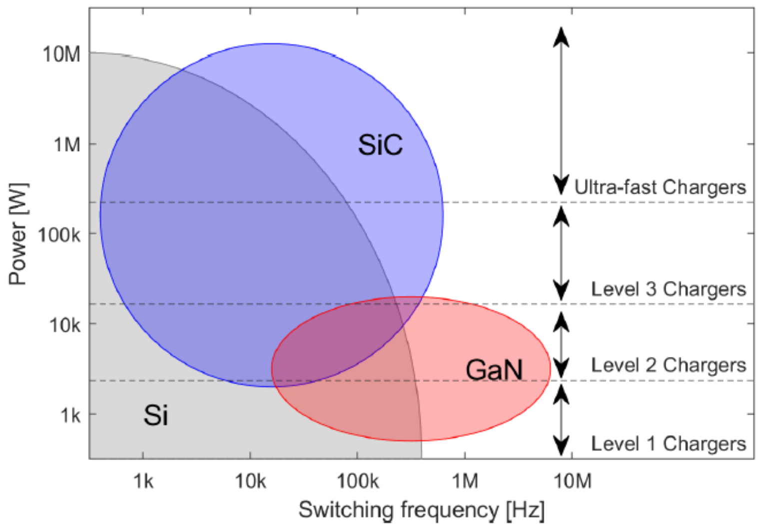

Fig. 19. Application of power semiconductors by type [137]

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5.5. Industrial Applications

As seen in Fig. 20, the modular 50 kW power cell designed by Semikron has an input Vienna rectifier and a PSFB converter for an output voltage up 1000 V. It is developed for easy paralleling to meet 350 kW and make it possible to recharge an EV in 11 min [189]. Fig. 21 shows an example of the topology proposed by Infineon Technologies for a 30-kW converter to be combined for the realization of a unidirectional very high-power charger. This charger consists of a Vienna rectifier followed by an LLC resonant converter [190]. Another example based on a three-phase two-level rectifier and three-phase interleaved DC-DC buck-boost power converter is illustrated in Fig. 22, where ABB's Terra High Power Series is used. These FCs achieve 150 kW by the unit, while each unit is composed of 50 kW modules, with galvanic isolation ensured by a power transformer. To achieve increased power levels, this unit is multiplied many times to attain a maximum of 600 kW for electric trucks and electric buses [82].

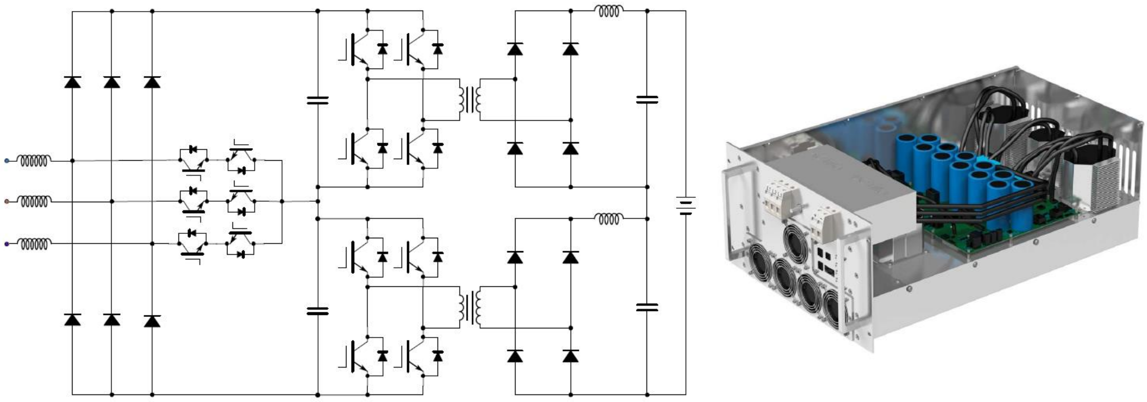

Fig. 20. Modular 50 kW power cell (Designed by Semikron)

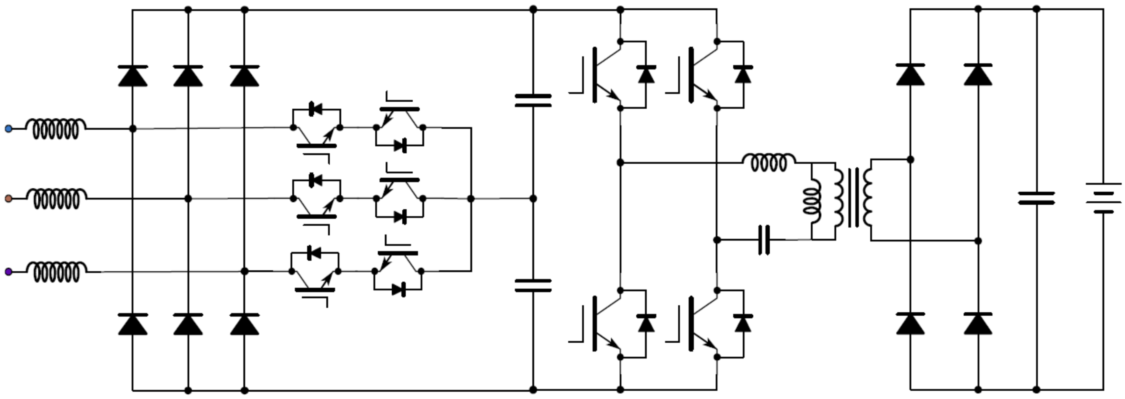

Fig. 21. Modular 30 kW charger (proposed by Infineon Technologies)

6. Cooling Systems

The cooling technique is crucial for power electronic converters as it can affect the system efficiency and lifetime. Moreover, cooling systems are one of the roadblocks in the development of FCs. Regardless of which architecture is selected, a DC FC consists of a grid-connected filter, AC-DC AFE stage, DC-DC stage, and isolation stage. Therefore, a power electronic cooling system consists of cooling the power semiconductors, power inductors [191], transformers [192], [193] and capacitors. There are several types of cooling systems commonly used for power electronic converters: forced air cooling, liquid cooling, and other more complex cooling methods, as shown in Fig. 23 [180]. Depending on the type of charger, i.e., on-board or off-board, the cooling system will have different requirements. The main parameters are the space and weight limitations, power level, and allowed temperature range. Since this review focuses on high-power FCs, the space and weight constraints are of reduced importance, while the dissipated power levels will be extremely high. If the best-case system efficiency of 97% is assumed, the dissipated power levels for FCs will range from 660 W for a 22-kW system up to 10.5 kW for a 350-kW system. Whereas for ultra-FCs of above 400 kW power rating, the dissipated power will be more than 12 kW. The advantages and disadvantages of air cooling and liquid cooling are presented in Table 8.

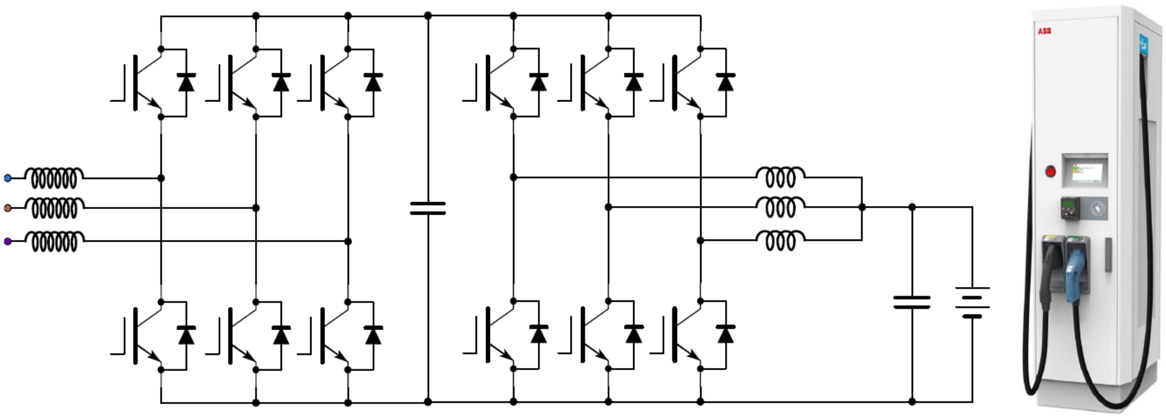

Fig. 22. Modular 50 kW charger (designed by ABB)

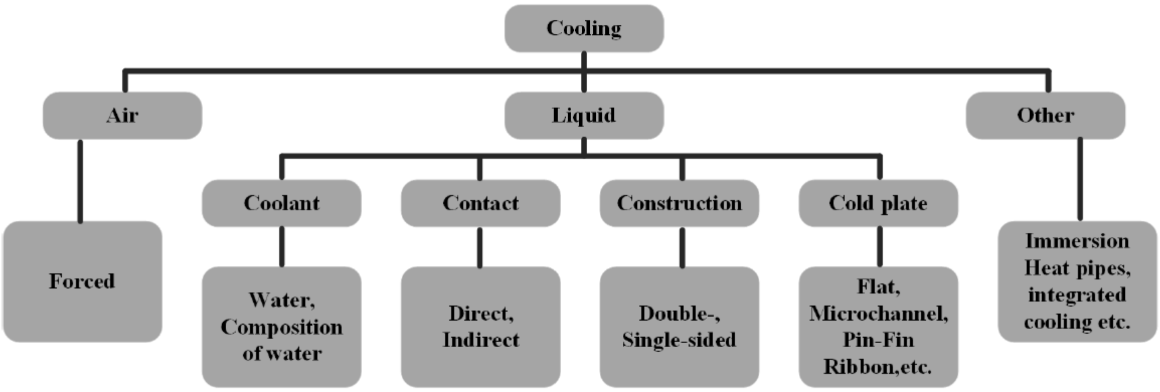

Fig. 23. Different cooling methods for power electronic cooling [180]

Air cooling is relatively simple and cost-effective [180]. It also uses fewer components compared to liquid cooling, which may have a positive effect on the power density of the FC system [194]. Air cooling can be either non-forced or forced air cooling; forced air cooling can remove more heat from the system. In some cases, using design and control optimization, researchers were able to succeed in using only natural (non-forced) cooling for SiC chargers [195] of up to 2 kW, which is below the power rating of DC FCs. The optimized design of the heatsink structure can further increase the efficiency of air-cooled systems [196]. However, according to [197], in forced air-cooled systems, the outside corrosive elements can easily enter and damage the system, causing shortened lifetime and difficult maintenance. A 90-kW modular DC FC that consists of 15 kW modules achieves 95% efficiency using forced air cooling in [198]. Moreover, a protective air inlet design is used to minimize the dust and particles entering the charger. Some of the commercially available DC chargers use forced air cooling of the power electronics. For example, EVBox Troniq modular (90 kW–240 kW) [199] and Blink HPC-180- 480 (60 kW–360 kW) [200] use forced air cooling of the power electronics while providing optional liquid cooling for the cables.

Liquid cooling has higher heat transfer efficiency [201]. Moreover, liquid-cooled systems have a high ingress protection class [197]. The type of liquid used in this cooling method and the exact construction can vary from case to case. According to [197], liquid cooling systems have a risk of liquid leakage, the equipment is complex, and the cost is high. A combination of a modular approach and liquid cooling can be a suitable solution for high-power FCs. An AFE drive with 200-kW modules presented in [202] is able to achieve a 97% efficiency using a liquid cooling system with water. A liquid-cooled 100 kW two-stage FC with 95% efficiency and modular design is presented in [203]. A 360-kW liquid-cooled DC charger is available commercially from Dekon [204]. Fig. 24 summarizes the cooling methods for a few industrial DC FCs where most of the manufacturers are using liquid cooling methods with a few using forced air cooling [84].

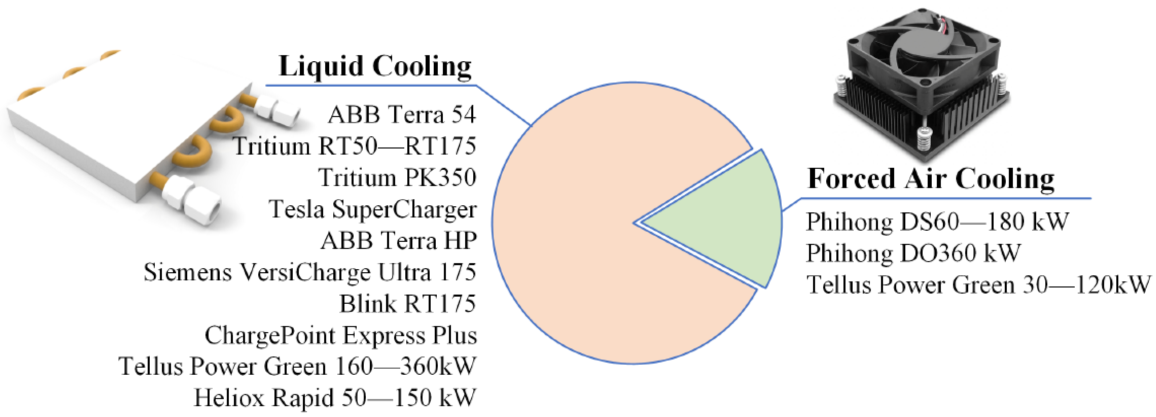

Fig. 24. Type of cooling used in the commercially available industrial EV DC FCs [84]

Table 8. Comparison of air and liquid cooling methods.

	Advantages	Disadvantages
Air Cooling	• Low cost • Does not need additional equipment like heat-exchanger, pump,.. • Active control of fans allow control of junction temperature.	• Performance depends on the environment. • Requires CFD analysis for complex systems. • Can be bulky for high-power applications. • Harder to achieve high IP ratings due to polluted air. • High operation noise. • Fan reliability effects the overall lifetime.
Liquid Cooling	• Higher efficiency • Heat removal from the enclosed system is easier. • Less space and lighter system • Low operation noise	• Requires CFD analysis for proper channel design. • Required pumps, heat exchanger ext.

7. Impacts of Fast Charging

Fast-charging may result in adverse effects on both the electrical grid and the batteries used in EV traction systems.

7.1. Electrical Grid

The advancement of EV fast-charging technology raises power demand, potentially resulting in adverse effects on the power infrastructure. This includes added load on the electrical grid, distribution transformers, cables, and fuses, along with increased load fluctuations [205], [206]. While the effects of EV charging on a distribution system may be negligible when viewed from the perspective of a single EV owner, the cumulative effect of numerous EVs charging simultaneously from the same distribution grid can result in significant and adverse consequences for the entire distribution system [207]. The use of power electronic devices in the EV charging process can introduce power quality issues within the distribution, primarily because of the switching phenomena that occur. EV FCs are essentially power electronic converters, akin to non-linear loads. This distinctive non-linear nature, which is different from general industrial or domestic loads, can result in the generation of harmonic currents and can impact the voltage profile of the electrical grid [208]. A significant presence of non-linear loading can lead to non-linear voltage fluctuations and consequently distort the voltage waveform. Accordingly, EV FCs need to maintain a high PF and a low THD in the AC input current. This safeguards the quality of power on the grid. Specifically, when operating at full power, it is preferable to maintain the THD of the AC input current below 5%, a standard commonly observed in industrial applications. Therefore, regulations are in place to restrict the acceptable THD levels in the AC input current, safeguarding the integrity of the power grid when fast-charging is employed. EV FCs meeting the necessary standards must ensure they stay within the specified limits for harmonics. However, the excessive harmonics generated by these chargers can have a particularly detrimental impact on distribution transformers. These chargers not only lead to a higher fundamental current draw from the transformers, which increases heat, but the harmonic currents may also create challenges. These challenges include skin and proximity effects within the transformer windings due to non-uniform current distribution. Harmonic currents may also divert electromagnetic flux beyond the intended transformer boundaries, leading to additional losses. This increased thermal stress is likely to shorten the operational life of the transformer [209]. Furthermore, the harmonic currents generated by these chargers can affect the cables. The high-frequency components, primarily causing a skin effect, are typically considered when determining the conductor's cross-sectional area. However, issues arise with the neutral cable that experiences multiple harmonic currents [210]. This occurrence leads to overheating of the neutral cable, giving rise to safety concerns, increased losses, and a shortened cable lifespan. Harmonic distortion [211], heightened power demands [212], breaches of voltage regulation limits [213], elevated power system losses [214], potential overloading of distribution transformers, and increased thermal loading of conductors [215] are the major problems for the electricity network during fast-charging.

7.1.1. Increased Power Demand

The increased power demand stemming from FCs has a destabilizing effect on the system due to its non-linear characteristics, and it exerts additional stress on the grid. To address this problem, a potential solution is to implement a rigorous schedule for EV fast-charging, ensuring that it predominantly occurs during peak and off-peak periods. This approach serves to reduce the impact of high-power demand. The power required for EV charging is mathematically described in (1) [28].

$$P_{EV} = \frac{C_{Batt} * (SOC_{max} - SOC_{min})}{T_D} \tag{1}$$

Where: C_{Batt} represents the battery capacity, T_D represents the charging interval, and SOC represents the level of charge present in the battery. It is a significant factor in determining whether the EV draws a high or low amount of power during charging.

7.1.2. Harmonics Disturbance

The presence of non-linear characteristics in an EV charger is a major contributor to voltage and current THDs within a grid. Given that EV chargers are typically connected to the grid for charging, the cumulative impact of these harmonics poses a potential risk to the entire power system [216]. These harmonics can be quantified by assessing the percentage values of THD for both current and voltage, as indicated in (2) and (3) [62].

$$THD_i = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_1} \times 100\% \tag{2}$$

$$THD_v = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1} \times 100\% \tag{3}$$

Where: n represents the harmonic order number, N represents the highest number of harmonics, I_n and V_n denote the RMS values of the current and voltage at the n^{th} harmonic component, and I_1 and V_1 stand for the RMS values of the base frequency current and voltage.

7.1.3. Transformer Overloading

Charging EVs rapidly has the potential to strain and overload transformers. This issue arises because the non-linear characteristics of fast-charging introduce harmonic currents, resulting in increased heat generation within the transformer core. These added losses compound the overall power dissipation and reduce the transformer's kVA rating. To address this, it is crucial to select a transformer that can withstand higher levels of harmonic currents associated with non-linear loads. This ability to handle harmonics is often quantified using a parameter called the k-factor, which is defined in (4) [215]. Therefore, opting for a transformer with a higher k-factor can effectively mitigate the power losses caused by harmonic effects.

$$K_{factor} = \sum_{n=1}^{N} n^2 \, [\frac{I_n}{I_R}]^2 \tag{4}$$

Where: I_n represents the current associated with the n^{th} harmonic, and I_R represents the rated load current.

7.2. Traction Batteries

Undoubtedly, the traction battery stands out as the most vital component of an EV. This is because it significantly impacts various critical aspects, including cost, weight, reliability, and the driving range of the vehicle [217]. The growing popularity of EV fast-charging has made it increasingly important for traction batteries to efficiently handle high currents while simultaneously preserving battery longevity [218]. Unfortunately, the adoption of fast-charging can have detrimental consequences for the performance and longevity of batteries by hastening their aging process [219]. The extent of this reduction in lifespan depends on several variables, including how frequently fast-charging is employed, the initial battery SOC at the onset of each charging process, and the specific chemistry of the battery. The reason behind this lies in the fact that fast-charging typically involves subjecting batteries to high current levels and elevated temperatures, both of which are primary contributors to the degradation of traction batteries [220]. The consequences of prematurely aging traction batteries can have a major impact on EVs, leading to reduced driving range and diminished acceleration capabilities.

To facilitate rapid EV charging without compromising performance, it is imperative to scrutinize the technical considerations associated with achieving fast-charging without expediting the aging of battery systems [221]. Achieving fast-charging involves focusing on two primary technical factors: (1) selecting the appropriate battery technology, which entails choosing a battery technology that possesses an architectural design optimized for fast-charging; and (2) implementing an effective fast-charging technique, which involves choosing and deploying a fast-charging technique that aligns with the selected battery technology. It's important to recognize the interconnected nature of these two factors because different battery technologies come with unique voltage and current limitations, which significantly influence the design of an appropriate fast-charging technique. Therefore, a comprehensive evaluation of both the battery technology and the technique design must be carried out concurrently to achieve a fast-charging solution that is not only efficient but also sustainable.

8. Battery Recycling

8.1. Environmental Impact

Because of the harmful compounds and heavy metals in batteries, such as lead, cadmium, and mercury, improper battery disposal can cause environmental damage. These compounds can potentially leak into soil and water, causing threats to ecosystems and human health.

8.2. Resource Conservation

Recycling batteries allows precious materials such as lithium, cobalt, nickel, and rare earth elements to be recovered. These materials are scarce resources, and recycling helps lessen the need for mining and extraction, which can have severe environmental implications.

8.3. Energy Intensity

Because battery recycling procedures can be energy-intensive, there may be a trade-off between the energy saved through material recovery and the energy lost in the recycling process.

8.4. Improving Recycling Techniques

Ongoing research and development in battery recycling technologies aims to increase efficiency, reduce energy consumption, and develop more sustainable material recovery methods.

8.5. Advancements in Battery Chemistry

New battery chemistries and technologies are being developed to improve energy density, charging efficiency, and recyclability.

9. Potential Future Research Trends

EVs are valuable resources in smart grid infrastructure. They can smooth out the power variations caused by the increasing share of intermittent and fluctuating renewable energy sources. However, widespread adoption of EVs would place an unnecessary strain on the electrical grid, increasing the risk of congestion, voltage drop, and other problems throughout the distribution system. Problems of varying severity are posed to power system operators by this issue. For EVs to be an advantage rather than a burden to the smart grid, smart charging and discharging (i.e., bidirectional V2G) solutions that incorporate security, smart metering, and communication between EVs, and the smart grid are essential. Thus, it is recommended that further study be directed toward improving smart charging technologies. EVs could be very interesting for smart grids. However, their presence in these grids could be very stochastic. In addition, minimizing grid-related problems and maximizing economic advantages through the use of appropriate optimization techniques depends on the strategic positioning and adequate sizing of charging stations [222]. As a result, studies may be conducted on improving optimization methodologies and the cost function for charging station optimization [41], [223], [224]. EV sales are smashing records worldwide, and EVs play a crucial role in moving toward more sustainable urban mobility. Utilities confront the dual task of decarbonizing power generation and keeping up with rising energy demand as they brace for the effects of climate change and the depletion of fossil fuel supplies. EVs have the potential to significantly contribute to the development of sustainable energy solutions for utilities, municipalities, and nations. The adoption of EVs in the market is predicated on the Smart Grid. This electrical supply network uses digital communications technology to monitor and react to local changes in demand. These are pushing the market towards the most recent innovations in EV charging, such as portable chargers and V2G technologies [225].

9.1. Portable Chargers

Although eliminating EV on-board chargers will make EVs more cost-effective and efficient in the long run, few automotive OEMs are investigating this prospect. Automakers may be working to do rid of on-board chargers in EVs by including a portable (compact form factor) DC charger with every EV. There are several upsides to doing away with the car's on-board charger system [225].

- Total system costs can be lowered if Q100-certified hardware and software are unnecessary.
- Lower fuel consumption and increased range result from a lighter vehicle's lower gross weight.
- Easier charger maintenance means less time without your electric vehicle.
- Most notably, unlike when utilizing a Level 1 or Level 2 charger, the charging rate will no longer be constrained by the on-board charger's power rating.

It is anticipated that these chargers will be tiny enough to fit in the palm of your hand and will rely on natural convection to cool themselves (rather than using fans). To achieve size reduction and low thermal emissions, manufacturers may use a GaN/SiC-based design that can switch from 100 kHz to a few MHz.

9.2. V2G and V2H technologies

Energy stored in EVs may be sent back into the national electrical grid to assist the supply of energy at times of peak demand called V2G technology. More than ninety percent of automobiles are parked at any given moment, wasting a lot of power while their occupants do nothing. This power may be used, regulating the grid's supply and demand for electricity. As a result, reversible converters will have to be installed at EV charging stations. Property owners who generate solar power on their roofs can store it locally in their automobiles and restore it to the residence when needed using V2H technology.

9.3. Technology for Ultra-Fast charging

Investigate innovative charging methods for quicker charging rates, such as solid-state batteries, supercapacitors, and novel materials.

9.4. Grid Integration and Smart Charging

Investigate strategies for effectively integrating fast-charging infrastructure into the electrical grid, reducing congestion, and ensuring grid stability during peak demand periods.

9.5. Battery Health Management and Degradation [226]

Research the effects of ultra-fast charging on battery degeneration and devise appropriate battery health management solutions to extend battery longevity.

9.6. Heat Management and Thermal Effects

Investigate thermal management approaches to limit the heat produced during fast-charging, which can cause battery stress and reduced efficiency.

9.7. Authentication and Cybersecurity

Investigate solutions for protecting rapid charging networks from cyber-attacks, such as authentication mechanisms and encryption techniques [227], [228].

9.8. Optimization of Materials and Components

Look into new materials for charging connectors, cables, and other components to improve conductivity, durability, and safety during fast charging [229].

10. Conclusion

The growing interest in EV technology is driven by the numerous advantages it provides. However, the extended charging durations and limited charging facilities currently limit the practicality of EVs for everyday commuting and short-range excursions. To overcome these challenges, there exists a demand for fast-charging technology that can rival the convenience of traditional ICEV refueling infrastructure. This review comprehensively discussed fast-charging concept in EVs, developed international standards for fast-charging, fast-charging techniques, and battery chemistries appropriate for fast-charging, which clearly show the development towards fast-charging. Possible FC architectures utilizing either an LF transformer or an HF transformer in the output stage are presented in detail. Besides, various power converter topologies that could be adopted to achieve fast-charging are introduced, analyzed, and compared as well as some industrial FC designs are presented. In summary, the ongoing advancements in power conversion topologies, the development of new standards, innovative charging techniques, and the promising progress in battery energy technology are collectively bringing us closer to the realization of fast-charging technology that can closely resemble the convenience of refueling at traditional gas stations. Moreover, an overview of various cooling methods for power electronic converters in FCs are discussed. Nevertheless, the integration of EVs with fast-charging technology can introduce certain adverse impacts on the power grid and traction battery. These impacts are discussed in detail, along with some remedies to counter these effects. Additionally, the integration of efficient EV battery recycling processes is paramount for sustaining the rapid expansion of fast-charging infrastructure, ensuring the responsible management of end-of-life batteries and fostering a cleaner, more sustainable future for electric mobility. Finally, future research direction in the field of EV charging are discussed.

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