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INVITED PAPER

Charging Infrastructure and Grid Integration for Electromobility

The rapid uptake of electric vehicles (EVs) resulted in a significant demand for charging infrastructure. This article demonstrates possible charging approaches and architectures, discusses related standardization issues, and explains associated control algorithms.

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ABSTRACT | Electric vehicle (EV) charging infrastructure will play a critical role in decarbonization during the next decades, energizing a large share of the transportation sector. This will further increase the enabling role of power electronics converters as an energy transition technology in the widespread adoption of clean energy sources and their efficient use. However, this deep transformation comes with challenges, some of which are already unfolding, such as the slow deployment of charging infrastructure and competing charging standards, and others that will have a long-term impact if not addressed timely, such as the reliability of power converters and power system stability due to loss of system inertia, just to name a few. Nevertheless, the inherent transition toward power systems with higher penetration of power electronics and batteries, together with a layer of communications and information technologies, will also bring opportunities for more flexible and intelligent grid integration and services, which could increase the share of renewable energy in the power grid. This work provides an overview of the existing charging infrastructure ecosystem, covering the different charging technologies for different EV classes, their structure, and configurations, including how they can impact the grid in the future.

KEYWORDS | Charging infrastructure; electric mobility; electric vehicles (EVs); EV charging; grid integration; weak-grid chargers.

I. INTRODUCTION

In a span of ten years, electric mobility shifted from holding the potential of replacing internal combustion vehicles in transportation, to becoming one of the main mechanisms to tackle climate change. The recent commitment to accelerate the 100% transition to zero-emission vehicles appears as a clear sign of its importance [1], where all the stakeholders (manufacturers, governments, service providers, commercial operators, and utilities) will work toward supporting a smooth transition toward clean and affordable transport choices.

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Overall, the market share of electric vehicles (EVs) has risen fast as sales numbers continue to grow annually in every market segment [2]. Notably, the strong commitment of original equipment manufacturers (OEMs) to further embrace electric mobility is paving the way to a brighter future for its large-scale deployment. This, along with a stronger policy support, battery technology improvements, and an expanding charging infrastructure are driving a sharp increase in EV sales for the next years. However, road transportation is still far from reaching the projections of carbon neutrality by 2050, especially in the market of larger and heavier vehicles, e.g., in freight transport [3]. Besides, with a rapidly closing window to remain on course to achieving net zero, more developments and stronger efforts from the stakeholders can be expected. Costwise, these vehicles are already economically attractive in some regions, and efforts are being made toward the development of megawatt-scale charging stations and batteries capable of delivering more energy with smaller size. These will positively impact the viability of electric long-haul in the upcoming years.

Regardless of the size of an EV, power electronics is essential at every level of its architecture: for conversion of electrochemical energy stored in the battery to propulsion via electric motors; for integration of the high- and low-voltage (LV) buses to energize on-board electronics and auxiliary loads; and for building the charging infrastructure responsible for battery charging. This article will focus on the latter, highlighting the role of diverse EV charging infrastructure that will accelerate EV adoption.

Charging of EV batteries inherently requires the conversion of energy from the ac mains into dc with well-controlled parameters, as the energy needs to be stored in a battery, which is dc by nature. To comply with the charging profile of batteries, power electronics converters are included in order to meet the precise requirements coordinated by the vehicle's battery management system (BMS). To this end, several charging voltage and power levels have been defined by different standardization organizations in order to enable different charging options [4], [5], [6].

The improvements in battery technology are also driving the evolution of power converters for charging, given that their performance and status completely dominate energy transfer. Regardless of the power handling capabilities of the charger employed, the BMS precisely commands the required current, voltage, and power levels during the charging process, setting limits in terms of deviation, ripple, speed of level adjustments, and safety limits. Further breakthroughs in battery technology can unleash the advances in power converters to achieve charging times in the range of refilling a gasoline tank. In addition, the development has led to a variety of technological solutions.

This article provides an in-depth look at EV charging infrastructure, underlining the role of power electronics in its deployment, and discussing the present status of different charging technologies. A wide variety of charging mechanisms and trends is presented for different EV classes, from light- to heavy-duty EVs including on-board and off-board power electronics converter solutions and their control schemes.

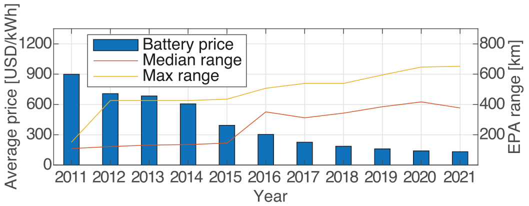


Fig. 1. ***Battery technology improvements: Li-ion battery pack weighted-average total price and mileage capacity for sold EV models in the U.S. Sources: Bloomberg NEF [7], the U.S. Department of Energy, and the U.S. Environmental Protection Agency [8].***

In addition, this article addresses the impacts of current charging technologies on the grid, assuming a large-scale deployment, and provides an outlook on the opportunities to perform grid services using the same infrastructure, with a wider scope than the majority of the literature, which typically focuses exclusively on vehicle-to-grid applications. Finally, challenges and future trends are discussed, such as chargers acting as grid assets and standard-compliant nonisolated chargers.

II. IMPROVEMENTS ON BATTERY TECHNOLOGY

Battery technology has improved substantially over the first decade of the EV market. Continued investment in research and development (R&D) alongside capacity expansion across the supply chain has led to improved battery technology and reduced costs, and is expected to continue over the next decade with the rise of next-generation batteries. According to Bloomberg NEF [7], the volume-weighted average pack and cell price has dropped over $1,000 since 2010, and it is expected to reach the break-even point of $100 per kWh by 2024 [7], [10]. The reported average prices are displayed in Fig. 1. There is an industry consensus that, below this price, automakers will have similar production costs as gasoline cars in global leading markets for mass-produced EVs while providing the same margins as conventional vehicles. This could mean that EVs will reach similar prices, and it could substantially facilitate the adoption of electric mobility for a wider audience [7].

In addition to cost reduction, battery packs are also showing an increase in performance. The latest batteries are able to provide higher energy capacities in lighter and smaller packages, and withstand higher charging/discharging currents with improved thermal performance, besides supporting more charge cycles [5], [11]. From a user point of view, these advancements have materialized in EVs that are able to recharge their batteries in shorter times while featuring longer mileage per single

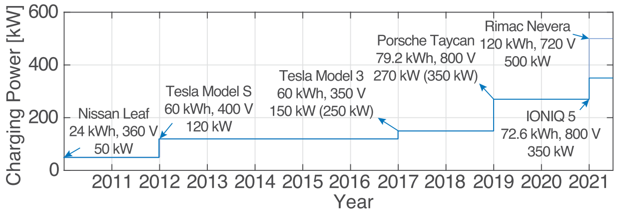


Fig. 2. ***Evolution of the maximum charging power for representative EV battery packs [3], [9].***

charge. This evolution is also indicated by Fig. 1, which displays the battery price and estimated EPA range for U.S. passenger EV sales, with the average range reaching 377 km in 2021 [2], [12]. It is further beneficial to the electrification of larger vehicles since the sharp reduction in battery prices may already render them cost-competitive in certain markets, and charging powers above the megawatt level are in sight [3]. Significant progress has already been demonstrated by controlling the conductor temperature at high current levels (using liquid-cooled cables and connectors) and reducing the current draw by increasing the battery pack voltage to the 800-V level [13], [14], [15]. Further evidence is presented in Fig. 2, which shows the maximum charging power ratings of mass-produced EVs from the past decade. It can be seen that newer batteries are capable of accepting higher charging rates, hence enabling further reductions in charging times. Considering that the voltage range is expected to reach 1500 V (the limit for LV as defined in various standards, such as DIN EN 50110-1:2014), similar breakthroughs in charging times could be foreseen for heavy-duty EVs [16].

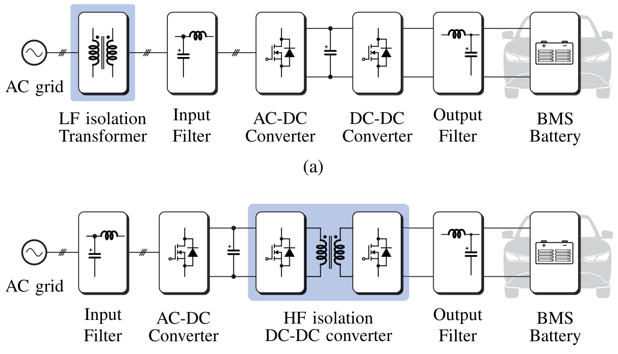
In the big picture, the reduction in prices and the improved performance also benefits the EV charging infrastructure since stationary grid-connected energy storage in charging stations becomes cost competitive. By enabling better utilization of clean energy sources through energy arbitrage, a charging station with an ESS could help to smoothen the intermittent behavior of nondispatchable energy generated from renewable energy sources (RESs) [17], [18], [19]. Apart from enabling transportation electrification, such charging infrastructure could facilitate the migration to a decarbonized energy matrix, thereby helping to reduce carbon emissions in both energy and transportation sectors. In addition, it facilitates the integration of stationary energy storage in charging stations, which, due to increasing charging powers, are more prone to produce large peaks during fast charging processes, which will impact the grid and can lead to demand charges [20], [21].

Finally, a larger EV adoption with high-performance batteries may likely turn EVs into an important distributed energy resource; hence, it could alleviate the problems arising in the transition toward a power-electronics-dominated grid. The storage capacity of the transportation sector can be used by system operators to help efficiently balance grid-level supply and demand, and provide ancillary services (reactive power compensation, harmonics compensation, general power-quality improvement, voltage support, frequency regulation, virtual inertia, and grid formation), besides other economic benefits for both users and operators [20], [22]. Sections V and VI will discuss those aspects in more detail.

III. POWER ELECTRONICS FOR EV CHARGING

The rapid advancement of power electronics has laid the foundation for the development of a highly versatile and diverse EV charging infrastructure. Power electronic systems used in EV charging face a range of simultaneous requirements, such as charging a vehicle's battery in a safe manner, adhering to grid harmonic standards, efficiency, compactness, and reliability. Moreover, the technological improvements in terms of modularity, packaging, and thermal management have enabled several charging options for the constantly improving battery packs (cost reduction and enhanced performance), supporting the acceleration of charging and facilitating the migration to cleaner transportation [23], [24].

The power electronics structure of a typical EV supply equipment (EVSE) is implemented as a two-stage system, as displayed in Fig. 3: a rectifier stage with power-factor correction (PFC) connected to ac mains, which can vary from single phase to three phases depending on the powers involved, followed by a dc–dc stage that performs the battery voltage and current regulation. The high common-mode (CM) impedance of a galvanic isolation stage is beneficial in ensuring that the leakage current requirements imposed by standards (IEC 61851-23, JEVS G105-1993, SAE J1772, and UL 2231) are adhered to. In this sense, the interaction with a galvanically isolated EVSE does not alter the vehicle battery protection scheme; hence, the battery remains protected as designed [25].



(a)

(b)

Fig. 3. ***General structure of an EV battery charger. Galvanic isolation can be either at (a) LF or (b) HF where applicable. Although less frequent, some approaches feature both isolations in order to enable simultaneous charging and other features.***

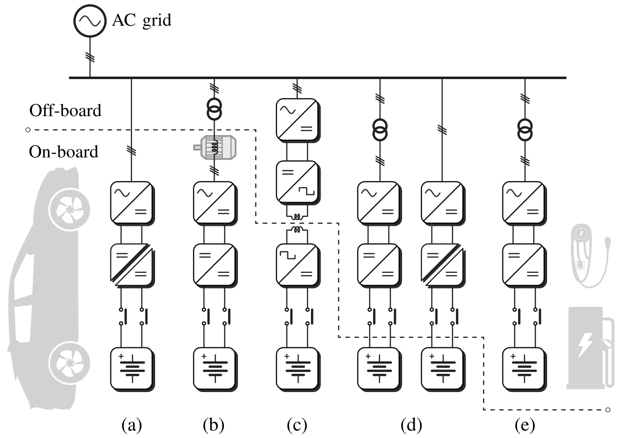


Fig. 4. ***Power electronics topologies for EV charging. (a) On-board dedicated charger. (b) On-board integrated charger. (c) Wireless or inductive charging. (d) Off-board dc charging. (e) Battery swapping or replacement.***

As required, this isolation can be deployed at line frequency (LF) at the ac input of the charger, as represented in Fig. 3(a), or at a higher frequency inside the dc–dc stage, as shown in Fig. 3(b), depending on the cost/volume and power losses tradeoff imposed by their nature [26], [27], [28]. Currently, isolation is almost exclusively of inductive nature although concepts for capacitive isolation exist [29], [30], [31].

The most dominant EV charging approaches are presented in Fig. 4. The main charging mechanism is overnight charging using the dedicated on-board charger (OBC), which is typically developed by or specifically for the vehicle manufacturer. Thus, it can be deeply embedded into the vehicle's architecture and access internal information of the vehicle, which manufacturers would not disclose to third-party charging stations. As it can be seen in Fig. 4(a), all power electronics are located on-board and rely on suitable domestic outlets in order to enable charging powers in the range from 1 to 22 kW from either single- or three-phase supplies. Fig. 4(b) presents an integrated OBC as an alternative that exploits the presence of the drive unit (inverter and machine in some cases), which is idle during charging. This is a cost-effective implementation for increasing the charging powers of on-board charging since inverters are typically rated in the range of 30–200 kW, hence being competitive with high-power OBCs and even off-board solutions [24]. Another widely studied concept is inductive or wireless charging, as presented in Fig. 4(c). As widely known, wireless charging performs the energy transfer through magnetic coupling between an off-board high-frequency (HF) inverter and an on-board HF rectifier. By featuring a contactless power transfer, wireless chargers are in principle safer with respect to potential electric shock risks compared to plugged ones, besides allowing dynamic charging, i.e., while driving. However, this technology still needs further improvements in terms of charging power and efficiency to compete with well-established alternatives [32], [33], [34], [35].

Furthermore, off-board dc charging concepts displayed in Fig. 4(d) have emerged as potential options for drivers to charge their vehicles, either enabling workplace charging or fast charging stations [23]. Since most of the power conversion takes place outside the vehicle, limitations of size, volume, and weight are less stringent, while interoperability and standardization have turned it into the second most common way of recharging EVs [36]. Finally, replaceable or swappable batteries as a faster and electrically less stressful alternative to fast charging [see Fig. 4(e)] have been suggested and demonstrated [37]. Swappable batteries do not need much power electronics but a sophisticated mechanical concept as the battery frame is often an inherent part of a car's crash structure. Accordingly, rapid replacement requires a reliable and fully automated replacement system. In this case, all the power conversion occurs outside the vehicle. Considering their relevance in the industry and the maturity of the technology, this work will focus on cases (a) and (d), specifically on the enabling role of power electronics.

Regardless of the nature of the EVSE, the charging process involves two different systems—a vehicle and the grid—interacting closely. Hence, several protection measures are needed to ensure a safe process, some of which also help with the maintenance and monitoring of the installations. The insulated high-voltage system within the vehicle is equivalent to a mobile unearthed (IT) system according to DIN VDE 0100-100 or IEC 60364-1, while ac chargers are typically earthed systems with separated conductors for the neutral and protective earth (PE) (TN-S). DC chargers are commonly also IT systems. Before the actual charging process can begin, the vehicle and isolated chargers should be free of isolation faults to mitigate any risks for users. Accordingly, isolation monitoring is crucial before and during charging. For dc charging, isolation monitoring devices (IMDs) are typically present in both the EVSE and EV. According to IEC 61851-23, the charger normally detects the isolation levels before closing its contactors.

The expected measured isolation resistance between the dc poles and PE should be above 500 Ω/V; otherwise, the system triggers an alarm or simply blocks any further charging. On the EV side, the vehicle first checks its own isolation and various brand-specific additional conditions before it closes its charging contactors to allow charging. Once the charging process is acknowledged, the on-board IMD typically goes into a passive mode to prevent undesired interruptions while handing over the isolation monitoring responsibility to the charging station's protection management.

During charging, the vehicle chassis is connected to the ground through the charging cable to protect the operator against electric shock in the case of any insulation breakdown, ground fault currents, loose cables, or similar failures. In such cases, the faulty contact is expected to touch the grounded chassis first. In most countries, ground refers to PE (in rare cases to neutral) depending on the domestic electric system. Connectors are ideally designed in a way that PE would connect first, before the other pins, during plugging in and detach last when disconnecting. On the other hand, protective control signals, e.g., control pilot (CP) and proximity pilot (PP) for CCS, connect last and disconnect first as they can initiate energizing the cable upon proper handshake with the car (CP) and proper connection of the plug (PP).

A. Dedicated On-Board AC Chargers

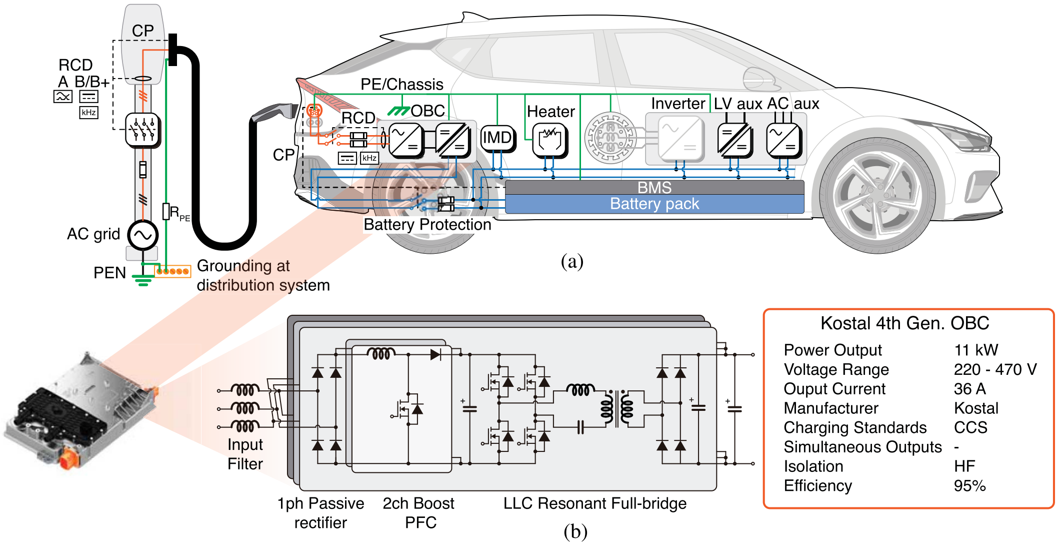
Considering the typical driving cycle of modern passenger or light-duty vehicles (LDVs), the main mechanism to replenish the EV battery remains to be their dedicated OBC. Studies show that 72.5% of the energy destined to charge LDV batteries comes from home charging, while the second preferred option is fast charging at 11.9% [36]. Vehicle manufacturers have tight control over the OBC and its development. Thus, OBCs communicate on the internal buses, receive and deliver more information than third-party off-board chargers as mentioned above, and are typically deeper integrated into the safety and battery monitoring programs. As such, they can typically decode rather detailed status information from the BMS and may use other vehicle resources; in return, they usually have to participate in internal connector monitoring, self-diagnosis, reporting, and power management, subject themselves to the vehicle's interlock loop(s), and offer interfaces to run third-party software modules, e.g., based on the automotive open system architecture (AUTOSAR) or in the future maybe the GENIVI development platform and automotive Linux. OBCs typically access high-voltage buses without dedicated contactors and communication buses, where erratic behavior could halt the car. In such situations, the rest of the car is not necessarily able to fully disconnect and isolate the OBC as it could with an off-board charger. Accordingly, OBCs typically need to closely follow the vehicle's specifications and subject to its internal monitoring in the eyes of vehicle manufacturers.

Thereby, OBCs must be designed to connect seamlessly to domestic outlets worldwide and operate with minimal additional hardware. In fact, from a designer's point of view, this universality represents a major challenge given the range of ac voltage magnitudes, frequencies, and supply quality in different regions [6]. As stated earlier, the average mileage capacity of batteries keeps growing, as seen in Fig. 1, which has translated into an ever-increasing power rating for these mobile power conditioning and conversion units, currently establishing 22 kW for three-phase high-power OBCs (3-ph 400-V ac and 32 A) [24]. The main drivers for further OBC development are related to their dependency on available outlets. It is very unlikely that OBCs will soon exceed these limits since this will require major modifications in conventional outlets, which may work against the universality of OBC designs. Also, since OBCs are a fixed part of the EV architecture, which, in turn, is highly package-sensitive and crowded with components, stringent limitations in terms of size and weight drive their design toward maximizing the power delivered to the battery.

In this sense, the latest developments in wide bandgap devices have directly translated to more compact high-performance OBCs, allowing unprecedented power densities. The higher switching speeds of silicon–carbide (SiC) and gallium–nitride (GaN) devices can downsize filter components due to the reduced voltage and current ripple and magnetics, such as transformers due to the larger flux change [38]. Despite higher costs, the reduced footprint and lighter weight of GaN solutions are attracting the attention of suppliers and OEMs. Currently, GaN transistors have been widely adopted in power-density-optimized converters and have the potential to dominate upcoming power electronics on-board applications for EVs and more-electric aircraft (MEA) [39], given their unmatched efficiency and power-density../figures at the system level. However, the appearance of unexpected performance defects, such as dynamic on resistance ($R_{\mathrm{ds_{on}}}$) and C_{oss} losses [40], [41], [42], [43], [44], has slowed their adoption. Moreover, their overloading capability is lower than silicon counterparts, and their reliability has not yet been established, mainly because they have not been a mature technology long enough. Hence, for automotive applications, GaN still needs more time to be able to compete with the reliability of current silicon switches and is still not widely used in OBCs. SiC, on the other hand, has already achieved the first step for OBCs and also charging stations. SiC field-effect transistors clearly outcompete silicon insulated-gate bipolar transistors (IGBTs) as they do not demonstrate large tail currents associated with the charge stored in a p-n junction and, therefore, allow lower switching losses. In contrast to super-junction silicon field-effect transistors, the shorter drift zones for the same reverse voltage capability and lower doping levels avoid critical levels of reverse recovery; furthermore, SiC can block high voltages on the battery side for 800-V architectures, e.g., for bidirectional units or synchronous rectifiers, without the need for series connection and reverse-current balancing as for super-junction transistors [45], [46], [47].

At present, most commercially available OBCs employ two cascaded power conversion stages. First, a grid-tied PFC converter sinks high-quality ac currents and stabilizes an intermediate dc voltage, which, in turn, feeds a galvanically isolated dc–dc stage that generates the battery currents and voltages in strict accordance with the requirements from the BMS.

In order to ensure the electrical safety of the charging process, this family of chargers is obliged to interrupt any fault current within a specified time window, for any of the current components that the charger is responsible for. This means that each charging port must include residual current devices (RCDs) in accordance to the IEC 61851



Kostal 4th Gen. OBC	
Power Output	11 kW
Voltage Range	220 - 470 V
Ouput Current	36 A
Manufacturer	Kostal
Charging Standards	CCS
Simultaneous Outputs	-
Isolation	HF
Efficiency	95%

Fig. 5. *On-board ac charger. (a) Typical configuration. (b) Industrial example Kostal fourth-generation 11-kW OBC. The OBC connects to a three-phase supply; hence, it features three rails using the PEBB shown in detail.*

standard, which is accessible by the BMS through the CP conductor to prevent abnormal charging processes. The relevant frequencies involved during charging require that RCDs of types A and B/B+ are included in the ac-EVSE, as displayed in Fig. 5(a).

In efforts for further reductions in terms of size and weight, active power decoupling techniques have been applied to single-phase OBCs [48]. This approach reduces the size of the intermediate dc-link capacitor by diverting the second-harmonic power fluctuation inherent in single-phase systems to a smaller auxiliary energy storage component. Another approach to reduce the volume of installed components on an EV is to integrate the LV auxiliary dc–dc converter [see Fig. 5(a)] into the OBC.

B. Off-Board DC Chargers

Off-board dc chargers fundamentally differ from ac charging solutions as the vehicle exposes its battery to the outside, and most of the power conversion takes place externally (see Fig. 6). This shift of the conversion and control burden, in turn, enables larger charging powers without the need to transport massive electronics on-board. Fig. 6 presents the typical configurations for off-board dc EVSE. Currently, dc chargers feature ratings in the range from 20 up to 350 kW for mid-sized EVs (for heavy-duty vehicles (HDVs), this can reach 600 kW and is projected to grow to 4.5 MW [16]), making them more suitable for public or fleet charging than domestic use. Regardless of the maximum power of these chargers, the EV ultimately sets the actual charging power by commanding exact current and voltage levels. The vehicle typically monitors those values and terminates charging upon violation.

Most vehicle manufacturers have limited control over the design and construction of the off-board chargers with which the vehicle may be confronted. Thus, beyond the relevant standards, charging stations and any kind of off-board chargers are unknown black boxes for the vehicle. However, only the vehicle knows the specifications, limits, current condition, and health-enhancing protocols of its battery. Hence, for safety and appropriate battery treatment, the car commands the charger via references set by its BMS, treating it like a controllable high-voltage high-current supply, and checks what the charger does with its own sensors. The vehicle's charging contactors, which are designed to interrupt current values several times larger than the charging current, are a car's fall-back solution. To allow an EV to command a charger, dc EVSE offers at least one of a number of well-standardized communication protocols. The communication interface, furthermore, establishes a combined safety system to protect users and the equipment, e.g., against electric shock or damage.

Similar to ac options, dc charging requires powering some of the auxiliary loads in the vehicle. In modern vehicles, the average load of only the 12-V auxiliaries can exceed 1 kW, with peaks of several kilowatts, if no power-saving measures are taken. Moreover, the cooling/thermal management system often also claims several kilowatts and should be turned off when it is not needed, e.g., to keep the battery cool during higher power charging. This system may include the refrigerating compressor of the low-temperature chiller and passenger air conditioning. Note that, with the increasing charging power, cooling/heating during and even before charging becomes mandatory to limit battery overheating and aging. In today's vehicles, the thermal management system can reach powers beyond 5 kW, and projections imply that, in order to effectively enable rates above 350 kW, they may have to be expanded substantially to make high-power charging viable [11]. Please note that this addi-

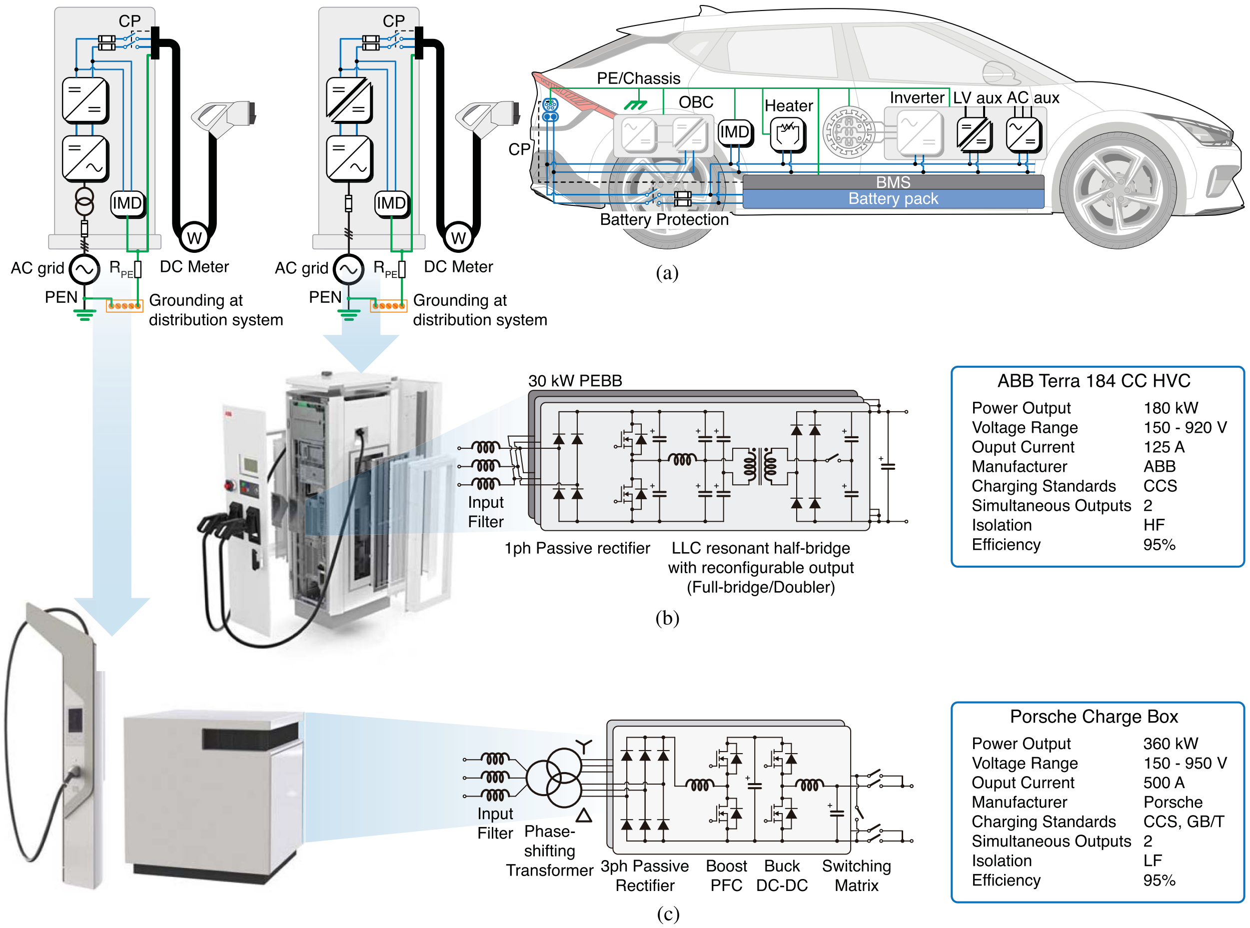


ABB Terra 184 CC HVC	
Power Output	180 kW
Voltage Range	150 - 920 V
Ouput Current	125 A
Manufacturer	ABB
Charging Standards	CCS
Simultaneous Outputs	2
Isolation	HF
Efficiency	95%

Porsche Charge Box	
Power Output	360 kW
Voltage Range	150 - 950 V
Ouput Current	500 A
Manufacturer	Porsche
Charging Standards	CCS, GB/T
Simultaneous Outputs	2
Isolation	LF
Efficiency	95%

Fig. 6. *Off-board dc chargers. (a) Typical configurations with isolation at HF and LF. (b) Industrial example of HF isolated: ABB Terra 184 HVC. (c) Industrial example of LF isolated: one variant of Porsche Charge Box.*

tional power consumption easily exceeds the ratings of an OBC and, hence, has to be branched off from the charging power.

As an attempt to accommodate the ever-increasing charging powers and feed the full spectrum of dc chargers, several manufacturers have adopted modular designs, employing so-called power electronic building blocks (PEBBs), which can be found in different packages depending on the case, typically in the range from 10 to 75 kW [49], [50]. The wide and assorted range of battery voltages and charging profiles among different models turns a single converter solution fitting all existing and upcoming EV models, simultaneously exceling in cost-effectiveness, power conversion efficiency, and reliability into an impossible proposition. Instead, modular designs enable superior performance at different load conditions, future-proof designs by facilitating power/current expansion, and benefits from economy-of-scale effects. Finally, the inherent reconfiguration feature permits better utilization of the installed power capacity, hence enabling several charging spots, and, more importantly, paves the way for charging heavy-duty EVs, such as buses and freight transportation trucks, as it will be discussed further.

As displayed in Fig. 7, the charging ports are fed through different configurations, depending on several aspects that are highly case-dependent (location and manufacturer, to name a few). The figure visualizes that such charging stations often interface with the medium-voltage (MV) grid through a dedicated connection. A local substation enables an LV ac grid, typically in the 208–480 V (<1000 V as defined in DIN EN 50110-1:2014, DIN EN 50110-2:2011, and corresponding automotive standards, e.g., LV 216-1, LV 216-2, and SAE J1654) range, for the connection of the front-end power converters. However, with appropriate transformers, the manufacturer can, for instance, use the same harmonized voltage (though potentially different frequency) in its installations worldwide to use the same electronics and only site-specific transformers, establishing a local protected grid according to the manufacturer's or operator's specification [51]. This represents another difference with ac charging as the dedicated LV grid enabled by the on-site substation offers flexibility as, technically, it represents a load to the MV system, which does not need to follow the same guidelines and requirements as the conventional LV distribution grid as long as the MV codes are met.

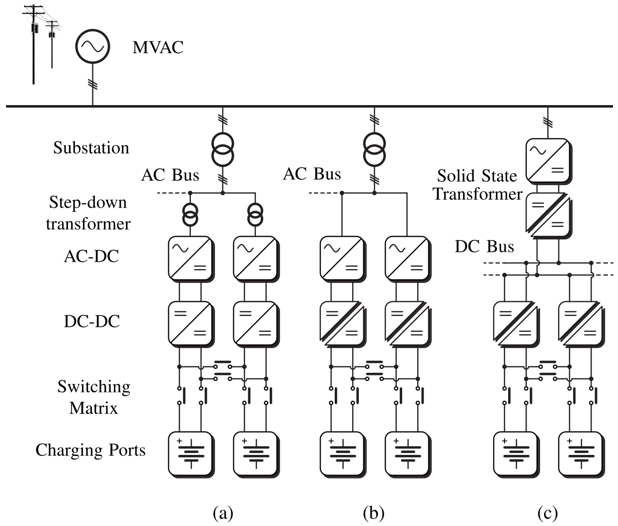


Fig. 7. ***Typical configurations for off-board dc charging stations. (a) Fast charging station with LF isolation and ac bus. (b) Fast charging station with HF isolation and ac bus. (c) SST-enabled fast charging station with dc bus. Please note that all of the above configurations can also include on-site generation or ESSs at different levels and may suit further expansion to MCSs.***

As mentioned earlier, each charging port is typically isolated from the grid and also other charging ports to enable energy transfer. Various possibilities for such isolation can be found. For instance, the use of a grid-frequency transformer in each of the charging ports is a simple and straightforward option, as represented in Fig. 7(a) [51], [52], [53]. This alternative can be seen in ABB Terra HP 150 or Porsche's fast charging park. Some approaches also include a reconfiguration switching matrix after the two-stage power conversion system, which can allocate more power to a single charging unit, or separate them completely in order to permit the simultaneous charging of multiple EVs (as recommended in IEC 61851-23). Alternatively, the transformer can be shifted toward higher frequencies, by means of isolated dc–dc stages, as the case in Fig. 7(b) and adopted by Enercon, Tesla's Supercharger, or the newer ABB Terra 360 [54], [55], [56]. Currently, these three-phase ac-bus-based charging stations prevail as the main solutions, benefiting from mature ac protection and metering technologies [57].

A different approach avoids the ac substation with a conventional transformer altogether and integrates the charger directly into the MV level. A solid-state transformer (SST), as illustrated in 7(c), which splits the voltage into smaller portions and isolates the voltage on a higher frequency, appears as an attractive solution [58]. SSTs concentrate the rectification, voltage step-down, and isolation functions in a single stage, leading to substantial benefits in terms of energy conversion efficiency, installation costs, and size: some reports reach a 65% reduction in footprint and 3% improvements in terms of energy efficiency [59], while others demonstrate a 40% reduction in the installation costs for a 50-kW charger [25].

As an additional benefit, modular SSTs are particularly scalable in contrast to conventional, passive transformers. The voltage and power ratings can be adjusted by simply adding more submodules. This aligns squarely with the ever-growing battery capacity and the efforts being made toward increasing the power being delivered to them in order to cut the charging times, especially with a focus on the deployment of heavy-duty freight transportation EVs.

Most interestingly, the latter concepts allow a common inverter/rectifier stage that establishes a shared dc bus to distribute the power to the individual charging poles [60], [61], [62]. Such a local dc system or grid could even ease costs for users (service) and charging operators (installation and ownership), besides reducing the footprint of equipment, by shifting this rectifier stage upstream to the utility-owned infrastructure. This concept is sometimes referred to as dc as a service (DCaaS) [63], which is also beneficial for installing storage stages or local generation based on RES, given that they are better suited for dc systems [64].

C. DC Chargers for Medium- and Heavy-Duty EVs

Larger EVs, such as buses, trucks, and freight transportation, are typically referred to as a medium-duty vehicle (MDV) and an HDV vehicle. Their heavier usage, larger size, and load capability demand more energy from the grid and battery. This leads to larger battery capacities capable of higher charging rates and, in order to keep the charging times reasonable, larger power from EVSE as well [63]. Moreover, efforts have already begun by standardization organizations to enable megawatt charging systems (MCSs) [16], [65], [66], [67], projecting a theoretical charger able to deliver up to 4.5-MW cost-effectively and conveniently, enabling drivers to charge under 30 min at a reasonable cost. This represents an increase in the maximum power by a factor of 12.5 compared to state-of-the-art-charging stations for LDVs, which recently reached 360 kW [56]. This increase will push state-of-the-art connectors and inlets to their theoretical limits (electrically, mechanically, and thermally) in order to provide up to 3 kA at 1.5 kV [16]. Thereby, newer cables, connectors, and inlets are being developed and tested in order to accommodate this new breed of chargers [63]. This also affects the battery thermal management system, increasing their power ratings up to 25 kW [11].

Heavy-duty EVs are not simply larger EVs, as their design, lifespan, usage, and charging regimes are completely different. A passenger EV is typically designed to last 100 000–200 000 km, 8000 h of driving, and 10 000–15 000 h of charging, considering a lifespan of 15 years for premium EVs [68]. Trucks, on the other hand, are expected to last 20–30 years, covering 1,000,000–3,000,000 km, which easily surpasses the lifespan of electronics components, hence requiring a

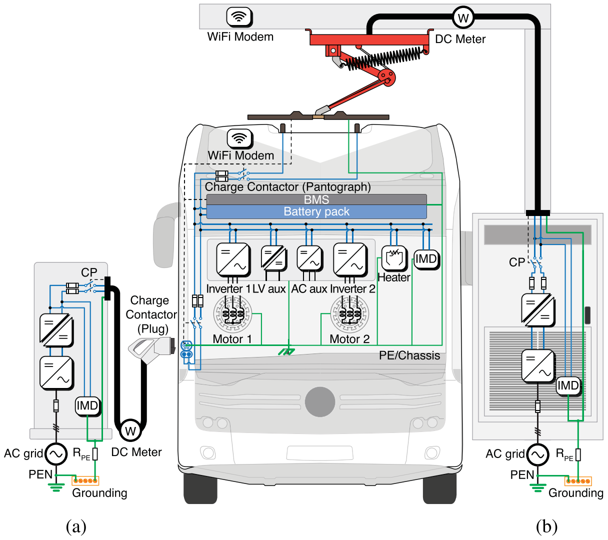


Fig. 8. *Typical configurations of heavy-duty EV chargers. (a) Depot/overnight charging. (b) Opportunity charging.*

replacement through the lifetime if current designs are employed [68]. These differences will also be translated to charging; hence, the design approach for HDV chargers will further show differences in terms of deployment, rate of usage, requirements, and grid connection conditions. Also, larger battery capacities along with shorter charging windows make the use of low-power OBCs impractical. As a result, HDVs typically lack this equipment and rely exclusively on off-board charging options, as shown in Fig. 8.

For instance, HDVs often drive along predefined routes and stops, enabling the possibility of installing chargers throughout the path. Given the short duration of stops, charging powers should be substantially larger than those used in traditional overnight charging in order to provide enough energy to continue the trip. In this sense, the decision on a charging strategy plays a central role and should be properly assessed [69].

Please note that, considering larger batteries and higher power charging intended for larger fleets, the HDV charging infrastructure represents a larger stress to the utility grid, especially in terms of power peaks. Different stakeholders have set charging powers above 1 MW in order to keep reasonable charging times [70]. For these reasons, such charging stations most likely include on-site energy storage elements and generation, as displayed in Fig. 9, in order to shave the peaks in the power demanded from the grid and also perform energy arbitrage, besides other ancillary services [71], [72]. Decreasing battery prices, as illustrated in Fig. 1, eventually will make the installation of local ESSs profitable for both grid-integrated charging stations and those based on dedicated energy storage and generation capability [63].

In terms of power electronics, the case for HDVs is similar to other scenarios; a one-fits-all solution does not exist. Moreover, these fleets operate in different cities, leading to diversity in terms of demand, structural conditions, or even financial capabilities [73]. Considering this, two charging pathways have shown superior performance while serving different needs and are depicted in Fig. 8: depot charging and opportunity charging. The former allocates charging stations at the bus operator/fleet logistic depots and uses similar configurations to previously discussed charging options, as seen in Fig. 8(a), with powers from 80 to 150 kW per slot [73], besides requiring buses with larger batteries and lower C-rates, since their routes should be completed before the possibility of recharging (charging once or twice a day depending on the case). The latter option, as presented in Fig. 8(b), distributes charging ports throughout the routes or charging corridors and, with the use of automated charging devices (ACDs) or pantographs, quickly recharges the smaller capacity but higher C-rate batteries (several times throughout the day). Typically, opportunity chargers feature powers from 150 to 600 kW for buses, with aims of expansion above the MW level for freight trucks [70]. This option also requires a charger on the depot with lower power in order to perform power balance and preconditioning for the batteries.

Communicationwise, almost all the aforementioned charging methods establish the communication link once the EV is connected to the EVSE. The exception to this rule is ACD charging since, before deploying the pantograph for connection, the system must confirm that the charging is allowed. Accordingly, the communication must begin before the EV–EVSE connection is made. With this purpose, both EV and EVSE include a wireless communication device or Wi-Fi modem, as shown in Fig. 8(b), as recommended in various standards (OPPCharge and SAE J3105) in accordance with IEC 61851-23.

IV. CONTROL AND OPERATIONAL ASPECTS OF CHARGERS

Power electronics are a vital part of modern EV chargers. However, in addition to the hardware, control is essential to ensure that the requirements of both the grid and the battery sides are met. Various control schemes have been proposed and exist in commercially available charging stations. This section will cover some of the most established and widespread control schemes, and the main considerations for an effective and safe EVSE grid deployment.

As previously described, with very few exceptions, all the charging processes require converting ac power from the utility grid into dc to recharge the battery. From a hardware point of view, this conversion is typically solved by adopting the aforementioned two-stage structure in Fig. 3. A first power electronic converter generates an intermediate dc voltage through rectification and serves as the grid interface, while the second one performs a dc power conversion in order to follow the EV specifications. This implies that the power conversion stages involved must simultaneously meet all the requirements imposed by the BMS in terms of current and voltage provided,

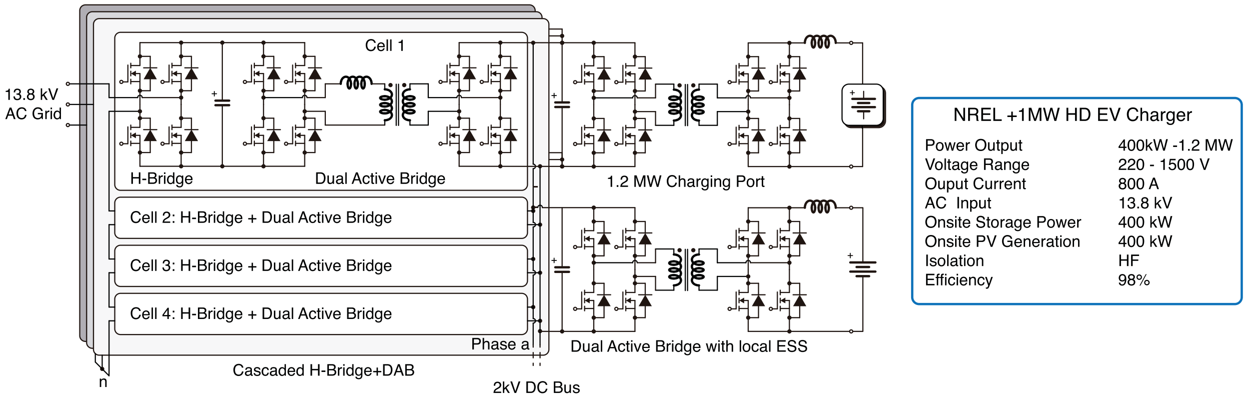


Fig. 9. *Circuitry of an SST-based megawatt charging station with local storage and PV generation [70]. The MV grid interface is a nine-level cascaded H-bridge (CHB) SST using dual active bridge (DAB) PEBBs to enable a local 2-kV dc bus.*

maximum allowable ripples, and harmonic output content, besides precharging its output to match the current battery voltage and ramping the controlled quantities adequately. In addition, the power supplied at the ac point of common coupling must follow grid codes, as well as safety and distribution system operator (DSO) requirements in terms of power factor, distortion factor, ground-fault currents, and available power, to name a few. These impose several challenges to the control system, leading to two dominating alternatives that have proven to be effective [49].

The first approach decouples the operation of the ac–dc stage from the dc–dc by using the ac–dc stage to regulate a fixed and relatively stable dc voltage. This dc voltage, in turn, serves as the required input for the battery-side stage with closed-loop current and voltage control. The grid-side converter has to actively regulate a predetermined or adaptively adjusted dc voltage as agreed upon with the subsequent stage and shape high-quality sinusoidal grid currents with minimal harmonic content. At present, from a system perspective, almost all grid interfaces of chargers are grid-following. They expect a stiff grid voltage with certain amplitude and frequency, and extract or inject current relative to that [74], [75], [76], [77]. Grid-forming alternatives, which may be needed in the future, are described in Section VI-F. Grid-following interfaces are most typically set up with a cascaded control design and in rarer cases as state-space control (see Fig. 10). The grid currents will be used as auxiliary quantities in order to improve the dynamics of the main variable to be regulated. This leads to the implementation of different types of cascade control architectures [78], where the grid currents are regulated in the inner loop, while the external loop is typically for dc voltage or power regulation.

The grid interface can use vector control for all phases combined or three separate controllers, one per phase. Whereas the individual single-phase controllers more or less intrinsically solve the inherent problems of unbalanced grids (i.e., when the phase voltages do not have the same voltage amplitude), vector-based control needs extra measures to deal with such situations without massive reactive or circulating currents [79].

If the grid input is formed by a rectifier with a PFC boost stage, the behavior of boost converters has to be considered. Various solutions exist, and turn-key-ready integrated circuits for the control of this stage are available from various chip design houses.

Although several options can be found in the literature, along with the use of coordinate transformations (either stationary or synchronous), each current component is tightly regulated to follow the commands of the outer loop. For individual control of each phase with ac values, each component is regulated to sinusoids of fixed frequency (50 or 60 Hz, depending on the location) through proportional–resonant (PR) and other second-order controllers. Alternatively, if the alternating frequency component is eliminated through coordinate transformation to generate a synchronous reference frame (Park's transform), the constant values of d and q (or amplitude

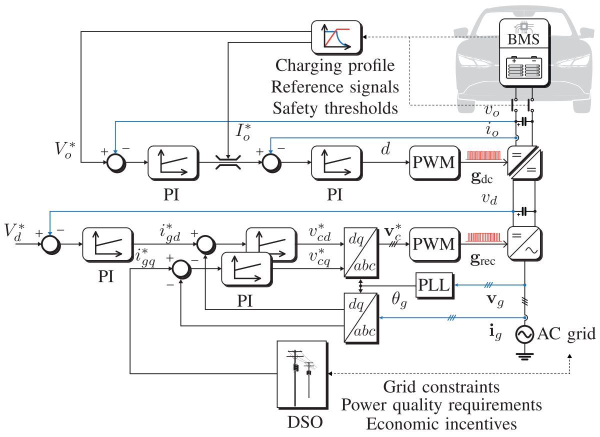


Fig. 10. *Conventional EVSE control scheme with fixed dc link and decoupled power conversion stages using a synchronous reference frame (d–q) transformation implementation.*

and phase) allow the use of proportional–integral (PI) regulators with zero tracking error in steady state. This reference frame allows simple control of the active and reactive power of each phase. Typically, the outer loop generates the reference for active power (d component), while the reactive power can be set arbitrarily through the selection of the quadrature current i_{gq}, following DSO or local operator requirements. Before or in the modulator, the variables are transformed back to the three-phase alternating abc frame to generate the necessary gating pulses for the grid interface (see Fig. 10). Also, if vector-based modulations are employed, e.g., these signals are transformed back to $\alpha-\beta$ stationary frame to generate the dwell times [61].

Regardless of the transformation employed, the charger typically needs to detect the frequency and phase of the grid voltage to inject or extract currents in phase with the grid, given that the majority of the chargers operate as grid-synchronized or grid-following systems. Independent of the shared three-phase or separated single-phase control, any detection of the grid frequency and phase can either be individually per phase or for all phases at once in a vectorized fashion. The vectorized three-phase synchronization allows an easier and more robust grid-frequency detection, e.g., through a single phase-locked loop (PLL), whereas single-phase PLLs or second-order integrators have to generate their orthogonal component. Finally, the outer loop is regulated to meet a certain fixed dc voltage, for instance, that will permit the proper regulation of input currents, given that ac–dc converters have limits for proper operation depending on their type [80], [81].

The dc–dc stage often contains two parts, an isolating resonant converter, e.g., an LLC, and a buck stage with one or several interleaved stages. In that configuration, the LLC is operated without much control but at its fixed resonance frequency with a fixed duty cycle for simplicity so that the output voltage of the LLC indeed just mirrors its input voltage with all its ripple and imperfections. The buck stage is responsible for all control and further has the benefit of low output ripple for the vehicle battery for low aging and compliance with the ripple limits of typical standards, such as IEC 61851-23. Single-stage dc–dc converters that isolate and control the output voltage and current are also possible but do not differ with respect to control. The widely same controller can be used for such a single-stage design or a buck stage after a fixed open-loop isolation stage. The relatively constant intermediate dc voltage gives the dc–dc stage enough freedom to follow the commands of the BMS and also allows its control to be largely decoupled from that of the grid interface, which can even run on different integrated circuits with often not more than a feed-forward signal from the dc-link voltage. As outlined in Fig. 10, the dc–dc converter control typically also involves a cascaded control loop, but, in this case, the inner loop regulates the current fed to the battery through the charging connector, while the outer loop regulates the output voltage. The current set point is provided as an upper limit, which saturates the output of the outer loop voltage controller, if this value is exceeded. The vehicle sends voltage and current requests on a regular basis, often several updates per second.

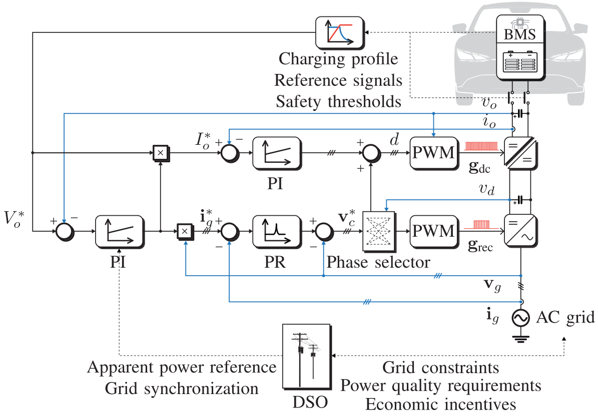


Fig. 11. ***Synergetic EVSE control scheme with adaptive dc link and coupled power conversion stages.***

The EV BMS commonly estimates battery SoC using Coulomb counting or model-based estimation methods [82], [83], [84], [85]. In addition, the BMS generates the battery voltage and current references shown in Fig. 10 used by the inner control loop governing the dc–dc converter. The communication method used to transfer these values to the charger dc–dc converter depends on whether the charger is off-board or on-board. OBCs coexist with the BMS on an EV's internal CAN bus and, thus, receive the voltage and current level requests through this interface. For off-board chargers, the means of communicating these levels from the BMS to the charger depends on the standard to which it adheres. For example, power line communication is used by the CCS standard, whereas a dedicated CAN line between charger and vehicle is used by CHAdeMO and GBT.

On the other hand, the controllers of both the grid and the vehicle stages can be tightly coupled. This means that the operation of the ac–dc stage aims to generate a variable dc voltage in order to accommodate the optimal operation point of the dc–dc stage (typically efficiency for resonant converters). An example of such approach is displayed in Fig. 11 [86], [87], [88], [89], [90]. In contrast to the previous case, the main voltage loop is now an output quantity (it can be voltage or current depending on the case), which will indirectly set the required grid current amplitudes, through the generation of a dc power reference. This loop is followed by an inner grid current control loop, which also can be implemented in different reference frames (three-phase, stationary, or synchronous) with no additional efforts relative to the decoupled architecture, given that, regardless of the implementation, the grid interaction implies a synchronization mechanism.

In a looser coupling, the two stages only exchange set points for the dc-link voltage in a slow manner. The dc–dc controller or a higher level control might send a request to adjust the dc-link voltage based on the vehicle voltage, e.g., to improve efficiency or the vehicle-side current ripple.

Please note that, as discussed earlier, virtually, every ac-coupled charging station operates its front-end converters under the grid-following mode, as displayed in Figs. 10 and 11, and, thus, cannot function without an externally regulated voltage [74], [75], [76]. Several studies have concluded that including a virtual synchronous generator control layer can be used toward grid support [91], [92], [93]. Based on this established control, Sections V and VI will discuss the issues of such control on the grid in light of the rapid spread of chargers and alternatives that can ease the stress on the grid or even actively support it.

V. IMPACT OF CHARGING ON THE GRID

A. Scale of the Issue and Potential

Transportation is one of the main energy consumers worldwide, as, during 2021, roughly one-third of the energy available was destined for this sector [12], [94]. Moreover, ground vehicles alone (with the exception of trains) concentrate 80% of this share. This means that 25% of the total energy usage eventually will be translated to electric demand, assuming that only BEVs are employed, giving a clear idea of the impact of transportation electrification and how it could affect the grid if not taken into consideration. Currently, the total energy usage of electrified transportation is just 1.1% [94]; hence, their influence up to date has at most only emerged locally.

However, a larger share of EVs in the system will necessitate a substantial growth of the charging infrastructure [95]. For instance, under a sustainable development scenario, as defined in [2], the projected power of publicly available fast chargers will reach 400 GW of installed capacity, and it will demand almost 100 TWh by 2030. This, in turn, further increases the presence of power electronics in the grid, leading to a sharp reduction in system inertia. Thereby, the grid deployment of charging infrastructure should follow a strategic path.

For instance, CharIN is promoting a categorization of the level of EVSE–grid interactions shown in Fig. 12, starting from simple grid connection for unidirectional charging up to aggregated bidirectional chargers that enable a large share of mobile storage, turning EV fleets into flexible and cost-effective grid assets [20]. The role of the DSOs in these charging categories will be increasing along with the deeper penetration and increasing sophistication of charging systems, especially for the bidirectional case, which currently requires further standardization and technical specification to effectively deploy the widespread usage of EVs for grid support [20].

The integration of large-scale vehicle charging entails considerable stability challenges for the electrical grid [5], [97]. It does not only influence the energy demand but also involves poorly predictable dynamic behavior, given their constant power control [98], [99]. This has promoted the development of more rigorous standards to harmonize the interconnection of chargers with the utility grid. Sections V-B and V-C discuss the different challenges, emphasizing how charging infrastructure can either cause static and dynamic problems, or become a stabilizing grid asset.

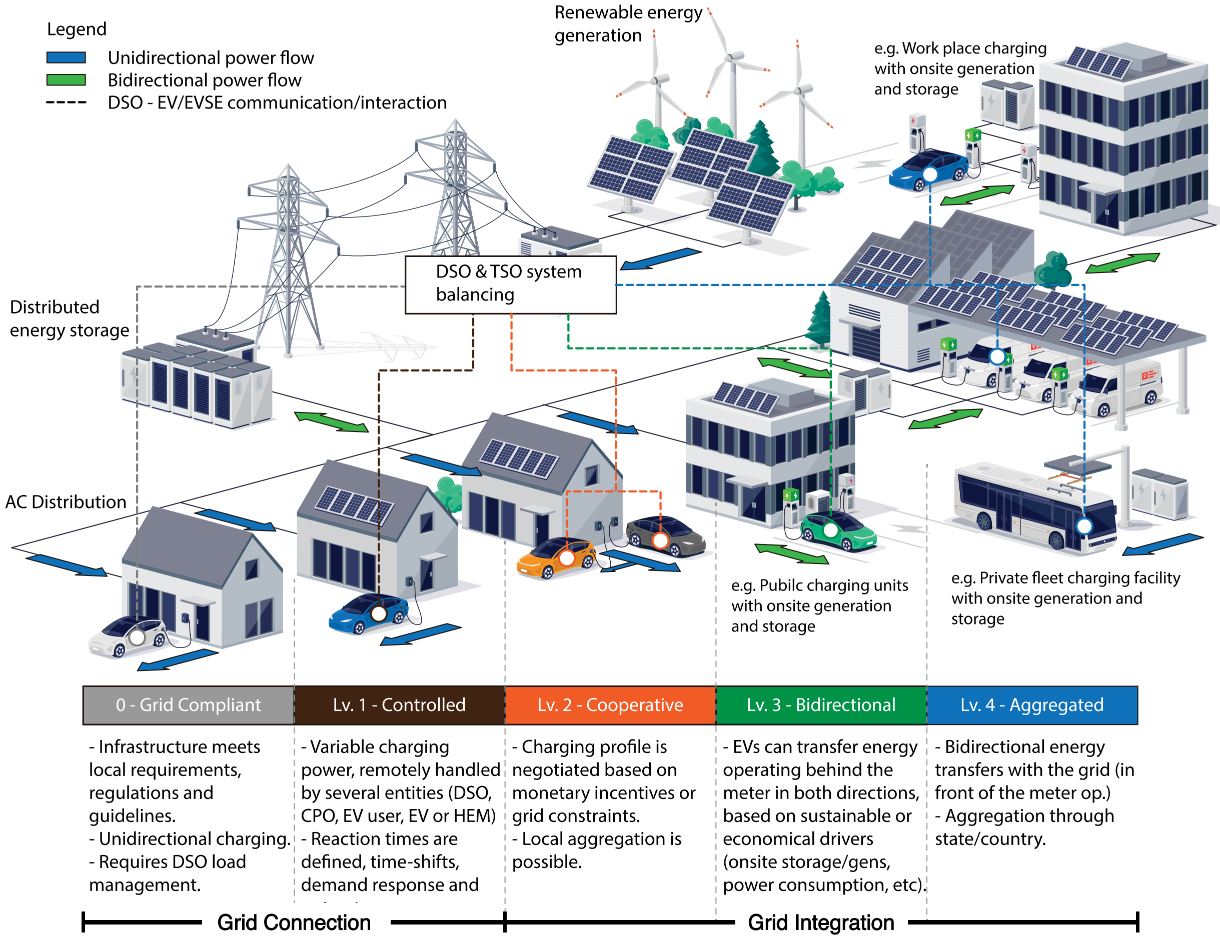
B. Power and Power Dynamics

With current technology, charging infrastructure risks turning into a major stressor for the electricity grid [100]. Chargers not only have higher cumulative power levels than any single conventional load type in the grid but also interface to the grid exclusively through power electronics with rapidly responding control, without any conventional mechanical inertia or delays. This rapid control causes immediate responses to changes in the grid and, compared to conventional mechanical loads, fast transients if requested by vehicles. Transition ramps and slewing are paramount but usually still faster than the grid control. These problems are not only associated with large high-power charging sites but are also expected from the higher number of lower power chargers in car parks and homes, each with, e.g., 11 or 22 kW. These levels are also above any conventional loads in homes and at most reached by stoves if all cook tops and the oven run at 100%.

In many countries, larger private photovoltaic installations can be remotely controllable for power curtailment, whenever their operation exceeds a predefined level (e.g., 25-kW peak, sometimes as low as 10-kW peak) [101], [102]. In such cases, the local grid operator at the distribution level can limit their generation levels during certain critical situations. To date, no such rules exist for chargers (see Section VI-B).

Conventional loads are only moderately correlated—with few very predictable and dynamically slow exceptions, such as relatively simultaneous cooking at a large scale on major holidays, including Thanksgiving or Christmas—smoothing rapid dynamics of individual households. Charging EVs, however, may be strongly linked with already existing rush-hour effects in traffic with a high risk of synchronicity of the individual chargers, leading to dynamics beyond the speed of primary control [103], [104].

In addition, present charger technology does not directly support the grid voltage beyond voltage-dependent reactive power injection or absorption. On the contrary, the charger as a grid-following system expects a rather clean and stable sinusoidal voltage from the grid. It requires this stable voltage to synchronize with low phase error and to sink a rather sinusoidal current to not further stress the grid. Neither do chargers support and stabilize the grid frequency nor contribute to the relationship between



0 - Grid Compliant	Lv. 1 - Controlled	Lv. 2 - Cooperative	Lv. 3 - Bidirectional	Lv. 4 - Aggregated
- Infrastructure meets local requirements, regulations and guidelines. - Unidirectional charging. - Requires DSO load management.	- Variable charging power, remotely handled by several entities (DSO, CPO, EV user, EV or HEM) - Reaction times are defined, time-shifts, demand response and	- Charging profile is negotiated based on monetary incentives or grid constraints. - Local aggregation is possible.	- EVs can transfer energy operating behind the meter in both directions, based on sustainable or economical drivers (onsite storage/gens, power consumption, etc).	- Bidirectional energy transfers with the grid (in front of the meter op.) - Aggregation through state/country.

Fig. 12. ***Various levels described by DIN/ISO 15118-20 for advanced grid integration of EVs [96].***

frequency and power balance. Instead, the frequency is only a parameter inside the synchronization filter, e.g., a PLL.

C. Weak-Grid Problems, Constant-Power Control, Grid-Filter Resonances, and Parasitic Feedback

In the scientific and popular science literature, EVs and their chargers have been proposed as solutions to weak-grid issues for more than a decade already [105], [106], [107], [108]. Surprisingly, it appears that the currently dominant technology is far from being a stabilizing agent since its actual operation loads the grid further and even drives it toward instability. Instead of supporting weak grids, circuit topologies and control of chargers in the field tend to fail and disconnect under weak-grid and other adverse conditions, where it is prone to problematic parasitic feedback and interactions with other systems at the same point of common coupling.

Weak grid conditions are often associated with low short-circuit reserve and high grid impedance [109], [110], [111]. The grid impedance can be a large resistance in the high milliohm and even ohm range, particularly in widespread LV distribution grids, but also contain considerable inductance values. Large inductances can further arise in situations that might be considered the opposite of a weak grid, e.g., when the charger is connected right at a distribution substation. In that position, the charger is confronted with the entire leakage inductance of the transformer, which can reach millihenries. The effect can be similar to a location extremely far from a substation. The grid impedance leads to voltage responses, such as dips, at the point of common coupling in response to changing load currents.

As known from other grid-tied power electronics, the grid impedance can add up with the grid-side part of the filter and particularly for higher order filters, such as CLC and LCL topologies, reducing the frequency of the first resonance [112], [113], [114]. If the first resonance reaches below the upper bandwidth limit of the grid-side controller, oscillations and loss of control are almost unavoidable without smart suppression strategies. In contrast to other systems, the power levels are larger so that the other loads at the same point of common coupling might not dampen the oscillation enough. Understandably, vehicle manufacturers have little control over the locations and grid conditions where a vehicle owner might plug in the on-board vehicle charger. The problem will be aggravated for bidirectional chargers in the future where the active front-end technically acts as a voltage source. Particularly, high-power off-board chargers might sometimes be installed right at a (potentially dedicated) MV transformer where large stray inductances have to be considered and risk unexpected resonances in combination with grid filters. Grid-impedance estimation and adaptive adjustment of the controller, particularly, the bandwidth, can be a solution [75], [115], [116].

In combination with the grid impedance, the constant-power control of most grid interfaces both with PFC or active front-end stage tends to destabilize the grid locally even more [117], [118]. If the local grid voltage at the point of common coupling drops due to instabilities or other loads, the charger's control intends to keep the power constant and increases the current with a fast response time mostly determined by the bandwidth of the controller. As the increasing current leads to an additional voltage drop along the grid impedance, the charger risks pulling the voltage down even further to provide the power demanded by subsequent states in the charger topology and, finally, the vehicle. The constant-power mode is also a direct or indirect consequence of decoupling the control of the various stages of the charger circuit (see Figs. 10 and 11 in combination with Figs. 5 and 6), which are sometimes also performed on separate microcontrollers, and the therefore necessary condition of approximately constant voltage on the dc links in between. Thus, a demand-side approach or curtailment response to dropping grid voltages and a reduction of the EV charging power can have a deeper impact on the dominant control design and require linking the control and enabling such a response with rapid dynamics within milliseconds (see Fig. 13 and Section VI). The destabilizing effect of battery-centered constant-power behavior is well known from EV chargers and can be critical when chargers reach local power dominance.

Beyond oscillations and stress of an individual charger on the grid, the grid impedance can couple several power-electronic loads or sources and let them interact [119], [120]. Power fluctuations of smaller loads or sources can be amplified by large-power chargers through their interface with the local grid voltage. If the various power-electronic loads and sources have similarly fast control dynamics, they can drive oscillations. The reason for such oscillations is parasitic feedback loops, which form between one actor (affecting its current), the common local grid voltage drop or rise across the shared grid impedance, and the voltage sensors in all other participants at the same point of common coupling. The pick-up of the feedback can be through grid-voltage sensors or through dc-link voltage sensors, from where it is fed as an additional contribution to the negative feedback of a controller. Since the latter control responds with an increase in current inflow to a falling voltage and a reduction to a rising one, it overall generates positive feedback, to which other units will respond in return, and, therefore, risks instability.

Specific weak-grid control methods can stabilize the filter–grid oscillations with state-space control in combination with models and additional sensors or reduce interaction between several chargers or with other units at a point of common coupling [121], [122]. However, such methods still do not support or stabilize a weak grid. On the contrary, they still harm it further and are just more successful in extracting the power the charger wants. In combination with the massive cumulative power of chargers, these methods are practically designed to operate the grid close to the border to a collapse and are not a viable solution to the problem.

VI. GRID SERVICES

A. Turning the Stressor Into a Reliever

Accordingly, state-of-the-art charging technology destabilizes the grid—from shortest time scales due to rapid control dynamics, oscillations due to parasitic feedback, and missing inertia to long time scales due to the massive energy demand [123]. The concurrent presence of high-power electronics and various storage elements ranging from dc-link capacitors (small energy content, high power capability, and low cost of aging) to the EV battery (high energy content, low power capability, and high cost of aging), however, provides close to ideal conditions to let chargers support the grid (see Table 1) [124]. However, those functionalities will require different solutions for control, circuit topologies, and likely communication for coordination.

The specialized literature has marketed the use of EVs for regulation services for transmission system operators (TSOs), DSOs, and municipal utility operators for more than a decade under the vehicle-to-grid (V2G), vehicle-to-home (V2H), and vehicle-for-grid (V4G) brands, to name a few [20], [95], [125], [126], [127], [128], [129], [130]. Unfortunately, the use of large distributed grid-storage batteries often dominates the discourse. The other services, however, might be even more pressing in the context of the wide-scale presence of power converters in our grids and the reduction of conventional rotational generation and loads. Interestingly, a number of such ancillary services do not necessarily need bidirectional power flow. The use of unidirectional hardware with appropriate control for grid services allows a cost-effective implementation and may catalyze the translation into the field [131], [132].

In addition to the potential of unidirectional chargers, various grid services aside from just grid storage have the little aging potential for the battery. Particularly, inertia involves very little energy and hardly cycles the battery. Other services can change the net charging power to avoid drawing energy from the battery. After all, battery aging, the associated risk for a car owner, and insufficient

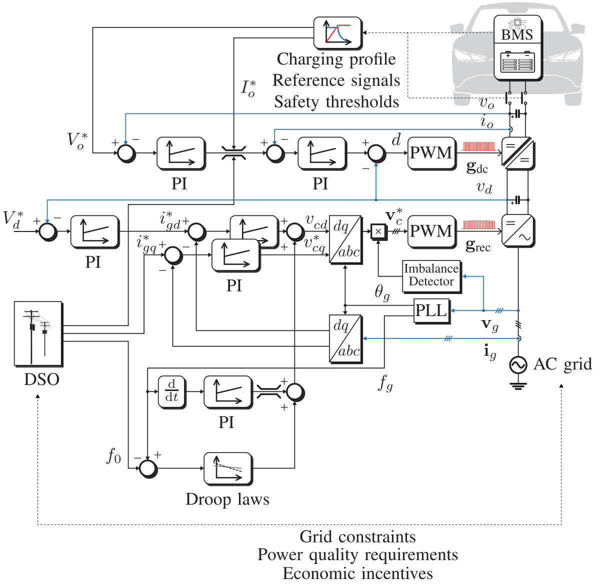


Fig. 13. *Example layout for an EVSE control scheme with several grid services implemented in the controller of Fig. 10. The control emulates inertia through the time derivative of the frequency (often also called RoCoF) to the inner loop of the grid interface and adds a frequency-dependent term to the active power, such as droop. The outer loop controls the dc-link voltage with slower dynamics, i.e., lower bandwidth than the inner loop to bring the voltage back to its steady-state level while allowing fast interventions. As the dc-link voltage is no longer constant, the dc–dc control has to consider that at least through a voltage feed-forward signal as shown here. As soon as the response, such as frequency droop, inertia, or power curtailment, exceeds the ultrashort-term range and is slower than the dc-link voltage regulation—which is typically the case—it has to be considered in the set values of the BMS in the dc–dc loop. Otherwise, the second stage will empty the dc-link capacitor.*

monetary compensation are major obstacles to the introduction of V2G or V4G [133].

Fig. 13 sketches an example control loop that implements various grid services in the context of a vehicle charger. These services have a substantial impact on the typical control structure used in chargers. The coupling between the control loops of the various stages has to become tighter. While, in conventional control, as shown in Figs. 10 and 11, the (real) power is often controlled close to the battery and the other stages follow indirectly, the grid demand now has to be included and acts on both the grid interface for a fast response, and the battery interface for adjusting the power as the dc-link capacitor typically cannot compensate the necessary power fluctuations. The power adjustment does not only involve DSO-initiated power curtailment but also frequency-dependent power adjustments and inertia, which can result in dynamics over a period of seconds.

B. Power Curtailment and Demand-Side Management

Due to the enormous cumulative power to be expected from a large share of plug-in vehicles in the future, numerous researchers and developers have warned that uncoordinated charging could become critical for the grid. This situation may be exacerbated by strongly fluctuating renewable energy generation [134]. Coordination in the form of demand-side management appears obvious and, in principle, not strictly novel, considering that storage heaters with timed or DSO control have existed for more than half a century [135], [136], [137]. Furthermore, simple curtailment measures are also well established for large residential photovoltaic systems, i.e., on the supply side [101].

The adjustment of power limits to reduce the load stress on the grid appears understandably simpler with slow charging when cars are connected for hours at night or during the day, such as residential chargers at home or electrified staff parking lots.

Conventional ripple control receivers and radio teleswitches are established technologies for ramping the power of all units in an area down, whereas modern receiver technology, including internet-based and cellphone connections, may allow more specific and even individual control in the future (see Section VI-H). For OBCs, the receiver could be installed in two different positions: with a wallbox that sends the power limits to the vehicle, e.g., through the CP, a curtailment signal receiver could feed rather rapidly precise limits to the vehicle; alternatively, the OBC would need its own receiver. If the charger in the latter case received signals through the communication links of the vehicle, it might need to include location information. Alternatively, the chargers can control their real power based on the current grid frequency and contribute to the primary control reserve [138]. In that case, all necessary information is extracted from the grid parameters, specifically the frequency.

C. EV-Based Grid Energy Storage

The use of large EV fleets as a distributed grid-storage system is regularly promoted as an effective solution to arbitrate between fluctuating renewable electrical energy generation and the demand, by providing the necessary control degrees of freedom with dispatchable energy or capacity firming. Through their chargers, EV batteries could store surplus electricity when the production exceeds the consumption and release banked energy to the grid when production fails to meet the demand [5], [139].

Such grid-storage operations may mostly involve low- and medium-power chargers, where vehicles are connected overextended periods of time. As many residential chargers may be occupied with an EV mostly at night, parking decks and staff parking lots at companies appear to grow in importance but are rarely available at that time. High-power chargers, e.g., on highways, however, may have little to no contribution as customers expect rapid charging during their short visit. The short time does not allow feeding back to the grid beyond the second range (see Section VI-E on inertia), and the charged vehicles leave the charger so that any stored energy is practically lost within approximately 30 min so that balancing over longer time frames would be impossible anyway. Instead, high-power fast chargers typically integrate local ESSs with a similar objective. By means of this load shifting, it is possible to schedule ESSs operation in such a way that releases the energy during highly congested periods, while being replenished when most of the chargers are idle, at a convenient pace in order to avoid additional costs [140], [141], [142], [143], [144]. During idle times, this energy could also be used for grid services, which diversifies and increases their value and potential revenue streams, and, when combined with the buffering capabilities, can alleviate charging costs by exploiting time-of-use (ToU) tariffs [20].

The operation of such systems can be further improved in order to minimize the recharging cost by adding local generation RES, as discussed earlier. This is translated into reduced power ratings in grid connection elements. The integration of stationary ESSs can help to mitigate grid impacts, by reducing the intermittent demand and contributing toward load balancing, especially for MCSs. Moreover, it can serve to flatten the station's load profile, adjusting its charging profile and rate, accordingly to be charged at reduced and constant rates [145].

D. Reactive Power, Power Quality, and Harmonic Compensation

Depending on the voltage level, i.e., low or medium voltage, chargers already have to contribute to reactive power in many countries.

At the MV level, the rules for grid access—despite some recommended harmonized grid codes—are often in principle agreed on a case-by-case basis. Although the conditions can vary, DSOs often do relax requirements on reactive power delivery if they can. In contrast, for LV grids, several standards set the power quality requirements for consumer electronics that need to be met, hence with less room for flexibility.

If a charger is bidirectional with powers beyond the negligible level (typically around 800 VA, where the conditions can be a little more relaxed; see U.K. Engineering Recommendation EREC G99 or German VDE AR-N 410), reactive power is required practically worldwide as it would be considered a generation device. In many countries, pure loads above a certain power level also have reactive power requirements. Taking Germany as an example, 12 kVA is at present the limit above which a unidirectional charger also has to allow a power factor down to at least 0.9 (inductive or capacitive). The relevant standards are VDE AR-N 4100 for LV grids and 4110 for MV grids.

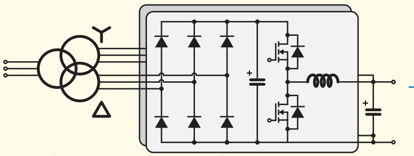
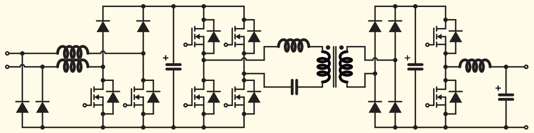
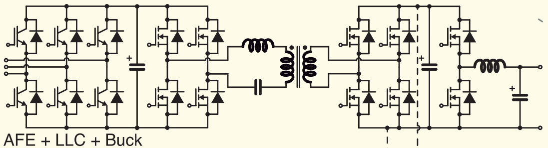
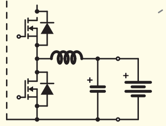
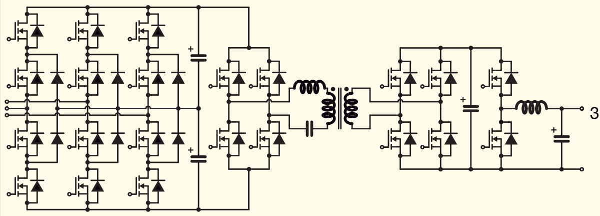
For reactive power generation or absorption, the charger has to either be controllable based on the commands of the DSO or provide reactive power based on the actual grid voltage ($Q(V)$ curves), the active power [$Q(P)$], or with a fixed phase angle. The curves or parameters have to be programmable so that the DSO can provide values based on local conditions.

Beyond the phase angle, chargers need to draw and deliver power with certain quality with respect to harmonics as other grid-connected electronic equipment. Dependent on the location, various standards, such as IEC 61000 or IEEE 519, regulate power quality [5]. However, chargers have a well-controllable grid front end for higher power chargers often even three-level systems (see Table 1). Thus, the grid interfaces could compensate harmonics and other distortions of other sources present in the grid, practically acting as a static compensator [146]. Multilevel systems, such as unidirectional Vienna PFCs or bidirectional neutral-point-clamped inverters as used in various higher power charging stations, would allow even subtle control and fast dynamics for compensating higher order harmonics [147], [148], [149]. Such a concept was discussed academically for on-board and off-board chargers [150]. Industrial implementations, however, are missing to date. While, at present, economic incentives are missing for manufacturers, larger commercial customers, with factories, large mills, and so on, might be interested in such an ancillary service of their personnel or fleet vehicle chargers when they have to otherwise operate separate compensation devices to fulfill their utilities' conditions.

E. Virtual Inertia

The growing share of RESs (e.g., wind and solar energy) that are mostly converted through power electronics, the increasing energetic relevance of consumer electronics and data centers, the shift from grid-tied motors to variable-speed drives, and, now, a large-scale roll-out of relatively high power vehicle chargers are all leading to a more electronic grid, where large mechanical generators with their energy-storing rotating mass lose influence [151], [152]. Instead, the grid is increasingly dominated by power electronics devices with active control, rapid response, no frequency–power-balance relationship, and often direct or indirect constant-power control [153]. The rotating mass of large generators, however, has three major functions in conventional ac grids: 1) in a first approximation, the generators act as voltage sources behind a series source impedance and set a robust voltage, as the inertia of the rotating mass stabilizes the voltage; 2) the speed fixes the grid electrical frequency, which likewise does not change rapidly because of the inertia of the rotating mass; and 3) the rotating mass is the only element in our grid that introduces the well-known relationship between frequency and the supply–demand balance of power with, e.g., a decreasing frequency indicating a supply shortage. The rotating mass, therefore, serves as an ultrashort-term energy storage on time scales before any primary control can respond. The increasing penetration of power electronics in the modern electrical grid can ultimately result in the loss of these three aspects.

Table 1 Topological Comparison With Respect to Grid Service Capabilities

Charger Circuit Topology	AC Input	EVSE state	Grid Storage			Active filter STATCOM						
			Long-term (days)	Short-term (hours)	Inertia	Reactive power	Harmonics	Phase imbalance	Voltage support	Grid forming	Short circuit current supply	Black-start support[3]
 LF isolation transformer + 12-pulse rectifier + 2 channel Buck	3-ph	with EV plugged-in	🟥	🟥	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥
		without EV	🟥	🟥	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥
 PFC + LLC + Buck (3-ph version uses 3 identical stages)	1-ph	with EV plugged-in	🟥	🟥	🟨	🟧	🟧	🟥	🟥	🟥	🟥	🟥
		without EV	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	3-ph	with EV plugged-in	🟥	🟥	🟨	🟧	🟧	🟨	🟥	🟥	🟥	🟥
		without EV	🟥	🟥	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥
 AFE + LLC + Buck	1-ph	with EV plugged-in	🟥	▪	🟩	🟩	🟩	🟥	▪	▪	▪	▪
		without EV	🟥	🟥	▫	🟩	🟩	🟥	▫	▪	▫	🟥
	3-ph	with EV plugged-in	🟥	▪	🟩	🟩	🟩	▪	▪	▪	▪	▪
		without EV	🟥	🟥	▫	🟩	🟩	▪	▫	▪	▫	🟥
 AFE + LLC + Buck + Stationary battery Local ESS	1-ph	with EV plugged-in	▪	🟩	🟩	🟩	🟩	🟥	▪	▪	▪	▪
		without EV	🟥	▪	▫	🟩	🟩	🟥	▫	▪	▫	▪
	3-ph	with EV plugged-in	▪	🟩	🟩	🟩	🟩	▪	▪	▪	▪	▪
		without EV	🟥	▪	▫	🟩	🟩	▪	▫	▪	▫	▪
 NPC + LLC + Buck	3-ph	with EV plugged-in	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▪
		without EV	🟥	🟥	▫	🟩	🟩	🟩	▫	🟩	▫	🟥

Capabilities: 🟩 Excellent ▪ Good ▫ Insufficient[2] 🟨 Limited[1] 🟧 Partially[2] 🟥 Uncapable

EVSE state legend: with EV plugged-in; without EV

1. Only limited because unidirectional impact, which can react relative to the previous load state.
2. Only for a very short time frame, given by the dc-link capacitances.
3. For black-start capabilities, chargers would need to power all necessary auxiliaries and control through the storage or vehicle battery.

Existing chargers may typically have relatively simple cascaded current–dc-link-voltage control, which establishes a near-constant-power behavior and considers the frequency mostly for synchronization. Dependent on the topology, however, they could actively contribute to establishing a relationship and frequency stabilization through control-generated virtual inertia [151]. In principle, such virtual behavior could be considered an extension of previous studies on power electronic dominant grids. After encountering issues and worries with early PV inverters that implemented a rather abrupt load dump, for instance, at 50.2 Hz, to terminate potential oversupply with the risk of massive oscillations when surpassing that limit, modern inverters typically include some droop to gradually reduce the power dependent on the grid frequency [154]. Accordingly, a control-based power–frequency relationship was developed. However, this control is typically slow and acts through the power-point tracking of the photovoltaic module(s) to curtail generation. The inclusion of frequency and frequency-derivative terms into the grid-side control law enables a rapid response with so-called virtual or synthetic inertia, while the dc-link capacitor's energy can be used for the initial response to actively counteract frequency transients in the grid to bridge the time until more powerful units, e.g., from the primary control reserve, can take over [155], [156].

Due to their comparably large power level and the expected ubiquity in the future, vehicle chargers operating in crowds appear as an almost ideal element in a virtual-inertia strategy [157].

To ensure a rapid response and to avoid the need to couple the control of the various stages tightly in established architectures, the dc-link capacitance may need to be increased moderately to substantially to reach the high Joule to kilojoule level to bridge several seconds, whereas, conventionally, dc-link capacitors only filter over few cycles [156]. A large number of plugged-in vehicles and chargers might, however, reduce the capacitor need per unit substantially in the future. The fluctuation of the dc-link voltage can be coupled to the subsequent stages through feed-forward terms (see Fig. 13).

Interestingly, for virtual inertia generation, chargers do not necessarily need a bidirectional active front end (AFE). Inertia responses involve rapid short-term power delivery relative to the present loading. Thus, also, unidirectional PFC stages can implement fast-responding frequency and frequency-derivative or rate of change of frequency (RoCoF) terms, while they are charging up to the charging power at the time of a stabilizing intervention [132]. During charging, the virtual-inertia response in the case of a grid frequency drop starts from the current baseline, e.g., at rated power, and will reduce the power accordingly for a net effect on the grid. Thus, the available power for the virtual inertia intervention is limited to the actual active power draw at the time of initiation. Understandably, an idling PFC stage connected to the grid without charging cannot provide virtual inertia.

With increased dc-link capacitance, both on-board and off-board chargers (the latter also without vehicles connected) could contribute to the fastest component of inertia until this internal energy storage is depleted. With a vehicle connected and at least a bidirectional dc–dc stage between the PFC or AFE and the battery, the response can bridge rather long times and move considerable energy into the grid during that time.

Due to the enormous cost of stream-lining in the vehicle industry, any implementation into on-board or off-board chargers may wait until the establishment of sufficient regulations or incentives.

F. Grid Forming

As power-electronic-interfaced energy sources become increasingly dominant compared to synchronous generators, synthetic inertia emulation via the controls of power electronic converters will eventually be insufficient to stabilize the grid frequency and particularly the voltage. When a large share of power is provided to the grid through grid-following converters, the grid voltage will no longer be stiff enough for this approach to work.

While, to date, vehicle chargers are almost exclusively grid-following on the ac side (see Fig. 10), a switch to grid-forming operation will likely become important if not mandatory for some installations [75], [153]. Various grid-forming schemes have been proposed in recent years [158], [159]. Grid-following operation expects the presence of a stiff grid with well-defined voltage, where the grid-interfacing inverter/rectifier stage synchroniizes to the grid frequency and operates in current control with the grid voltage as a feed-forward input at best. As the most important difference, grid-forming operation controls the inverter as a voltage source. The voltage control is typically already embedded in the inner control loop, with some sort of power control and frequency referencing cascaded around it. Then, the grid interface accordingly has to necessarily implement a bidirectional voltage-source topology. PFC grid interfaces, which are currently dominant for cost reasons, do not suffice. For enough perseverance, the grid interface needs sufficient power to stabilize and enforce the voltage for at least a grid period through a large dc-link capacitance or a bidirectional dc–dc converter to a connected vehicle or a stationary battery [160].

Whereas information about the grid impedance had already some importance for grid-following rectifiers/inverters to stabilize their control in weak grids, it is practically mandatory in practical grid-forming setups [75]. For grid forming, the grid impedance and its dominant character determine how the degrees of freedom, specifically voltage amplitude and phase relative to the grid voltage, lead to active and reactive power flow [161]. For dominantly resistive grids, typically on the LV level, the voltage amplitude controls the active, whereas the phase sets the reactive power. In dominantly inductive grids (typically at higher voltages or when the system is close to a transformer), the situation is practically inverted. Understandingly, the interference of active and reactive power control in the case of mixed inductive–resistive impedances is a major control challenge, and methods for robust decoupling despite poor knowledge of the grid are under research [162]

Most grid-forming concepts use droop control [163]. However, some more intricate control approaches imitate the behavior of synchronous generators in the control layer with more or less detailed models [159], [164], [165], [166], [167]. Virtual synchronous machines copy the behavior of synchronous machines and can, therefore, follow established relationships and grid control concepts. They introduce a natural link between frequency and power through simulated inertia and voltage support, and are relatively robust. These systems can, however, be computationally complex dependent on the implemented model. In contrast to grid-following rectifier/inverter stages, which typically need additional loops and feedback, a grid-forming system can naturally be designed to provide inertia, voltage support, and usually also frequency control [168]. Furthermore, they allow a seamless transition from a stiff grid via weak grids and high grid impedances to islanded operation [169].

Despite these advantages and opportunities, grid-forming control is mostly under research due to the conditions that grid-forming chargers would typically have to manage: while grid forming is well defined and robust in islands and near-islands with only one dominant converter, situations where there are several converter-interfaced energy storage sources without a dominant converter in a distribution grid pose many open questions. Particularly, if these furthermore do not feed into the very same point of common coupling but couple through intermediate impedances, parasitic feedback loops can emerge. Furthermore, the coordination of various nondominant grid-forming converters is not yet satisfactorily solved. If there is no central supervisory control at all, the various converters would need to fully self-organize and use decentralized control with some level of robustness so that inaccurate or wrong information received from other sources does not harm the overall stability. Thus, despite the likely high importance of grid forming for chargers in the future, substantially more research and operating experience particularly under exceptional conditions is required.

G. Black-Start Initialization or Support

A crowd of chargers could, in principle, initialize or contribute to a black start and bottom-up system restoration, which, at present, is, in most areas, a function dedicated to conventional power plants, including hydro power [170], [171], [172]. For this purpose, the relevant chargers should be at least grid forming, bidirectional, and have access to a battery (either stationary or a vehicle). The dc-link capacitors and even double-layer capacitors, which may be sufficient for elementary grid forming, would be stretched beyond their limits here and may even self-discharge faster than the black-out lasts. Furthermore, practical aspects should not be underestimated. For acting as a seed during a black start of a cell, the charger most importantly would further need a concept for supplying the control and all essential auxiliaries, such as cooling, through the battery or vehicle. To date, no commercial charger appears to provide such a feature but instead supplies those units through separate lower power ac power supplies from the grid. While some ancillary grid services could, in principle, be achieved without major central coordination in a distributed manner, a black-start procedure does not appear to be one of them. Such an intervention certainly will have to be commanded and controlled by the responsible utility company [173], [174].

H. Coordination—Centralized Versus Autonomous Distributed Control

Several of the described grid services can be performed by individual chargers only based on the available information on that device. Frequency droop, some kind of inertia, and harmonic compensation are examples that do not necessarily need information beyond the electrical conditions at the local point of common coupling [175]. Simple forms of voltage support through reactive power in dependence of the voltage through parametric curves programmed into the grid interface (so-called $Q(V)$ curves) are already established.

While limited use of additional features for improving the grid performance is possible at present, the full exploitation of this potential will need coordination [176], [177], [178]. Research on distributed control is ongoing, but the risk of instabilities under certain conditions and of parasitic feedback due to the interaction of controllers of separate units remains [179]. Central or hierarchical coordination, e.g., through the local DSO, may be an option but require a communication link to the various chargers [180]. While conventional ripple control as historically used for load management or the abovementioned solar curtailment is not directly designed for modern grid services, power-line communication, Ethernet, or cell-phone links might enable coordination of grid services of chargers similar to the IEC 61850 standard as used for the control of substations [181], [182], [183], [184]. Public chargers typically already have Ethernet or cell-phone modems installed for payment and remote monitoring, while residential chargers are usually in the range of wireless internet. While these channels would need methods for randomly delayed and lost packages, the ultralow-latency mode and quasi-real-time packages in 5G and subsequent generations may also allow the coordination of lower level control [185], [186], [187], [188], [189]. Importantly, for black-start services, the necessary communication link has to be available in the event of a black out.

In order to illustrate the topological differences in terms of the grid support capabilities discussed above, Table 1 presents a comparison of various state-of-the-art charging converters, highlighting how the sophistication of the power electronics involved along the presence or not of a car plugged-in, or stationary ESSs increase the functionality of the EVSE aiming to a net zero scenario for transportation. By qualitatively comparing the different functionality and reach of grid services possible, a further sophistication of charging converters may be foreseen since it directly impacts the performance of the chargers in different grid services. On the other hand, the presence of stationary ESSs can benefit their service way beyond the often mentioned peak shaving functionality.

VII. CHALLENGES AND FUTURE TRENDS

A. EVSE as Flexible Grid Assets

Sections V and VI provided a wide set of possibilities regarding the potential functionality of the charging infrastructure toward the modernization of the grid. Future scenarios may require active contributions from this growing asset in order to maintain the functionality and robustness of the electric system. Fig. 13 displays an alternative for implementing various grid services in existing control structures for EVSE. It can be seen that both BMS and DSO regulate the operation of the equipment at a supervisory level, and it is expected that the BMS will remain as the main regulator of the process, i.e., has priority on any interaction with the battery. However, the DSO tasks can be extended through additional control loops to request specific behavior from the charger. For instance, during highly congested periods of the grid, power curtailment can be requested by limiting the output current requested by the BMS. Similarly, if the charger needs to modify its reactive power consumption/generation, DSO can arbitrarily request a certain value through the quadrature current component. Moreover, if frequency regulation is needed, a set of droop laws could be included to modify the voltage generated by the grid-tied converter.

The production of synthetic inertia can be also considered, by means of controlling the rate of change of the grid frequency, as suggested in Fig. 13. Please note that all of the above grid services will have limited influence on the system and will depend strongly on the controllability provided by the existing grid interface, as illustrated in Table 1. Despite the technical feasibility of the discussed grid functionalities of charging infrastructure, its deployment and implementation will depend strongly on the requirements imposed by the standards being developed by different system operators (TSOs, DSOs, and so on) and the incentives offered to OEMs and users. Up to date, the only product that features embedded grid services is Enercon's E-Charger 600, which employs 300-kW AFEs from their wind turbine portfolio; hence, it is a turn-key solution for their EV business [54], [55].

B. Nonisolated Charging Systems

As discussed in Section III, the vast majority of commercialized charging systems include a galvanic isolation barrier between the battery being charged and the grid, which is mainly addressed by the presence of a transformer either at LF or HF. By including such a feature, the system naturally presents a high CM impedance, which, in turn, attenuates the leakage current generated by the operation of the power converters combined with the parasitic path between the chassis and the ground (this can be further aggravated by the battery coolant liquid, which is at chassis potential as well, leading to a considerable CM capacitance), keeping the personnel operating the equipment safe from shock hazards [26], [190], [191], given that the expected magnitude of this current and the use of a nonisolated converter represent a challenge in terms of safety and electromagnetic compatibility [26].

However, the good CM performance of isolated systems enabled by transformers is detracted given their additional costs, efficiency, and power density issues [27], [28], [192]. These drawbacks can be eliminated through the development of transformerless charging systems, which feature simpler circuit structures and have the potential to reach higher efficiency, besides representing a more compact solution. Compared to isolated solutions, nonisolated chargers are prone to a higher CM leakage current, making compliance with safety standards and codes a challenging process. It should be noted, however, that the widespread usage of WBG devices in charging systems will even challenge the inherent good CM performance of galvanic-based isolation systems (their higher frequency operation will reduce the CM impedance seen due to parasitic capacitances of the isolation transformer).

Three broad approaches exist for achieving standard-compliant nonisolated charging. The first is to use semiconductor-based isolation, where dedicated semiconductor switches are used in a power electronic converter topology to carry differential mode current while in the ON-state and block CM current in the OFF-state [192]. The second approach involves leveraging symmetrical power electronic converter topologies that are modulated according to a strategy that produces zero CM voltage (which will theoretically result in the production of zero CM current) [27]. The approach adopted by Viana et al. [27] is also an integrated charging solution (leveraging power electronics from the traction inverter and motor winding inductances), which further enhances the power density of the charging system. The third design approach of nonisolated chargers involves the usage of CM filtering techniques and control strategies that provide a bypass path for CM currents away from the grid [26], [28].

A further application of nonisolated topologies is to achieve backward compatibility between vehicles with 800-V battery packs and legacy 400-V fast charging stations. A solution for this has been proposed by Lee et al. [193] and Herke and Spesser [194], where the motor winding inductances and traction inverter are leveraged as an interleaved boost converter to step up the lower charging station voltage to the higher voltage of the battery pack. This integrated solution does not require the installation of any additional power electronics on the vehicle and does also not suffer from CM current issues as galvanic isolation is already provided by the fast charging station.

Nonisolated EV chargers typically have a simple circuit structure and could have higher efficiency and greater power density. However, compared to isolated solutions, these chargers are prone to a higher CM leakage current, adding difficulty to safety standards and code compliance. The leakage current issue and safety concern remain the most critical challenges in the adoption of nonisolated chargers. However, in general, nonisolated integrated charging will remain a very attractive option for future EVs because of the potential to achieve charging, V2G, and V2H functions at a lower cost, weight, and volume. Thus, more innovations are expected from both academia and industry to address these challenges.

VIII. CONCLUSION

Zero-emission vehicles will contribute substantially to tackle climate change, making power electronics technology critical for achieving a net zero scenario. By enabling the energy transfer between distribution grids and EV battery packs, the impact of charging infrastructure will persistently increase as EV adoption accelerates. Different configurations and approaches allow performing this energy transfer effectively aiming to support a seamless transition toward electrified transportation. This expected proliferation could be driven toward extending their functionality and pave the way for the transformation of the grid.

Existing charging topologies are already capable of providing various grid-supporting services but still require standardization and incentives from system operators, besides efforts from OEMs. Also, modifications in control, coordination, and communication layers are needed for their implementation. EV-based grid storage often dominates the benefits of deeper EV penetration, while other services that do not require AFEs can be more useful to soften the ongoing grid transformation.

By promoting the inclusion of grid services in EV chargers, further sophistication of power conversion stages could be expected, where WBG devices and multilevel converters may bring improved functionality, unprecedented efficiency, and smaller packages.

Further improvements in battery technology can lead to another steep reduction in charging times. The projected 1500-V architectures will enable megawatt charging with lighter and manageable cables. Even higher power charging capacity gives more reasons to further develop nonisolated solutions, which are enabled by advanced power electronics circuits and control schemes.

Finally, along with these opportunities, becoming a critical technology will further challenge power electronics development. The ever-increasing presence of power converters in the path from renewable electron to battery may impact the system's reliability, demanding new levels of fault detection and fault tolerant operation in power converters. In addition, cybersecurity is arising as a major concern due to increasing communication-dependent layers and protocols. These will govern a more-connected power grid and charging infrastructure. Hence, although it might appear as a mature technology, there is still plenty of room for R&D. ■

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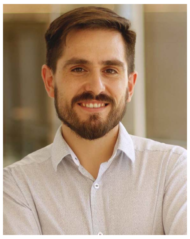

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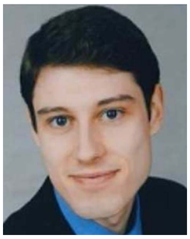

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