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Review

Current Trends in Electric Vehicle Charging Infrastructure; Opportunities and Challenges in Wireless Charging Integration

Konstantina Dimitriadou [1], Nick Rigogiannis [1], Symeon Fountoukidis [1], Faidra Kotarela [1], Anastasios Kyritsis [2,3] and Nick Papanikolaou [1,*]

[1] Electrical Machines Laboratory, Department of Electrical and Computer Engineering, Democritus University of Thrace, Kimmeria-Xanthi, 67132 Xanthi, Greece
[2] Environmental Physics, Energy and Environmental Biology Laboratory, Department of Environment, Ionian University, Panagoula-Zakynthos, 29100 Zakynthos, Greece
[3] Department of Photovoltaic Systems and Distributed Generation, Centre for Renewable Energy Sources and Saving (C.R.E.S.), 19th km Marathonos Av., Pikermi, 19009 Athens, Greece
* Correspondence: npapanik@ee.duth.gr; Tel.: +30-25410-79739

Abstract: Nowadays, the imperative need for the reduction of Greenhouse Gas (GHG) emissions leads to the wider adoption of environmentally friendly transportation means. As a result, various policies underpinning the Electric Vehicle (EV) deployment are legislated globally, and several technical advances contributing to the electrification of the transportation sector are pursued. In this paper, a comprehensive overview of the current status of the infrastructure utilized for the realization of both conductive and contactless (wireless) charging of an EV battery is conducted. Furthermore, the issue of EV integration in conventional distribution networks, as well as in future power system architectures, is discussed in detail. Particular focus is given to wireless (i.e., inductive) charging. A detailed presentation of the respective standards and charging levels, as well as the magnetic couplers and the compensation network configurations, is carried out. Moreover, innovative concepts such as dynamic and quasi-dynamic wireless charging, as well as future challenges and opportunities, are presented and discussed. Finally, smart control and communication techniques applicable to EV charging are presented in the context of the future Internet of Energy (IoE) concept.

Keywords: electric vehicle (EV); EV charging; conductive EV charging; wireless EV charging; smart EV charging; charging infrastructure; vehicle-to-grid (V2G)

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1. Introduction

The adverse environmental effects caused by Greenhouse Gas (GHG) emissions and the ever-increasing public awareness regarding the impact of GHGs on the climate have stimulated significant changes in the transportation sector. Conventional transportation means equipped with Internal Combustion Engines (ICEs) constitute one of the most significant air pollution sources. Indeed, according to the European Commission findings, transportation represents almost a quarter of Europe's GHG emissions [1,2]. Therefore, many EU countries, in order to meet low-emission targets, intensified their policy regarding the electrification of road transportation by adopting key measures that promote the deployment of Electric Vehicles (EVs) and their corresponding charging infrastructure.

According to the data provided by the Global EV Policy Explorer of the International Energy Agency (IEA) [3], China, the leading EV market, announced in 2022 its ambition to deploy adequate charging infrastructure to accommodate 20 million Non-Emission Vehicles (NEVs) by 2025. NEVs include Battery Electric Vehicles (BEVs), i.e., vehicles powered solely by the on-board battery; Plug-in Hybrid Electric Vehicles (PHEVs), i.e., vehicles that are propelled by an ICE along with an electric engine and a small battery [4]; and Fuel Cell Electric Vehicles (FCEVs), i.e., vehicles that convert hydrogen stored on board, using a fuel cell to power an electric motor [4]. Additionally, China aims to support the management of its lithium-ion battery industry, as this battery technology is dominant in the automotive industry. Furthermore, in 2022 the federal government of the United States announced its targets regarding the promotion of EV penetration in the transportation sector. These targets include a 50% EV sales share, as well as the development of 500,000 public chargers by 2030, by introducing new incentives and subsidies. In 2021, Canada pushed forward the federal government target for achieving 100% zero-emission light-duty vehicle sales from 2035 to 2040. Moreover, the "Fit-for-55" package in the European Union features a list of stimulus measures to expedite the shift from ICEs to zero-emission vehicles. Within this list, an initiative for 100% zero-emission vehicles by 2035 and charging infrastructure deployment targets are included.

The above positive measures and policies, the continuous improvement of electric battery technologies, the increase in the available EV models, the expansion of publicly accessible charging stations and the enhancement of charging infrastructure capabilities have led to the boom of EV sales worldwide. Indeed, in 2021, more than 16.5 million NEVs (mainly BEVs and PHEVs, as registrations for FCEVs remain quite low worldwide) were being driven globally, marking a tripling in EV stock in just three years [5]. Nevertheless, the major increase in EV penetration rates does not come without its challenges. EV prices remain considerably high compared to conventional ICE vehicle prices [5,6]. In more detail, the electric battery is the most expensive component of an EV [7], and therefore battery packs with relatively small capacities are preferred in order to limit the total cost. On the other hand, EV battery lifespan is also critical [8,9].

Additionally, the EV sales growth does not always match the deployment of new public charging infrastructure [5,10]. EVs can be charged either by the mains or by the fast-charging points to reduce the charging time. Without a doubt, charge points should be close to an electrical supply. Therefore, finding charging stations can be challenging on routes in mountains, the countryside, or coastal and rural areas. Apparently, things are much easier when you move around a city center, where EV owners have access to private or public charging networks. Furthermore, considering that the vast majority of people in urban centers live in flats, the above is the only feasible option, whilst domestic charge points look impossible. In addition, uncontrolled charging of EVs constitutes a burden for the power system [6,11–17]. Moreover, two major concerns of a potential EV user are the significant waiting time required for a full recharge [6,18], which is disproportionately higher than the time needed to fill up the tank of a conventional vehicle, and the available driving range, which may have improved in recent years but still remains restricted [5,6,19,20]. The authors of [7] investigate the required energy density of an EV and the importance of its maximization (by utilizing a lightweight EV body design, advanced battery technologies and improved powertrain architecture) for the relief of the range anxiety issue.

Over the last few years, a significant effort has been carried out, according to recent scientific literature [21,22], in order to obtain a comprehensive overview of EV charging technology, including the integration of renewables in charging infrastructure, charging levels and the respective international standards, as well as the smart charging concept and the role of aggregators. However, limited investigation has been conducted regarding innovative wireless charging technologies and their classification, as well as the smart charging and control/communication infrastructure, in order to end up with a broad review. Hence, in this work, we aim to present a thorough overview of current EV charging schemes, with a special focus on inductive charging concepts, which are distinguished into static, dynamic and quasi-dynamic and are described in detail. In addition, as EV charging increasingly incorporates smart charging features (modern communication protocols, Internet of Things (IoT), cloud services, etc.), those concepts are broadly reviewed, along with the interactions and benefits of the mass integration of EVs into the electricity network.

In more detail, first, the current status of the infrastructure utilized for both conductive and wireless charging of an EV battery is presented. In particular, the operation, the related charging standards, and the power converter topologies as well as the techniques used to control them in conductive EV charging are thoroughly elaborated. Subsequently, the possible ways to wirelessly transfer power are briefly mentioned, with the focus being directed towards the most popular wireless charging method, i.e., the inductive method. The operating principle, the charging standards/modes, and the associated energy conversion system components and their control schemes are described in detail. Next, the issue of the mass integration of EVs is discussed. Various strategies that can be implemented for the mass integration of EVs and their corresponding impact on the utility grid are examined. Moreover, the procedure followed and the communication protocols utilized during an EV battery recharge are presented. Finally, an introduction to EV integration into the future power system framework is performed.

2. State of the Art for Conductive and Wireless Charging

2.1. Conductive Charging

Conductive charging is the most commonly used charging method for BEVs. Generally, to charge an EV, AC power from the utility grid is fed to the EV via the charger socket outlet, using the charging cable and the vehicle inlet. Depending on the power delivered to the EV, conductive charging is categorized into AC and DC. When an AC conductive charger is utilized, the EV is supplied with AC power. The charger is located inside the vehicle, and its size and weight define the maximum power that can be delivered to the EV. Thus, electric power from the mains is converted on board to the optimal DC voltage and current levels in order for the battery pack to be charged. On the contrary, when the latter method is applied, the EV is fed with DC power via an off-board charger, which enables the transfer of increased power levels and thus shorter charging times.

Figure 1a,b illustrate the general schemes for DC and AC charging, respectively. In the first stage of DC charging, the AC power provided by the grid is rectified, inside the DC charging station. Subsequently, the control unit regulates the DC/DC converter voltage and current, according to the information signal, transmitted by the charge controller, in order to adjust the variable DC power delivered to the battery. The Battery Management System (BMS) communicates the State of Charge (SoC) to the charge controller and, in the case of an emergency situation, triggers the protection circuits. The main responsibility of the BMS unit is to assess the battery condition by monitoring the voltage and current of each cell and to appropriately regulate them, ensuring that the charge/discharge process is accomplished in compliance with the respective safety requirements [4,23,24]. There are also safety interlock and protection circuits to stop the charging process whenever there is a fault condition or an improper connection between the EV and the charger.

In AC charging, the power converters are located inside the EV. Nonetheless, the operation of each of the aforementioned components remains the same. The only exception is the charge controller, which exclusively communicates with the BMS so that the protection circuits are triggered in case the battery voltage and/or current limits are exceeded or the connection between the EV and the charger is unsuccessful.

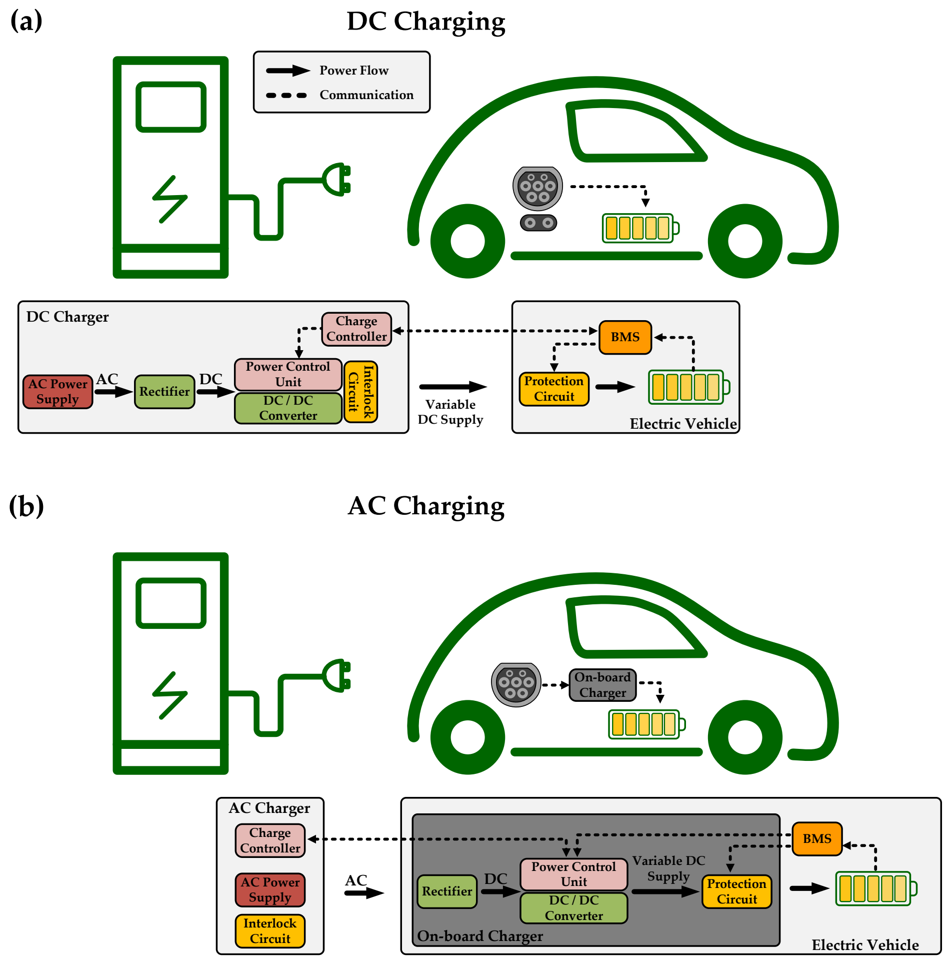


Figure 1. General schemes for (**a**) DC charging and (**b**) AC charging [25–27].

Concurrently, an alternative implementation of DC charging is being examined in Germany. Within the ELISA field trial, overhead lines were built on 10 km of the A5 motorway between the Langen/Mörfelden and Weiterstadt junctions. Hybrid heavy commercial vehicles traveling along this route can draw power using the built-in pantograph, while on the move. The trial seeks to evaluate the feasibility of such a practice, whose main goal is the reduction of the CO_2 emissions of Heavy Goods Vehicles (HGVs) [28].

2.1.1. Charging Levels and Connector Types of DC and AC Charging

AC and DC chargers are classified by the output power provided to the EV. In Table 1, the charging power levels according to the Society of Automotive Engineering (SAE), the International Electrotechnical Commission (IEC) and the Charge de Move (CHAdeMo) standards are summarized. The charging infrastructure in the USA complies with the SAE standard regulations, whereas IEC policies are legislated mainly in Europe [4]. The CHAdeMO standard was developed by the Tokyo Electric Power Company, in cooperation with Japanese automakers, and is applied worldwide. Specifically, in Table 1, the output voltage and power level of the charger, as well as the current supplied to the battery, are described [4,16,24,29]. Moreover, the charger location (on-board/off-board) is defined. The Table 1 data verify the fact that without size and weight restrictions, the maximum DC charging power can reach notably higher levels compared to those of AC charging.

Table 1. Charge ratings of IEC 62196, SAE J1772 and CHAdeMO standards [4,16,24,29].

Standard	Charging Level	Voltage (V)	Maximum Current (A)	Maximum Power Rating (kW)	Charger Location
IEC 62196	AC Level 1 (Mode 1)	230–240 V_{AC} (Single-Phase) 480 V_{AC} (Three-Phase)	16	3.8 7.6	On-Board
	AC Level 2 (Mode 2)	230–240 V_{AC} (Single-Phase) 480 V_{AC} (Three-Phase)	32	7.6 15.3	On-Board
	AC Level 3 (Mode 3)	230–240 V_{AC} (Single-Phase) 480 V_{AC} (Three-Phase)	32–250	60 120	On-Board
	DC (Mode 4)	600–1000 V_{DC}	250–400	400	Off-Board
SAE J1772	AC Level 1	120 V_{AC} (Single-Phase)	16	1.9	On-Board
	AC Level 2	240 V_{AC} (Single-Phase)	80	19.2	On-Board
	DC Level 1	200–500 V_{DC}	80	40	Off-Board
	DC Level 2	200–500 V_{DC}	200	100	Off-Board
CHAdeMO	DC Fast Charging	1000 V_{DC}	400	400	Off-Board

In particular, according to the IEC 62196 standard, Level 1 AC chargers (Mode 1) provide the lowest power level and are mostly utilized for charging light EVs, such as electric scooters and bicycles, since charging large-capacity batteries would be a rather slow process, inadequate for daily use. They are connected to a single-phase or three-phase 230 V/480 V domestic outlet and can supply the vehicle with up to 7.6 kW/16 A. The Level 2 AC chargers (Mode 2) are suitable for both domestic networks and publicly accessible areas. They are connected to a single-phase or three-phase supply and their output power reaches 15.3 kW/32 A. It is noted that for Level 2 chargers, as well as for those classified at higher levels (Modes 3 and 4), a control pilot conductor is built into the charging cable, which is responsible for communication, control and protection.

As for the Mode 3 AC chargers (Mode 3, Fast On-Board AC chargers), they feature the highest levels of AC output power. They are suitable for public facilities since they feed electrical power of up to 120 kW/250 A. It should be highlighted that, in some cases, the AC power conversion to DC can be achieved using the power unit that is used to provide propulsion (in reverse mode). Thus, high power density and weight reduction are achieved. A prime example of this practice is the Caméléon Charger on the Renault Zoe model, which is able of AC charging in the range of 2.3 kW to 22 kW [25].

DC chargers (Mode 4) are the fastest possible way to charge an electric vehicle. According to the IEC 62196 standard, they are capable of supplying up to 400 kW to the EV. They are used for commercial purposes in publicly accessible charging stations and they are rarely employed in residential areas [24].

However, there are several limitations to the power of DC fast chargers. The rising charging current values cause the generation of significant amounts of heat, which contribute to the degradation of the battery and the inevitable reduction of its lifespan [8,9]. Furthermore, higher charging power implies heavier and bulkier cables, which prevent a user-friendly charging procedure.

In addition to power levels, AC and DC charging are supported by different types of connectors. The three standards that integrate DC fast charging are Combo Charging System (CCS), CHAdeMO and Tesla Supercharger. The CCS standard was established by the SAE and uses the Combo 1 and Combo 2 connectors, which can supply up to 350 kW, enabling AC charging as well [24]. The revised CHAdeMO specification uses 1000 V_{DC} and

400 A to feed the vehicle with power up to 400 kW [22]. Additionally, Tesla developed its own proprietary fast-charging system that supports both AC and DC charging and delivers 250 kW to the vehicle [24]. China established its own GB/T fast-charging standard, and a port based on GB/T 20234-3 with a rated voltage of 750 V_{DC} and rated current of 250 A is used [30].

For the realization of AC charging, a port that conforms to the SAE J1772 [24] is deployed in USA and Japan [4], while in Europe it is based on the IEC 62196-2 standard. The latter has a current rating of 32 A [30]. In China, a port almost identical to the one that complies with the IEC 62196-2 is used.

Table 2 illustrates the SAE J1772, IEC 62196 Type 2, GB/T20234-3, SAE/IEC DC Combos, CHAdeMO, and Tesla plugs. Their connection ports (i.e., for AC charging: R, S, T correspond to the three Phases, N to the Neutral, GND to the Ground and PE to the Protected Earth, or for DC fast charging: +DC and -DC correspond to the two poles of the DC source), their electrical specification, their communication protocol, the countries where they are mainly used their charging mode are included [4,25,30]. Additional ports such as the Connection Switch, the Control Pilot, the Proximity Pilot and the Proximity Detection (represented as CS, CP, PP and PD correspondingly), the Controller Area Network (CAN-H/L), and the Auxiliary Power Supply (aux±) are mentioned too. The CP terminal allows the charging current regulation, while the PP detects the unsuccessful connection between the EV and the charger and terminates the procedure for safety reasons [4]. These terminals enable the communication between the charger controller and the BMS when chargers of Mode 2 or higher are used [4,26,27]. Finally, CS and PD terminals execute a similar function to that of PP, whilst Not Connected ports are mentioned as NC.

Table 2. Standards of charging connectors [4,25,30].

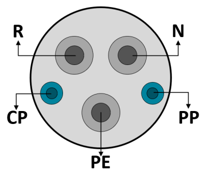
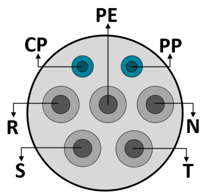
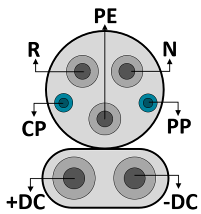
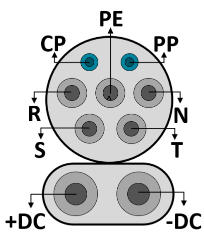
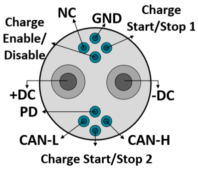
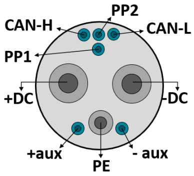
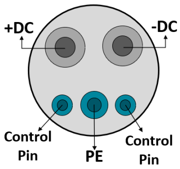
Connectors	Topology	Charging Method	Country	Voltage, Current, Power	Communication Protocol
SAE J1772 Type 1		AC Charging	USA/ Japan	120 V_{AC} (Single-Phase), ≤16A, 1.9 kW 240 V_{AC} (Single-Phase), ≤80A, 19.2 kW	
IEC 62196-2 Type 2		AC Charging	Europe/ China	230 V_{AC} (Single-Phase), ≤32 A, 7.4 kW 400 V_{AC} (Three-Phase), 63 A, 43 kW	
SAE J1772-CCS/Combo 1		DC Fast Charging/ AC Charging	USA	200–1000 V_{DC}, ≤350 A, 350 kW	PLC
IEC 62196-2-CCS/Combo 2		DC Fast Charging/ AC Charging	Europe		

Table 2. *Cont.*

Connectors	Topology	Charging Method	Country	Voltage, Current, Power	Communication Protocol
CHAdeMO		DC Fast Charging	Japan	200–500 V, ≤400 A, 200 kW CHAdeMO 2.0: 1000V, ≤400 A, 400 kW	
GB/T 20234-3		DC Fast Charging	China	750/1000 V_{DC}, ≤250 A, 237.5 kW	CAN
Tesla Supercharger		DC Fast Charging/ AC Charging	USA	240 V_{AC} (Single-Phase), ≤72 A, 17.2 kW 400 V_{DC}, ≤650 A, 250 kW	

Moreover, the chargers that comply with the CHAdeMO and GB/T 20234-3 standards incorporate a CAN bus port, utilized for the communication between the vehicle and the off-board charger. The charging system developed by Tesla uses this communication protocol as well. The remaining chargers employ the Power Line Communication (PLC) protocol. In addition, the capabilities of charging the EV auxiliary battery and implementing both types of charging from the same port are unique attributes of the GB/T 20234-3-based port and the Tesla Supercharger, respectively. Finally, it is worth noting that Tesla deploys a separate connector for DC charging across Europe. This connector complies with the regulations of the IEC 62196 standard and can provide up to 56 kW to the EV [25].

2.1.2. Power Converters

Power converters constitute an integral part of an EV charging system since their specifications are related to the two main challenges encountered in designing an efficient charging system, i.e., the time required to fully charge the vehicle battery and the issues that may arise from the thermal stress the battery will undergo. Thus, the development of low-cost, highly efficient, reliable and compact power converters is necessary for the establishment of reliable and efficient charging infrastructure.

It is possible to use topologies for AC-to-AC, AC-to-DC and DC-to-DC power conversion, depending on the requirements of each specific application. The block diagram of a conductive unidirectional EV charging system is depicted in Figure 2. Its main components are the following:

1. Single-phase or three-phase back-end AC/DC converter;
2. Front-end DC/DC power converter.

The first component rectifies the grid power, whereas the second one adjusts the rectifier output voltage and current to the optimal DC voltage and current levels in order for the battery pack to be charged. The inherent non-linear behavior of the power converters results in the generation of harmonic distortion. Consequently, in order to eliminate these higher harmonic components and comply with the respective power quality standards, Power Factor Correction (PFC) control techniques are implemented in the front-end rectifier. A Phase-Locked Loop (PLL) structure is utilized for the realization of these techniques. Additional control schemes are applied, aiming at the DC link voltage regulation or the compensation of the reactive power drawn from the utility grid. Apparently, such control strategies require active rectifier topologies [27,31–33].

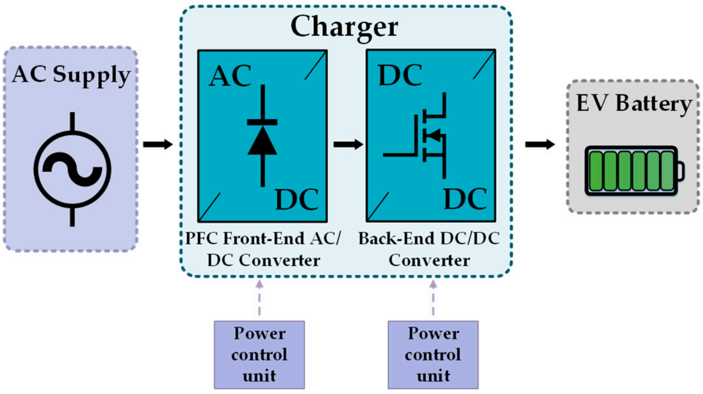


Figure 2. Block diagram of a conductive unidirectional EV charging system.

A variety of topologies are considered appropriate for the front-end DC/DC converter of a conductive EV charging system [26,27,31–33]. Isolated and non-isolated converters are included, whilst the selection among them is a matter of each application. In [27,32–34], an extensive analysis of both front-end (AC/DC) and back-end (DC/DC) topologies is performed and a detailed comparison of available converter configurations is conducted. Bidirectional topologies, which allow EV batteries to inject energy into the electricity grid, are also highlighted.

Regarding the back-end converters, they include various passive elements (i.e., inductors, capacitors) for power conversion. The increase in switching frequency allows a reduction in the size and weight of the aforementioned passive elements. However, this also leads to higher switching losses. Thus, resonant circuits and soft-switching methods are utilized. Two soft-switching techniques that are most widely adopted are Zero Current Switching (ZCS) and Zero Voltage Switching (ZVS). Finally, the control strategies applied to the converter aim at the fulfillment of the required battery charging strategy (i.e., constant current, constant voltage or a combination of both), being either current mode or voltage mode control.

2.2. Wireless Charging

Wireless charging is achieved with the presence of galvanic isolation between the input side and the output circuitry [35,36]. Nowadays, wireless charging is widely used in low-power applications such as the charging of home electronic appliances and several portable and wearable devices. The rapid development of power electronics, along with the expanded capabilities provided by improved semiconductor materials [37], lead to the increase in power levels that a wireless power transfer system can supply. As a result, this technology can be applied to EV charging. This charging method introduces certain advantages:

1. It offers an easy, safe and user-friendly charging process with low maintenance costs because of the absence of mechanical parts.
2. It eliminates any potential risk arising from the use of cables (e.g., use of worn cables in rainy or snowy weather conditions) by offering galvanic isolation between the vehicle and the power source.
3. There is the option to install the charging transmitter underground, which prevents exposure to inauspicious environmental conditions, thereby significantly increasing the charging infrastructure lifespan and avoiding the possibility of vandalism (charging cable theft, removing of other components, etc.).

The methods that enable Wireless Power Transfer (WPT) can be divided into two broad categories: far-field and near-field. The far-field methods are capable of transferring energy to considerable distances away from the transmitter, unlike the near-field technologies, the range of which is quite small. In Figure 3, all WPT technologies are listed. One of the far-field wireless charging techniques is Microwave Power Transfer (MPT), which utilizes frequencies in the microwave spectrum to transfer energy to the receiver. The microwave is generated by a magnetron (a vacuum tube that acts as an oscillator), passes through a waveguide and finally is radiated via a transmitting antenna. The receiver uses a rectenna (antenna and rectifier in the same device) to convert the microwave signal into a DC signal, which charges the EV battery [38,39].

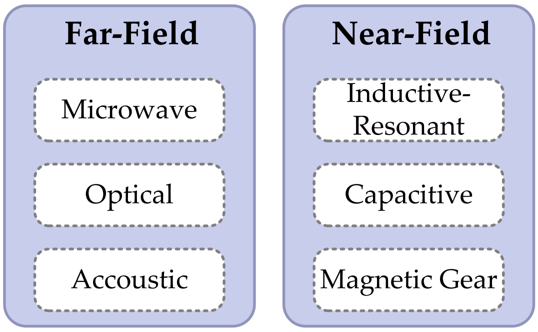


Figure 3. Categorization of WPT technologies.

Moreover, the optical WPT operates using waves in the terahertz range. A light beam is generated by a laser diode and is guided to the receiver. The receiver comprises photovoltaic cells, which convert the delivered electromagnetic energy into DC power [38,39]. The photovoltaic cell bandgap should be close to the light beam wavelength in order to minimize losses. Nevertheless, both of these technologies suffer from poor efficiency and low power levels. Furthermore, increasing the transferred power would entail bulky antennas and hazardous human exposure to radio frequencies in the first case, whilst in the second one, the high intensity of the light source may cause optical disturbances, or in extreme cases even blindness. In addition, optical WPT and MPT exclusively allow unidirectional power flow. Finally, the last far-field wireless charging method presented in this paper is the acoustic-based power transfer that uses frequency in the kilohertz range. As in the previous cases, a poor efficiency performance is achieved [24].

Among the near-field methods is the capacitive WPT. The capacitive method exploits a high-frequency electric field in the kilohertz or megahertz range, which is generated in the area between two capacitors. These capacitors are constructed between the transmitter and the receiver with two parallel plates, placed close to each other. Consequently, an induced current appears in the receiver, and the power is rectified and then delivered to the EV battery [38–40]. This technology has evolved over recent years, whereas there are some implementations reaching several kilowatts and gaps up to 300 mm [38]. However, the efficiency of the developed prototypes ranges between 50% and 80% [24], making it the second most efficient way to wirelessly transfer power. In parallel, the system requires very high operating voltages and can transfer power within smaller air gaps compared to those of inductive systems, and its efficiency is negatively affected by the parasitic capacitances of the vehicle.

Wireless charging via a magnetic gear system uses the interaction between two synchronized remote magnets as the main coupling mechanism [36]. Its operation is summarized as follows: A rotating base magnet driven by electricity from the grid causes the permanent magnet rotor of the transmitter to rotate. A voltage is induced to the winding of the receiver permanent magnet rotor, which now rotates synchronized with the transmitter. As a result, the receiver acts as a generator, feeding the vehicle battery, with the aid of a rectifier [41]. There are several issues that arise from the mechanical system components, the two major being the high maintenance needs and the noise produced. Additionally, the efficiency of this charging method is highly dependent on the alignment conditions.

2.2.1. Inductive Power Transfer

The last and most commonly used near-field WPT method is the inductive, i.e., energy transfer between loosely coupled coils, via magnetic induction. This technology is the most popular among the WPT methods and has reached commercial status for EV charging applications [24]. It can transfer significant amounts of power (up to 100 kW) over distances of a few tens of centimeters (i.e., distances comparable to the physical size of the coils) with high efficiency (90–95%) [39].

The operating principle of this WPT system is fairly straightforward. The primary circuit is powered with a time-varying current. According to Ampere's law, an alternating electromagnetic field is generated in the primary coil, which results in the induction of a voltage at the secondary coil, according to Faraday's law, and thus the flow of AC current in the receiver circuit [35]. In order to increase the system efficiency and compensate the magnetic flux leakage, the system is designed to operate under resonance conditions. Hence, circuits of passive elements are included in the overall system [39,42]. In this case, this method is also known as Coupled Magnetic Resonance (CMR)-based WPT [39,41,42]. Moreover, high switching frequencies are employed so as to increase the transferred power level. Consequently, its operation is similar to that of the typical transformer, with the important difference being the large air gap separating the two coils (loosely coupled coils). The coupling coefficient k of such a topology does not exceed the value of 0.6. As a matter of fact, typical values of k range from 0.1 (or even lower) to 0.4 [35].

The block diagram of a unidirectional inductive power transfer system is depicted in Figure 4 [43]. Its main components are the following:

1. Input single-phase or three-phase AC/DC converter;
2. DC/AC inverter;
3. Compensation networks;
4. Magnetic coupler;
5. Output AC/DC converter.

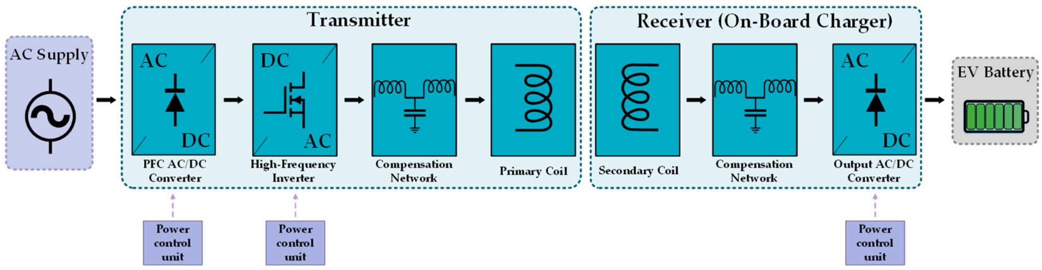


Figure 4. Block diagram of a unidirectional inductive charger.

The AC power drawn from the utility grid is rectified, and subsequently, with the aid of the inverter and the compensation network, a sinusoidal high-frequency current is supplied to the primary coil. PFC control schemes can be applied to the input rectifier for the mitigation of current harmonics. Furthermore, the high operating frequency leads to the employment of soft-switching methods, thereby reducing inverter switching losses. The conversion of the induced voltage at the secondary coil to a constant DC value, in order to charge the EV battery, is achieved via the output rectifier. An additional compensation network is placed on the secondary circuit to achieve the same operating frequency on both sides. It should be noted that the secondary side is installed inside the EV and constitutes the on-board charger.

The techniques used to adjust the system power flow can be applied on either the transmitter or the on-board charger. In the first case, power regulation is achieved by controlling the primary side converters. The most commonly adopted control schemes for the inverter are the frequency control strategy and the phase-shift modulation. The frequency control strategy is accomplished by varying the switching frequency above the resonance, in the inductive region of operation, so as to increase the inverter output impedance and decrease the injected power [44]. In phase-shift modulation, the phase difference between the pulses driving each converter leg is controlled at a constant switching frequency. In this way, the voltage across the coupling coil is regulated along with the power delivered to the vehicle. Alternatively, an additional DC/DC converter is connected to the PFC rectifier output, allowing the inverter input DC voltage to be adjusted. The applied control scheme of this converter could focus on impedance matching in order to improve the system efficiency [45]. Apparently, information on factors such as the charging current, the voltage across the EV battery and the SoC of the EV battery needs to be transmitted to the primary side controller for an effective charging process. Other key pieces of information are as follows: the power requirements (appropriate voltage and current values), the misalignment conditions (when the transmitter and receiver coils are not perfectly aligned with each other), ground clearance and foreign object detection [24]. This can be implemented using wireless near-field communication mechanisms based on various protocols such as Qi, Wi-Fi, Bluetooth, cellular and Zigbee [24,45–47]. When the control is applied on the on-board charger, either an active rectifier or a DC/DC converter connected to the rectifier output is utilized [48]. Moreover, various control strategies can be implemented for the converters of both sides.

2.2.2. Compensation Networks

The compensation circuits of the primary and secondary sides are an integral part of an inductive power transfer system. Their goal is to compensate for the effect of leakage inductances and thus maximize the efficiency and the system power transfer capability. These circuits are composed of passive elements (capacitors and/or inductors). In order to increase the energy transferred through the air gap, they must operate under resonant conditions. In particular, the purpose of the compensation circuit on the secondary side is to improve the system power transfer capability by matching the load impedance, reflected to the primary side, with the source impedance. The compensation network of the primary circuit is used to reduce the amount of reactive power that fluctuates in the system and thus to ensure power transfer under the unit power factor. Figure 5 illustrates the various topologies of compensation circuits used in WPT systems. Specifically, the Series–Series (SS), Series–Parallel (SP), Parallel–Series (PS) and Parallel–Parallel (PP) topologies, as well as topologies that contain more than one passive element, are depicted [24,49].

The design of the compensation topologies aims to attain specific objectives. These objectives are as follows: (a) the minimization of the reactive power in the resonant circuits; (b) a wide operating range under zero-current or zero-voltage conditions, for the reduction of switching losses [50]; (c) system stability, independent of load and coupling factor variations; (d) the design of a simple device with high efficiency, low cost and small size/weight. Apparently, a number of compromises and limitations must be considered when selecting the right configuration. For instance, in compensation topologies with multiple passive components, in order to lower the nominal voltage and current values of the capacitors as well as their corresponding stress, additional inductors are required. Furthermore, since the high-frequency inverter acts as a voltage source, parallel compensation in the primary circuit requires an additional series-connected coil for the inverter output current regulation [51]. This increases the size, overall cost and complexity of the topology. It may also lead to reduced efficiency due to the power losses of each additional element [50]. Moreover, when the parallel configuration is utilized, the capacitance value depends on the coupling factor, as well as the load type [39,42]. In contrast, series compensation in the primary circuit does not require any additional components, and the value of the primary capacitance does not depend on the variation of the coupling coefficient [52]. Additionally, when parallel compensation is connected in the secondary circuit, a capacitive reactance is reflected on the primary side, which also depends on the load value and type [35,39,42,50]. Particularly, the SP compensation topology requires higher capacitances to achieve better coupling, and therefore its maximum efficiency is reduced compared to that of the SS topology. In [51,52], the advantages, drawbacks and equations governing the operation of the various compensation schemes are thoroughly elaborated upon. In conclusion, the selection of the appropriate topology depends on the requirements of each application.

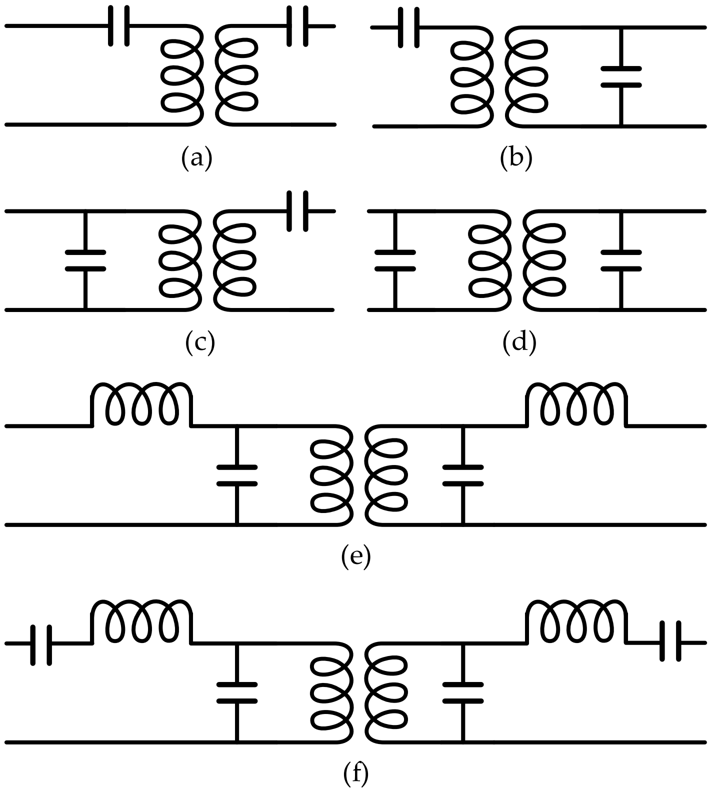


Figure 5. Compensation network topologies: (**a**) SS; (**b**) SP; (**c**) PS; (**d**) PP; (**e**) LCL; (**f**) CLCL [24].

2.2.3. Magnetic Couplers

The magnetic coupler is a component of major importance in a WPT system. It consists of the primary and secondary coils, which exchange power through an air gap. The desirable characteristics of a magnetic coupler are a high coupling coefficient and a high quality factor Q, since its efficiency is a function of these parameters, as well as relatively high tolerance to misalignment conditions [52]. The quality factor is the ratio between the frequency-dependent inductance and the resistance coil components. The higher the Q value at the operating frequency, the lower the copper losses. To increase the coupling factor, ferrite bars or plates are usually utilized. Indeed, ferrite components can improve the inductance value, as well as both the quality factor and the mutual inductance of magnetic couplers [49,52]. However, their excessive use can lead to an increase in system losses due to the modification of the magnetic field spatial distribution in the conductors. Furthermore, magnetic couplers are usually constructed using Litz wire (in order to reduce the skin effect losses and improve the quality factor) and include aluminum shielding to minimize the leakage field and avoid human exposure to high-frequency electromagnetic fields [53]. The misalignment (i.e., the displacement of the two coils) causes a decrease in the coupling coefficient k. As a result, the resonant operating frequency and power factor of the circuit, the voltage induced on the receiver and the overall power transfer capability are affected. In order to abate the impact that misalignment has on the charging procedure, certain coil structures are utilized.

A plethora of magnetic coupling topologies is documented in scientific literature. Based on the coil winding strategy, two types of lumped charge pads can be distinguished: (a) solenoid or double-sided flux couplers and (b) planar or single-sided flux couplers [54]. Planar couplers can be classified into two categories based on the flux path: (a) non-polarized couplers such as circular and rectangular geometries and (b) multi-coil polarized couplers such as Double D (DD), Bipolar Pad (BPP), Double D Quadrature (DDQ) and Quad

D Quadrature (QDQ) [24,54]. Non-polarized couplers produce vertical components of flux using a single coil, whereas PPs use multiple coils to produce vertical as well as horizontal components of flux [24]. In [54], a comparative analysis of the circular, rectangular, Double D Transmitter with Double D Receiver (DD-DD) and the Double D Transmitter with Double D Quadrature Receiver (DD-DDQ) topologies is carried out, with respect to their efficiencies, their tolerance to misalignment and their performance regarding stray field exposure. In [55], the coupling coefficients and the self and mutual inductances of a circular and rectangular coil transformer are compared. It is proved that polarized couplers such as DD-DD and DD-DDQ present more tolerance towards misalignment compared to circular and rectangular couplers, which perform better regarding the stray fields. Furthermore, couplers with sharp edges are not preferred due to increased eddy currents [24]. The assessment of both polarized and non-polarized charge pads conducted in [52] yields similar conclusions regarding the coupling coefficient, the misalignment tolerance and human exposure to high-frequency electromagnetic fields. Indeed, the selection of a suitable topology is subject to the application. In Figure 6, the most common magnetic coupler configurations are listed [24].

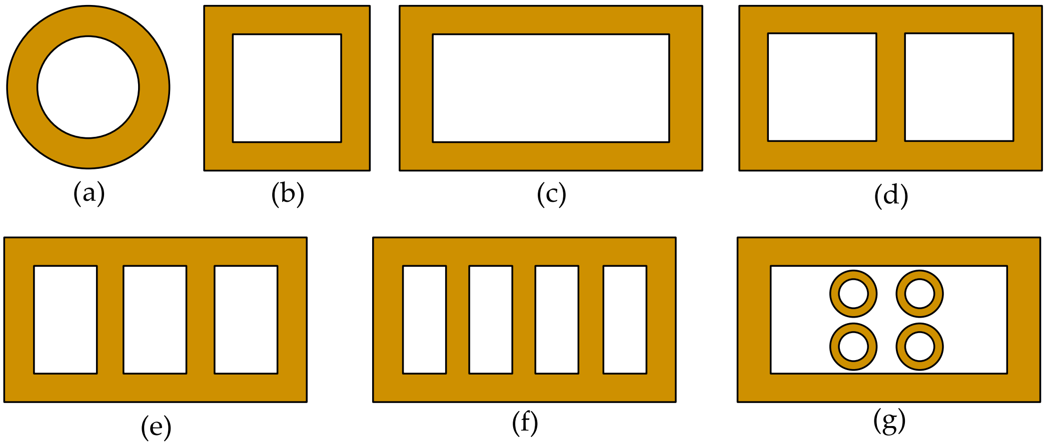


Figure 6. Magnetic coupler configurations: (**a**) circular; (**b**) square; (**c**) rectangular; (**d**) DD; (**e**) bipolar; (**f**) DDQ; (**g**) QDQ [24].

2.2.4. Inductive Charging Modes

There are three possible ways to implement wireless inductive charging of an EV. When Static Wireless Charging (SWC) mode is used, the vehicle is parked at a fixed place and remains stationary with its engine turned off until the charging process is completed. This is the most widely adopted method of wireless charging, whether in public or private stations. In terms of charging infrastructure and the required time for a full battery refill, this method is similar to the conventional conductive charging methods.

In recent years, a new concept called Quasi-Dynamic Wireless Charging (QDWC) has also emerged. Quasi-dynamic wireless charging occurs when the vehicle is stationary for a relatively long period of time but its engine is still running. For instance, public transport vehicles or private EVs can draw energy at stops while picking up passengers or at traffic lights, respectively [36,39,41]. An initiative already utilizing this way of wireless charging can be found in Mannheim, Germany, where electric public buses of the "63 route" are charged at stops along the route. This project is part of Bombardier's trial of their PRIMOVE inductive charging technology and aims to validate that a demanding passenger route can be operated by an electric bus without the need for scheduled recharges [56]. Last but not least, the Dynamic Wireless Charging (DWC) mode might be the most interesting yet challenging of the charging methods. It takes place while the vehicle is moving on the roadway [36,39,41].

The required infrastructure resembles the one of a static inductive power transfer system. The transmitter coil is embedded in the roadway, along with the required components that compose the primary circuit of a static inductive system. The secondary circuit is located inside the vehicle. Based on the transmitter coil configuration, dynamic wireless charging systems are distinguished into track-based and segmented transmitter array types [57]. In Figure 7, the two configurations are presented. Track-based applications use longer transmitter coils compared to the ones in the receiver and offer continuous power transfer to the moving vehicle. However, this leads to low efficiency due to the reduced coupling coefficient. On the other hand, segmented-based solutions utilize multiple transmitter coils of a size similar to that of the receiver. Even though the feature of individual control can increase system efficiency, challenges are still present. Specifically, the transmitters will not be equally loaded, as their currents depend on the corresponding receiver position. To address this issue, more complex control strategies have to be applied. Furthermore, the LCC resonant network is connected since the current in the primary side coil is independent of the load [58,59].

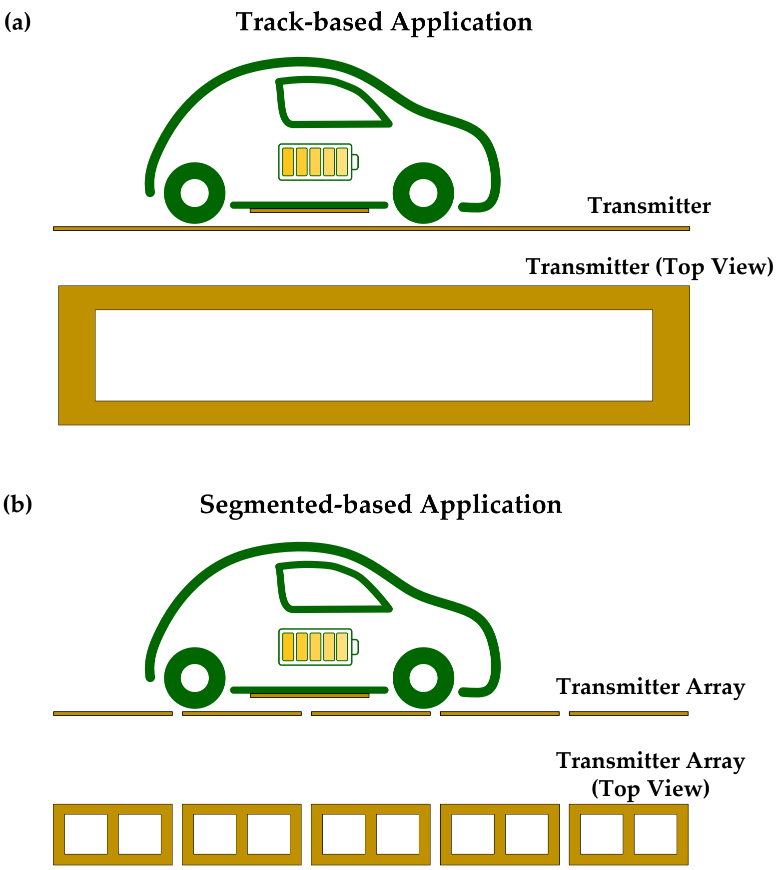


Figure 7. Transmitter coil configuration: (**a**) track-based; (**b**) segmented-based.

One additional challenge when implementing this configuration is the power supply scheme that needs to be used. It can be centralized, i.e., a central utility supplies all the segments simultaneously, or distributed, i.e., the utility supplies one coil at a time using switches [24]. Each technique has its advantages and corresponding drawbacks. The fact that the entire infrastructure must tolerate harsh weather conditions should also be considered during the design process. Finally, the rapid dynamics of this application must be taken into account when selecting the communication protocol used for data exchange between the transmitter and the receiver [24,45]. It has to provide low latency, increased communication range and the ability to communicate with multiple receivers simultaneously. Studies indicate that Dedicated Short-Range (DSRC) and cellular communications are the most suitable options [24]. Another alternative could be 5G due to its capability to transfer data at fast rates across multiple receivers.

There is no doubt that the DWC constitutes a challenging concept to implement. Undeniably, the significant capital investment required for the extensive roadway modifications is an additional burden [60]. Nevertheless, this charging method might be the most competent solution to the rise of EV penetration in the transportation sector. Since users can charge their EV continuously, this charging technique is capable of extending the limited cruising range and thereby contributing to the reduction of the EV battery size and weight. Some countries are already testing the feasibility of DWC. Two prime examples are the OLEV project in South Korea, which was initiated by the Korea Advanced Institute of Science and Technology (KAIST) [50,61], and the Victoria project in Spain [62]. Moreover, Electreon has launched two projects in Brescia, Italy, and Tel Aviv, Israel, employing dynamic EV charging. In Italy, a 1 km test trial was constructed, and both passenger EVs and electric buses are utilized in order to investigate the energy transmission from the roadway [63]. In Israel, a combination of quasi-dynamic and dynamic charging is applied [64]. Electric buses traveling along a 5 km route can charge while on the move via the 700 m power transmitter embedded in the roadway and whenever passengers are boarding the vehicle.

Indeed, wireless EV charging, even the simplest implementation of it (i.e., SWC), has not yet been accompanied by mature and widely accepted products. The challenges related to the large-scale deployment of wireless chargers are definitely not negligible. Apart from the technical difficulties that have been previously discussed in this work (i.e., dependency of the charger efficiency on misalignment conditions and air gap, the necessity of an on-board coil structure resulting in increased EV weight and possible modifications of its chassis in order to achieve electromagnetic immunity), there is additional burden regarding the significant cost of the required infrastructure, the interoperability between multiple automakers and EV charger manufacturers and the consolidation of universal guidelines [65]. Furthermore, the higher EV penetration level entails adverse consequences for the distribution grid stability, which will inevitably lead to the need for its reinforcement. The existing standards for wireless EV charging along with the impact that its establishment will have on the power system are analyzed in the next sections of this paper.

2.2.5. Charging Levels of Inductive WPT

In terms of power levels, wireless electric vehicle chargers are classified, according to SAE J2954 and IEC 61980, into four categories: Wireless Power Transfer 1 (WPT1) features the lowest power transfer level. The maximum input power of systems that fall under this category is equal to 3.7 kVA. According to SAE J2954, the minimum allowed efficiency is 85% and may be reduced to 80% when the primary and secondary sides are not perfectly aligned. WPT2 inductive charging systems can supply higher amounts of energy to the EV, with a maximum input power of 7.7 kVA, whereas WPT3 inductive chargers can draw 11.1 kVA from the utility grid. The restrictions on the minimum permitted efficiency, according to SAE J2954, are similar to those of WPT1. Finally, the WPT4 chargers feature a maximum input power of 22 kVA but are not fully defined by the established standards. The abovementioned categories refer exclusively to static inductive chargers and apply to both light-duty and heavy-duty EVs. There are still no developed standards for DWC.

The compatibility requirements between systems of different power levels are defined by SAE J2954 [42]. A WPT2 on-board charger must be compatible with WPT1 primary circuits and vice-versa. In addition, compatibility of WPT3 and WPT4 wireless power transfer systems with systems of lower power levels is considered desirable. The permitted operating frequency range of commercially available chargers is 79–90 kHz, with a central operating frequency of 85 kHz. Moreover, the distance between the primary and secondary coil, i.e., the air gap, is classified into three classes ("Z" classes), as shown in Table 3.

Table 3. Summary of the SAE J2954 standard recommendations [35,42].

Maximum Input Power Level	Z-Class (Distance in mm from the Surface of the Secondary Coil to the Ground Level)	Frequency Range
WPT1 3.7 kVA WPT2 7.7 kVA WPT3 11.1 kVA WPT4 22 kVA	Z1 100–150 Z2 140–210 Z3 170–250	85 kHz center oper-ating frequency with a frequency range of 7–90 kHz

Finally, it is worth noting that there is a third, alternative way to charge an EV, known as battery swapping. It is based on switching out the depleted battery with a similar, fully charged one [4,25,66]. By employing this method, the need for long holdups in charging stations is limited, and thereby the range anxiety is eased. Additionally, the bulky power converters deployed for EV charging are no longer necessary, since the battery is charged outside the vehicle. Nevertheless, there are some obstacles that restrict the application of this charging technique. Its deployment demands a universal battery interface between the different EV manufacturers. This means that battery manufacturers would have to share any new revelation regarding the battery design. The aforementioned, along with the fact that the EV owners' acceptance of not owning a battery and having to switch to a battery of unsure state is required, are the main drawbacks of this method [67].

3. Integration of EVs and the Internet of Energy (IoE) Framework

3.1. Charging Techniques

The charging of EVs can be implemented in either a controlled or an uncontrolled way [11,12,14–16]. When uncontrolled charging is used, EV batteries either start charging immediately when plugged in or start after a user-defined delay and continue charging until they are fully charged or disconnected. No integration strategy is performed. This charging method, although simple, constitutes a potential problem for the utility grid since it leads to an increase in the peak power demand and causes voltage deviations and overloads to the distribution transformers and lines. Consequently, the higher the EV penetration level is, the lower the grid reliability becomes, and inevitably grid reinforcement will be mandatory.

On the other hand, controlled charging enables the scheduling of charging profiles. The goal of this method is the mitigation of the negative impact of EV integration into the electrical grids (i.e., the increase in load demand, the potential overloading of system component capacity, voltage and frequency imbalances, excessive harmonic distortion and power losses) in order to ensure the stability of the distribution grid and retard the need for its reinforcement [11,12,14–16]. Undeniably, important parameters in establishing this charging method are the EV users' convenience and the economic benefits that should be provided for their cooperation.

Probably the simplest indirectly controlled charging method is the off-peak charging that economically encourages the charging of EVs during a specific time of the day when the grid load is minimal. This passive technique contributes to the flattening of the overall demand profile, but it may produce a sudden load increase at specific grid areas if there is not sufficient spatial dispersion of the charging points. Moreover, the willingness of customers is assumed.

When active load control strategies are employed, i.e., scheduling to draw power at times of low grid demand ("valley filling"), reducing peak energy demand ("peak shaving"), providing ancillary services (primary or secondary frequency control, voltage regulation, reactive power compensation, spinning reserve services) or facilitating the integration of Renewable Energy Sources (RESs), the intermittent behavior of which prevents them from accommodating the base load, this charging type is considered smart [14,15,25]. When the first two operations are implemented, the network operator communicates with the EV (directly or through aggregators) so that its charging rate is throttled or maintained. In this case, the EV battery is exclusively handled as a flexible electric load from the grid, and unidirectional power flow between them is sufficient.

However, the application of the latter operation entails bidirectional power flow. The bidirectional Vehicle-to-Grid (V2G) concept serves as an extension to smart charging, and even though it is complicated to implement, it constitutes the most competent offset method of the aforementioned drawbacks of EV integration [14,15,25]. This technology enables energy injection from the EV to the utility grid. In parallel, it introduces challenges regarding EV battery degradation due to the more frequent charging/discharging cycles and the higher investment costs needed for the hardware (installation of bidirectional power converters) and software (utilization of advanced communication mechanisms and control algorithms) infrastructure upgrade. In addition, the adoption of this technology requires the offer of appealing benefits to EV users in order to address their potential hesitation to exchange energy with the grid.

In [17], a review of simulation-based case studies performed in various regions (where an increase in peak load is observed due to the uncontrolled EV integration at different penetration levels) is summarized. Additionally, the model used for grid impact assessment and the results obtained by utilizing smart charging strategies are also reviewed.

Smart charging can be implemented using several control algorithms to fulfill different objectives. For their realization, an entity capable of decision making is needed. This entity is called the aggregator, and it acts as an interface between the grid and the EVs. Depending on the functions executed by the aggregator, the smart charging control architectures can be categorized into centralized and decentralized [14–16].

The decision-making procedure in the centralized control scheme relies on the aggregator. It is responsible for both the technical and market operation of the charging infrastructure, i.e., regulating the charging profiles of the EVs under its region and managing their participation in the electricity market. Hence, it has to perform daily demand forecasts based on historical data, user preferences, etc., to be accepted or denied by the distribution grid operator as well as power purchase bids directly in the intraday market or through a utility [15]. Subsequently, the transmission system operator evaluates the demand profile, and charging setpoints are issued for each aggregated charging station according to the operator assessment and the commitments made with the electricity market. Furthermore, the aggregator can benefit from the energy provided by the EV batteries by participating in the ancillary services market. To achieve the abovementioned purposes, the aggregator collects data from each EV (battery SoC, charging preferences, EV identification, etc.) and executes an algorithm that aims to fulfill a certain goal while not compromising the EV user's needs. This goal could be the maximization of aggregator profits, the minimization of deviations between the demand profile expected by the aggregator and the real-time power demand of EVs, or the reduction of generation costs or power losses in the grid. In Figure 8, the block diagram of a generic centralized control architecture is depicted.

On the contrary, in the decentralized control scheme, the EV owner is actively involved in the decision-making process. Specifically, each EV aims to minimize the cost of charge, considering user preferences without the obligatory sending of sensitive private information to external entities [15]. The only way that the aggregator influences the on-going charging is by providing real-time information on the electricity prices. This technique features less computational burden and is more focused on user convenience. Nevertheless, it should be noted that bidirectional information flow is required and the EVs must acquire some intelligence [15] in order to perform the needed instructions. The block diagram of the decentralized control architecture is illustrated in Figure 9.

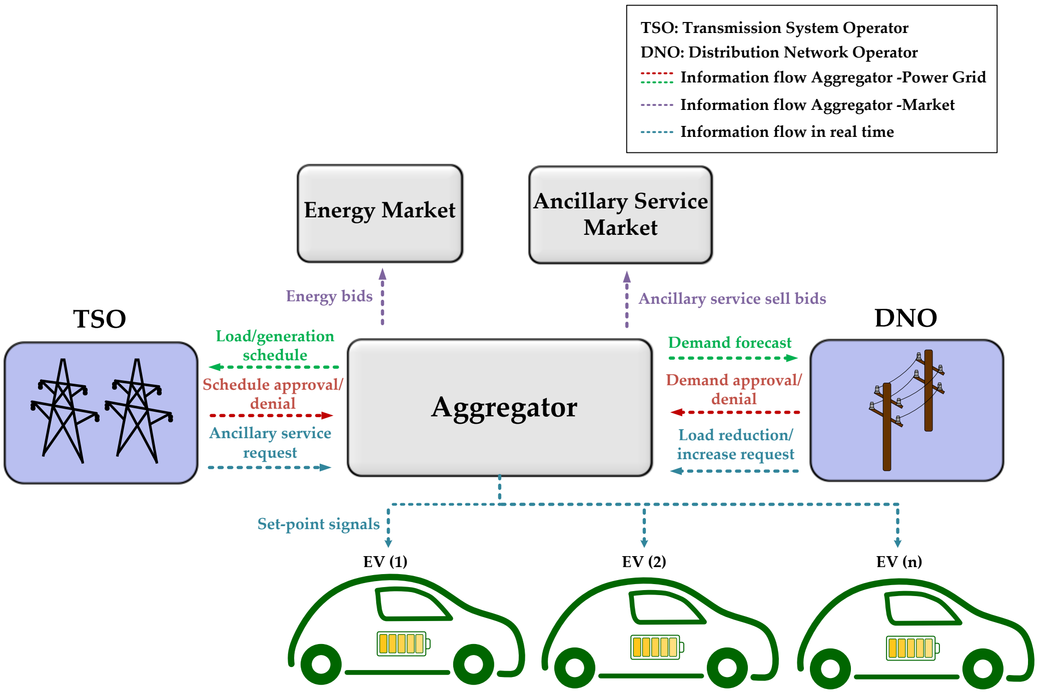


Figure 8. Centralized control architecture of EV charging [15].

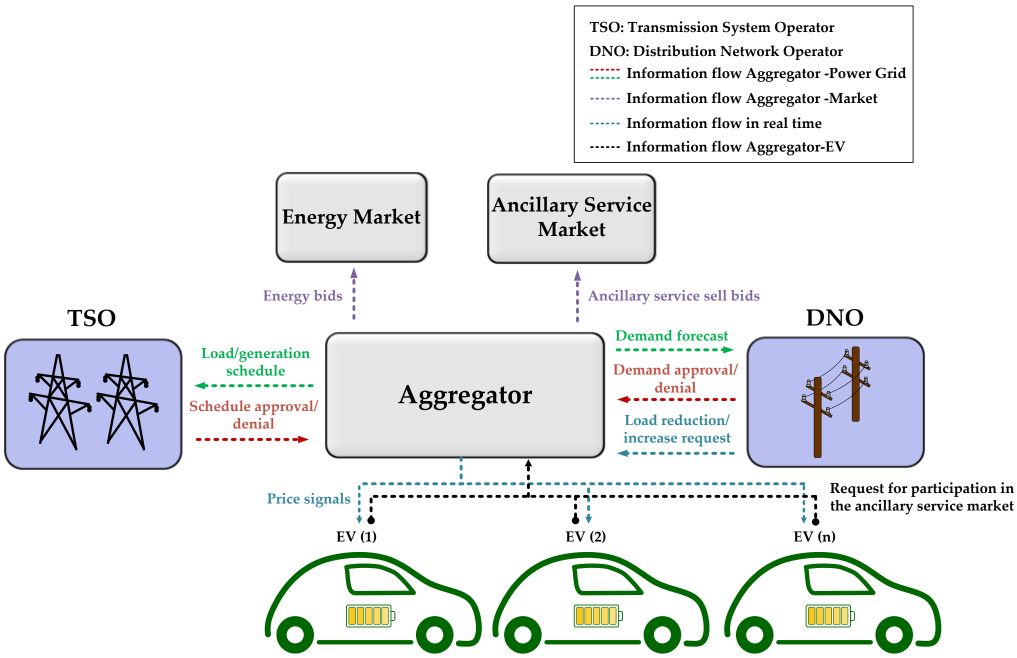


Figure 9. Decentralized control architecture of EV charging [15].

In [14,16], full summaries of the control algorithms applied in both schemes are featured. The objective and the constraints that define each computational method are presented. Moreover, in [68], the main optimization techniques to achieve different V2G services are elaborated upon.

In [69], a hierarchical control system design that is not fully centralized or fully decentralized is discussed. In Figure 10, its block diagram is presented. The decision-making process, along with the computational load, is distributed to multiple aggregators through a tree-like communication structure. Each aggregator decides the charge schedule and set-point of each vehicle connected under its region or sends information signals to moderate the charging profiles of a wider EV group, while influencing the decisions of the other aggregators. Similar to the decentralized control scheme, this architecture divides an optimization problem into a set of subproblems of a much smaller scale that is locally solved by several EVs and/or aggregators. However, both of these techniques are still in the early stages of research and are not widely implemented.

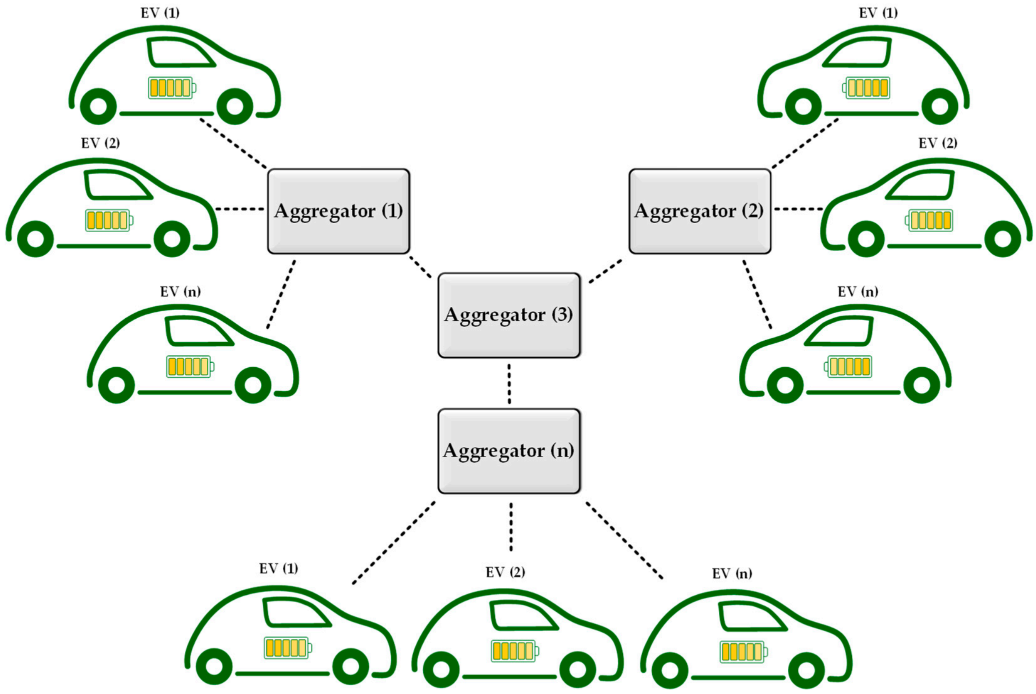


Figure 10. Hierarchical control architecture of EV charging [13,69].

Nowadays, the strategy employed by most utilities is the uncontrolled charging method. Alternatively, a passive strategy, mainly the dual tariff strategy or "Time of Use" (TOU) pricing, is implemented. EV users are motivated by financial incentives to shift their consumption to low-demand hours, when the price of electricity is low, e.g., during the night [5,28,70]. Nevertheless, the desirable results, i.e., the smoothing of the demand profile, may not be obtained via dual tariff charging schemes, since the peak load will simply appear at a different hour of the day. Moreover, EVs mostly constitute an electric load for the distribution grid, since the V2G concept is not yet extensively adopted [5]. In the next section, the current process followed during the charging transaction and the communication protocols used are described.

3.2. Charging Procedure and Communication Protocols

The charging process of an EV involves various interrelated actors, such as charge point operators, e-mobility service providers and roaming hubs [71]. The charging point operator is a party that operates the charging infrastructure from an operational and technical point of view, i.e., access control, management, data collection, repair, etc. Concurrently, it might be engaged in commercial activities, since it is capable of purchasing electricity on the supply market and selling charging services [72]. The e-mobility service provider is a party that sells e-mobility services to e-mobility customers. Its main obligation is to enable access to charging stations controlled by different Charging Station Operators (CSOs). It may also provide other services (charging station location, monitoring of availability of charging slots, charging reservation, etc.). These services are usually accessible by the EV driver via smart mobile applications developed by the e-mobility provider. Lastly, the roaming hub (or clearing house) is a global platform responsible for the organization and processing of data exchanged between the CSOs and e-mobility operators so that flexible access to charging stations of different CSOs is permitted to e-mobility customers of any e-mobility service provider. The successful operation of the charging process requires communication between all these entities. Depending on the business model adopted by a given country for the deployment of publicly accessible charging infrastructure, one party could play multiple roles [72,73]. For instance, an e-mobility service provider could also own and operate a charging station.

The EV communicates with the charging station through the pilot terminals discussed previously in this work, using the International Organization for Standardization (ISO)/IEC 15118 standard [25,71,74,75]. The ISO/IEC 15118 is the most recommended communication standard for this purpose [76]. The data exchanged relate to the EV battery SoC, the allowed charging power, customer identification, etc.

Charging Station Management Software (CSMS), i.e., the back-end system of a charge station operator, often uses the Open Charge Point Protocol (OCPP) to control the charging process remotely, via the internet [75,77]. OCPP is an open standard based on the WebSocket communication protocol. It is the industry-supported de facto standard for communication between the charging station and the CSMS and accommodates both charging techniques (AC and DC) [75]. Via OCPP, the charging stations can communicate with the CSMS, thereby enabling the management of charging points. Simultaneously, the CSMS communicates with the mobile application in order to reserve or cancel charging slots and inform EV users about the status of their vehicle during the charging process.

Specifically, when the EV is connected to the charging point, the user interacts with the charger using various customer authorization options (RFID (Radio Frequency Identification) card/token, ISO 15118-1 Plug and Charge, payment terminals, local mechanical key, smart phones, etc.). The CSMS sends messages to the charging station to be displayed to the user, regarding the transaction, the language to be used, the applicable tariff before the EV driver starts charging, the running cost and the estimated end-time of a charging transaction [75]. When the authorization stage is completed, the CSMS proceeds with the unlocking of the specific charging point connector. The central system can fully control the charging process and monitor the recharge status of each EV. It also enables the payment procedure [74]. To achieve the aforementioned functions, it utilizes a database that contains information regarding the available charging points, the registered users and the billing process. The revised version of the OCPP protocol allows the CSMS to provide different schedules with their corresponding tariffs to the user. Thus, end users can choose the desired service according to their preferences (TOU pricing).

The smart mobile applications deployed by the e-mobility service providers act as an interface between the EV users and the CSMS. In this way, the user is informed about the charging power injected into their EV, the estimated end-time and the cost for a full charge, not only through the charging slot screen but also remotely through their mobile device. Moreover, they are capable of fully controlling the payment process. In parallel, since the CSMS enables the charge point reservation or cancellation using user identification tags and the availability verification of the charging slots, the user can monitor the free chargers in their region in real time and reserve them [74]. Additionally, some applications feature navigation services. Consequently, they truly contribute to an efficient and user-friendly experience.

Furthermore, in order for an EV driver to have access to public charging stations that are not operated by the e-mobility service provider with whom they have a contract, the Open Charge Point Interface Protocol (OCPI) roaming protocol is primarily used [78]. Via OCPI, the needed information is exchanged between the two service providers who either have a contractual agreement or use a roaming hub for the accommodation of all EV users. For users without contracts, most charging point operators allow a direct payment procedure at their stations. In Figure 11, the communication protocols utilized during the charging procedure are depicted.

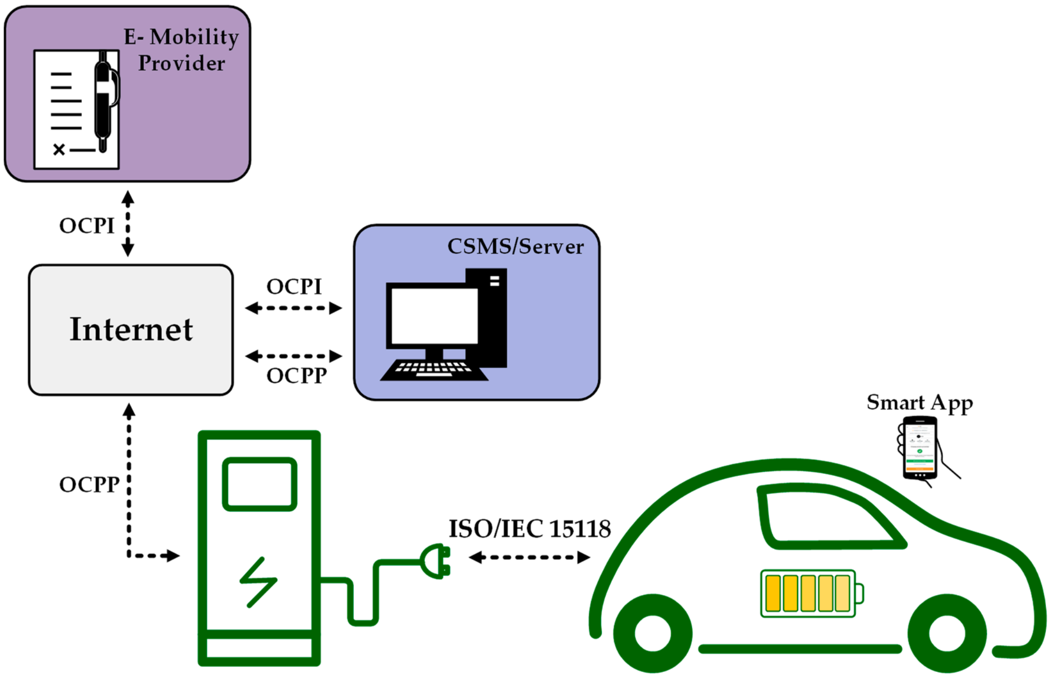


Figure 11. Communication protocols used during the charging procedure.

3.3. IoE Framework

In the future, the power system structure and its communication network will drastically differ from its current framework. A decentralized configuration, known as a smart grid or Internet of Energy (IoE), will replace the conventional centralized power generation, thereby modifying the way that electric energy and information are transferred and distributed between the power system and the end users. Additionally, small and large dispersed renewable energy plants will constitute the primary energy source [16], whilst industrial and domestic consumers will be able to not only draw but also provide power to the grid (prosumers) [14,16]. Concurrently, IoE seeks to unify the power, transportation, gas and thermal networks into one entity. In this entity, energy exchange will occur between a wide variety of sources and loads, including renewable energy sources, distributed energy storage, thermal systems, EVs and prosumers [16,79,80]. In other words, in the IoE framework, the number of large-scale power plants is reduced, the power generation from renewable sources is considerably increased, each participant (energy device/storage) can either sell or consume energy and is connected to the physical power system in a plug-and-play manner (just like how a computer detects and starts communicating with a USB device) without the need of any reengineering [14,16]. Whether the participant will source or absorb power depends on the current condition of the grid, the equilibrium between local power generation and electricity consumption and individual benefit/profit.

Therefore, a power system of such infrastructure requires the deployment of a robust and efficient Energy Management System (EMS), whose primary goal is to monitor and control the power interactions between the multiple components/participants so as to ensure the reliability and system flexibility and to optimize the profit of producers and customers [14,16]. In particular, in the IoE framework, all power generators, prosumers, storage systems, etc., of a certain region coordinate with neighboring devices along with a local controller, thereby enabling a decentralized control scheme. All the involved participants exchange energy with each other utilizing bidirectional power converters. Moreover, for the management and coordination of the energy flow, data need to be transferred between the adjacent entities and the controller via the internet.

The communication network of the IoE is based on an internet-like information flow also known as IoT [14,81,82] which allows two-way data exchange between devices. The communication infrastructure can be wireline, wireless or a combination of both. Consequently, each IoE entity acquires some intelligence accompanying the needed equipment (sensors, smart meters, actuators, processing units, communication modules, etc.) in order to receive, process and broadcast information. The main aim is for each component connected to the IoE to attain decision-making capabilities and communicate with other devices. It is worth noting that the communication systems used should be reliable and enhance the connectivity between devices. In [76,81,83], a comprehensive review of the communication systems that could be used in a future smart grid is performed. Moreover, in [79], a comparison between the structure and functionalities of the IoE concept and the present-day distributed computing and internet infrastructure is conducted, and the similarities of their overall operation are highlighted. In Figure 12, the architecture of the IoE framework is presented.

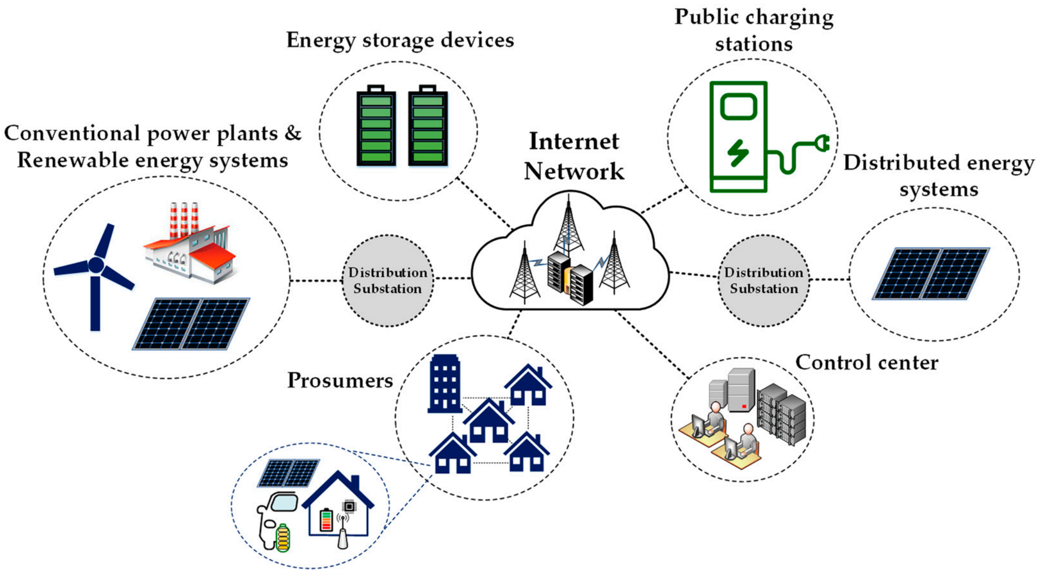


Figure 12. Architecture of the IoE framework [13,15,77].

In this context, the improved real-time monitoring and control of the grid that defines the IoE framework facilitates flexible EV integration. The active load control strategies discussed previously in this paper can be implemented with the aid of the advanced communication network. The scheduling of the charging profiles and the real-time regulation of the charging rate according to the regulatory and operational grid limitations are technically feasible. Hence, demand profile flattening is enabled. Furthermore, EVs constitute an integral part of this decentralized power system structure due to their ability to stabilize the intermittent behavior of renewable energy systems, their dual role as flexible electrical loads and dispatchable power sources and their capability to abruptly connect and disconnect (plug-and-play interface). In summary, the grid handles the EV battery as an essential energy source that can provide ancillary services and contribute to the balancing between generation and consumption. Thus, the V2G technology truly resonates with the IoE framework.

Additionally, the concept of Connected Mobility (CM) can evolve further in the future smart grid. CM deals with the communication between an EV and a roadside base station, passenger, traffic signal, another EV, etc. [16]. In an IoT-based network, the improved connectivity of devices and the increased utilization of smart equipment (advanced sensors, embedded processing and communication modules, etc.) especially in EVs facilitate their ability to process and exchange data with their surroundings. Consequently, information such as speed, position, temperature and SoC of the battery and status of the different EV compartments/systems can be collected. These data could be applied to traffic management for the reduction of traffic congestion and holdups. Furthermore, the EV user can be informed about their vehicle's condition and whether it requires charging and/or maintenance [8]. As a result, CM can improve the driving experience, safety and comfort.

In addition, it promotes vehicle development towards autonomous vehicles and their corresponding advantages (lower accident rates, passenger comfort, etc.) [16]. An autonomous or self-driving vehicle can drive itself without any human interaction, employing sophisticated sensors (ultrasonic, GPS, radar, LiDAR, cameras, etc.) and control schemes [84]. It can decide the traveling route, identify environmental changes and adapt the speed and position of the vehicle in order to maintain lane control and safe following distance on the road and to reach the desired destination. The expanded deployment of such vehicles will also facilitate the establishment of wireless charging (a fully autonomous EV should also charge without any human interference). In fact, at the 2022 Beijing Winter Olympics, autonomous vehicles including shuttle buses, freight trucks and road sweepers were tested, proving that the advancement of the communication infrastructure enables the utilization of self-driving EVs [85,86].

4. Discussion and Future Outlook of EV Charging

The continuous increase in EV sales provides strong evidence of the constant improvement in charging infrastructure. Over the recent years, the deployment of high-voltage off-board DC chargers equipped with sophisticated power electronic devices (characterized by greater power density and efficiency) has allowed higher quantities of charging power, whilst keeping the current values and the corresponding stress of grid and charger components confined. Hence, the required holdup time for a full recharge has been significantly decreased [21], and it will decrease even more, thanks to the forthcoming advancements in semiconductor and battery technology. Nevertheless, several issues regarding the impact of EV charging on the power system still remain. For the time being, there are no globally established standards, so regulations vary depending on the given country. As for wireless charging, its commercialization is not yet achieved. Its benefits, with the unplugged charging transaction being the most prominent, are undeniable. Additionally, the implementation of the QDWC and DWC concepts will facilitate the reduction of the needed battery capacity, thereby eliminating range anxiety. However, along with its technical obstacles (system efficiency drop due to misalignment conditions, increased EV weight due to on-board coil structure, etc.) and the absence of common practices, wireless charging is an additional burden for the distribution grid; this is due to its uncontrolled integration strategy that is utilized, nowadays, by most utilities. What is more, the first attempts at smart charging employment (i.e., the dual tariff strategy) do not sufficiently mitigate the drawbacks of EV integration. Apparently, EV commercialization will eventually lead to an intelligent grid featuring information broadcasting and real-time power flow regulation capabilities. In this way, the implementation of smart charging techniques and concepts such as V2G, QDWC and DWC will be enabled. Furthermore, the imminent mass integration of EVs and the corresponding energy demand rise will enforce the further exploitation of RESs, since the decarbonization of the transportation sector calls for an increase in the production of zero-carbon electricity [7].

5. Conclusions

In this paper, the current status of both the conductive and wireless EV charging infrastructure has been reviewed. The operation principles governing the conductive and contactless (wireless) charging of an EV battery, the various components and power conversion units utilized for their realization and the associated charging standards have been thoroughly elaborated upon. Furthermore, this work aimed to investigate the mass integration of EVs into established and future power systems. The burden accompanying the increase in the EV penetration level and the several integration methods that can be implemented have been presented in detail. Finally, has been concluded that the shift from the modern-day grid to a decentralized structure along with an evolved communication network will facilitate the penetration of EVs, as they will constitute a valuable asset in the future. The progress of smart charging techniques and the further exploitation of V2G and CM technologies will showcase the attributes of EVs.

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Abbreviations

AC	Alternating Current
BEV(s)	Battery Electric Vehicle(s)
BMS	Battery Management System
BPP	Bipolar Pad
CAN	Controller Area Network
CHAdeMO	Charge de Move
CM	Connected Mobility
CMR	Coupled Magnetic Resonance
CP	Control Pilot
CS	Connection Switch
CSMS	Charging Station Management Software
CSO(s)	Charging Station Operator(s)
DC	Direct Current
DD	Double D
DDQ	Double D Quadrature
DSRC	Dedicated Short-Range Communication
DWC	Dynamic Wireless Charging
EMS	Energy Management System
EV(s)	Electric Vehicle(s)
FCEV(s)	Fuel Cell Electric Vehicle(s)
GHG	Greenhouse Gas
GND	Ground
HGV(s)	Heavy Goods Vehicle(s)
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IoE	Internet of Energy
IoT	Internet of Things
ISO	International Organization for Standardization
KAIST	Korea Advanced Institute of Science and Technology
MPT	Microwave Power Transfer
N	Neutral
NC	Not Connected

NEV(s)	Non-Emission Vehicle(s)
OCPI	Open Charge Point Interface Protocol
OCPP	Open Charge Point Protocol
PD	Proximity Detection
PE	Protective Earth
PHEV(s)	Plug-in Hybrid Electric Vehicle(s)
PFC	Power Factor Correction
PLC	Power Line Communication
PLL	Phase-Locked Loop
PP	Parallel–Parallel
PP	Proximity Pilot
PS	Parallel–Series
QDQ	Quad D Quadrature
QDWC	Quasi-Dynamic Wireless Charging
RES	Renewable Energy Source
RFID	Radio Frequency Identification
SAE	Society of Automotive Engineering
SoC	State of Charge
SP	Series–Parallel
SS	Series–Series
SWC	Static Wireless Charging
TOU	Time of Use
USA	United States of America
V2G	Vehicle-to-Grid
WPT	Wireless Power Transfer
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching

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