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Chapter

Vehicle Electrification: Technologies, Challenges, and a Global Perspective for Smart Grids

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Abstract

Nowadays, due to economic and climate concerns, the private transportation sector is shifting for the vehicle electrification. For this new reality, new challenges about operation modes are emerging, demanding a cooperative and dynamic operation with the power grid, guaranteeing a stable integration without omitting the power quality. Besides, new attractive and complementary technologies are offered by the vehicle electrification in the context of smart grids, valid for both on board and off board systems. In this perspective, this book chapter presents a global perspective and deals with challenges for the vehicle electrification, covering the key technologies toward a sustainable future. Among others, the flowing topics are covered: (1) Overview of battery charging systems, including on board and off board systems; (2) State of the art of communication technologies for application in the context of vehicular electrification, smart grids and smart homes; (3) Challenges and opportunities concerning wireless power transfer with bidirectional interface to the electrical grid; (4) Future perspectives about bidirectional power transfer between electric vehicles (vehicle to vehicle operation mode); (5) Unified technologies, allowing to combine functionalities of a bidirectional interface with the electrical grid and motor driver based on a single system; and (6) Smart grids and smart homes scenarios and accessible opportunities about operation modes.

Keywords: vehicle electrification, smart grids, smart homes, communication technologies, wireless power transfer, renewable energy sources, power quality, power electronics, energy storage systems

1. Introduction

Nowadays, the transport sector is responsible by 33% of final energy consumption in the 28 countries of the European Union (EU28), where road transports represent about 82%, contributing to about 27% of the total final energy consumed in EU28 [1]. Associated with this consumption is the emission of greenhouse gases for the atmosphere, contributing for the global warming, as well as for deteriorate living conditions on the planet. Indeed, the environmental problems are affecting

the societies around the world, obliging to change the paradigm targeting moderating the greenhouse gas emissions [2, 3] Globally, the transports sector contributes in 26% for the final energy consumption and 13.1% for the total CO_2 emissions [4], and in particular, contributed nearly 21% of the EU total emissions of CO_2 [5]. As a contribution to overcome this paradigm, the vehicle electrification (electric and hybrid electric vehicles) is pointed-out by many specialists as a prominent solution to reduce the CO_2 emissions [6–8] and to support the future transportation sector [9–11]. From the different solutions offered by the vehicle electrification, plug-in electric vehicles (EV) and plug-in hybrid EV are particularly interesting due to the capacity to be charged directly from the electrical grid. In fact, the changing of paradigm for the electric mobility is already underway and the global sales of EV reached the 174,000 units in the first trimester of 2018 with a consistent growing of about 67% by year. In terms of geographic distribution, China leads the sales of EV followed by United States and Japan, and by Norway and Germany in the EU [12]. The global sales of plug-in EVs reached 2.1 million units in 2018, growing 64% in relation to 2017 [13]. At the end of 2018, the global fleet of plug-in EVs reaches the mark of 5.4 million [13].

Also as a complement to revolutionize this paradigm change, new technologies are appearing targeting a common harmonious objective for the smart grids [14]: decrease of greenhouse gas emissions. Thereby, besides electric mobility, other technologies are influent for the same purpose, as renewable energy sources (RES) and energy storage systems (ESS), at residential or industrial level, strategic installed as support of the electrical power grid [15–19] These three technologies are accepted as elementary pillars for a profound and exciting revolution of paradigm toward, each more, smart grids as well as smart homes, where the developments in the industrial and electronics field are indispensable [20–23]. Additionally, based on the presence of vehicle electrification, RES, and ESS when engaged with smart grids and smart homes, further advances in the field of information and communication technologies are welcome, where the Internet of Things (IoT) concept appears as a key contribution to help to obtain an autonomous, dynamic, and flexible electrical grid [24–27].

Analyzing the introduction and maturation of RES along the last decades, especially the imposition offered by wind and solar, the power production from these sources has grown expressively, signifying a vital input for enhancing the power management and the energy necessities, both at residential and industrial level. In an ample perception, it is clear that the involvement of RES represents a positive effect for disseminating the new paradigm of smart grids [28]. This is also valid from the point of view of a microgrid, where the planned distribution of RES also represents a pertinent participation for an optimal power control process in smart grids [29]. Nonetheless, RES has a disadvantage that cannot be solved by itself: the dependence on weather conditions that is reflected in the intermittent power production. In this way, the inclusion of ESS technologies is indispensable to establish a support between the power production and consumption in collaboration with the necessities of the electrical grid (more precisely, for instance, the necessities of smart homes). In this context of using ESS to balance the power production and consumption, it is established an efficient engagement of unpredictable power production from RES, flexible storage, and controlled or uncontrolled power consumption. This is valid for the existing status and for the future viewpoints encompassing large-scale of RES with the intrinsic irregular and unpredictable power production [30], as well as taking into account the user demand profile for optimizing the power consumption exclusively from RES [31]. Although the investigated control methodologies to deal with the power production from RES, the

presence of ESS offers new possibilities of power management, also requiring dedicated control methodologies [32].

The vehicle electrification is also recognized as vital for a cooperation control between RES and ESS [33, 34], supporting the reduction of energy costs and greenhouse gas emissions and commit for a cooperative power optimization [35–40]. This cooperative scenario is pertinent when framed with smart grids and also with smart homes [41–44], where the scheduling uncertainties of the EV is also an issue that must be considered, targeting to enhance the grid performance [45–48]. Moreover, advanced topologies for simplifying and unifying RES and EVs are also fundamental [49].

Despite the advantages of the vehicle electrification for the smart grids, its impact on the electrical grid operation is of utmost importance and must be handled properly [50–53]. An on-line adaptive strategy for coordinating the EV parking schedules, in the perspective of maintaining the operability of the electrical grid, as well as the user convenience, is proposed in [54]. Similarly, an approach to minimize the peak loads of the electrical grid and the EV charging costs at the same time is proposed in [55] for a coordinated integration of the vehicle electrification. Concerning the analysis about the impact of the vehicle electrification in electrical grids, exemplification research works developed around the world are presented, respectively, in [56–60], for the Australia, Canada, China, Sweden, and Portuguese cases.

As the title specifies, this chapter deals with challenges and a global perspective of the vehicle electrification in smart grids. Contextualizing the above-mentioned subjects, this chapter incorporates contributions and overviews in the following fields: Section 2 introduces the different structures concerning the internal constitution of an EV battery charger (EVBC) in terms of power stages, as well as its principle of operation; Section 3 summarizes the main communication technologies for the vehicle electrification, establishing different perspectives in smart grids and smart homes; Section 4 presents a global overview about challenges and opportunities of wireless power transfer in the perspective of the vehicle electrification; Section 5 discusses the relevance and the future perspectives about a direct or an indirect bidirectional power transfer between EVs, operation denominated as vehicle-to-vehicle; Section 6 introduces unified technologies for the vehicle electrification, permitting to combine the functionalities of an EVBC and a motor driver in a single equipment; Section 7 contextualizes the operation modes for the vehicle electrification and presents a set of opportunities offered for future scenarios of smart grids and smart homes. The book chapter is finalized with Section 8, where are presented the main conclusions according to each section.

2. EV battery chargers: an analysis of the principle of operation and of the power stages

An EV battery charger (EVBC) is classified either as on-board or as off-board, depending if it is installed inside or outside the EV, respectively. Regardless the on-board or off-board concept, internally, an EVBC incorporates power electronics converters with the respective control system. **Figure 1** illustrates an EVBC in its conventional structure, organized by two power stages: an ac-dc front-end interfacing the electrical grid and controlled by a current feedback; and a dc-dc back-end interfacing the EV battery and controlled by a voltage or a current feedback. The presented variables are the main required for a closed-loop control. This figure also shows the signals for the power stages. Although there are two distinct power

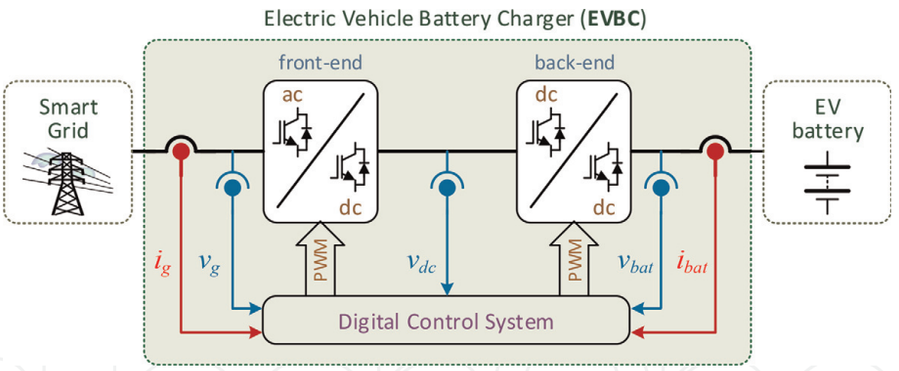


Figure 1.
EVBC constituted by two power stages (a front-end and a back-end, respectively, to interface the electrical grid and the EV battery) and by a common control system.

stages, each one with a specific strategy to ensure that current and voltage are precisely controlled, the control system should be viewed as a whole, since both power stages are linked by a dc-link. This is crucial to emphasize since, for example, the grid-side current of the front-end power stage is controlled according to the voltage and current levels of the battery-side of the back-end power stage. This means that the amplitude of the grid-side current is a function of the charging power in the battery-side. Therefore, a global power theory for the EVBC is applied for determining the reference of current for the front-end power stage [61, 62]. On the other hand, the reference of voltage or current for the back-end power stage is determined by the battery management system (BMS) [63, 64]. Based on the established references, individual and dedicated control strategies are applied for each power stage, basically, to determine the status of the switching devices during each control period [65–67] Besides the aforementioned low-level control requirements for both power stages (in terms of the switching devices), a communication platform, within the whole control system, is essential for establishing a bidirectional communication with the smart grid or smart home. The different technologies for the communication, as well as the functionalities framed with the EVBC, are analyzed in Section 2.

The conventional structure of an EVBC is based on two power stages, regardless the on-board or off-board concepts and the topology [68–70] Nevertheless, other structures are possible, for example, by combining these two concepts for an EVBC (this means that an EVBC can be constituted by an off-board power stage and by an on-board power stage) or a structure based on a single power stage. Analyzing the power stages in more detail, different arrangements are possible, for instance, based on multilevel structures [71–74] interleaved topologies [75, 76], and with or without galvanic isolation [77, 78] Independently of the arrangement, high-levels of power quality concerning low harmonic distortion, high power factor, and balanced currents (in the case of three-phase EVBC) must be guaranteed [79]. Similarly, a voltage and a current with low-ripple must be guaranteed for the battery-side in the perspective to preserve the battery lifetime. **Figure 2** shows the possible structures that can be implemented for an EVBC, highlighting on-board and off-board concepts, as well as power stages encompassing galvanic isolation.

Figure 3 illustrates an EV with the two possibilities of interfacing the electrical grid: an on-board and an off-board. As demonstrated, the power stages permit a bidirectional power flow, from the electrical grid to the EV and vice-versa. This possibility is denominated as grid-to-vehicle (G2V) or, in reverse, denominated as vehicle-to-grid (V2G). Dedicated control algorithms are responsible for controlling the EVBC in one of these modes, where the power management is accomplished by the smart grid or by the smart home. Moreover, the EV user has also some privileges

(for instance, financial incentives) when allowing the EV operation in a flexible controllability of G2V/V2G modes, but without ignoring the information provided by the BMS.

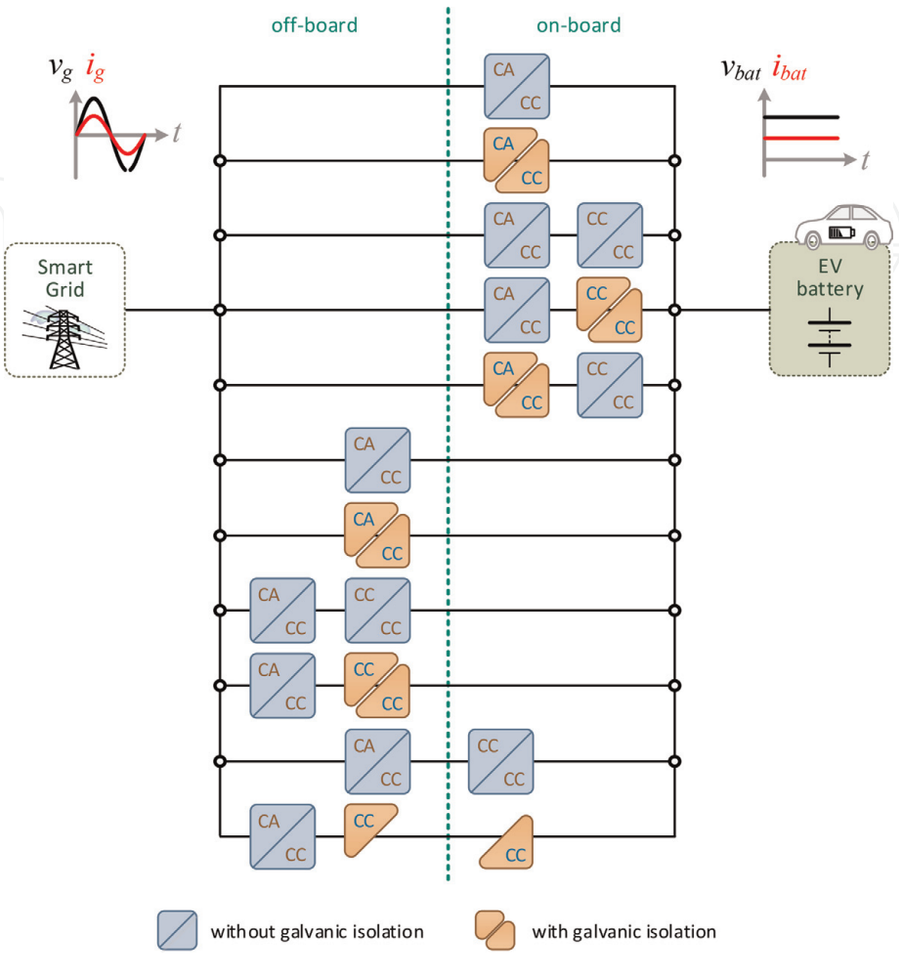


Figure 2.
Possible structures that can be implemented in EVBC, highlighting on-board and off-board concepts, as well as power stages encompassing a galvanic isolation.

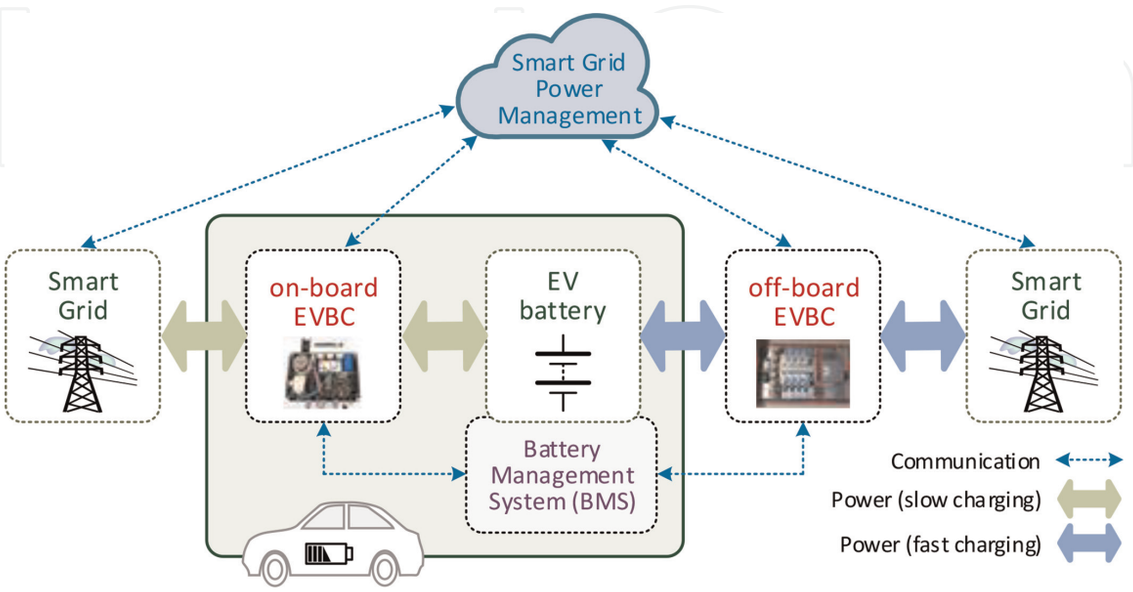


Figure 3.
EV interface (through an on-board and an off-board EVBC) with the smart grid, and establishing bidirectional communication and bidirectional power flow.

The same way as for an on-board EVBC, and also permitting a bidirectional exchange of active power from the electrical grid to the EV and vice-versa, is the operation of an off-board EVBC. Moreover, in terms of controllability, the same principle is applied by combining the requirements and benefits of the EV user, the battery BMS, the smart grid, and the smart home.

3. Communication technologies for vehicle electrification

This section presents an overview of communication network standards in the context of vehicle electrification. A communication network is a communication system that enables bidirectional communication between the multiple devices that are part of the network (called nodes). This is in contrast with broadcast communication systems (e.g., TV and radio), which only allow communication on one direction (from the station to the users' devices), and with bidirectional point-to-point communication systems, which only allow communication between two devices. In order to be able to communicate, the network nodes must use the same protocols. In this sense, the use of standard network technologies and protocols is normally preferable due to criteria such as compatibility, variety of choice and cost. The term "network" may apply to a set of nodes that exchange data using a specific network technology and its respective protocols (e.g., Wi-Fi or Ethernet) or may be used in a broader sense to refer to a communication system that interconnects devices that communicate using different networks technologies and protocols (e.g., the Internet). Most of the traffic on the Internet (e.g., audio, video, and data files) is produced and consumed by humans. In contrast, the concept of IoT [80, 81] extends the use of the Internet for the exchange of data generated, processed, stored, and analyzed by devices, either autonomously or with the participation of the users. Given the relevance of the IoT for vehicle electrification and smart grids [82], the communication technologies presented in this section are framed in the scope of the IoT.

3.1 IoT architecture

The IoT paradigm is also being deployed in several other contexts and applications areas, including different industry sectors [83, 84], smart cities [85, 86], and healthcare [87, 88]. Besides data communication, an IoT system has to perform a multitude of other tasks. Therefore, it is useful to organize these tasks in an IoT architecture composed of different layers. Several authors proposed different architectures [80, 84, 89, 90], but there is not yet a consensus regarding a reference model. A basic proposal that is suitable for this chapter divides the IoT architecture in three layers: sensing, network, and application.

The sensing layer is mainly responsible for collecting data from the physical world using sensors. These sensors are integrated in electronic devices (sensor nodes). These nodes include other hardware components [91] that are essential for the proper operation of the device in the context of the IoT, such as: (i) a communication transceiver, which needs to be compliant with the specific network technology used by the device; (ii) a processing unit, which executes the software for the higher network layers, as well as application-specific code; and (iii) a power source, which may be a battery or an ac power supply (when available), depending on the application requirements. Some devices of this layer may also integrate actuators, which perform an opposite role compared to sensors, acting on the physical world based on the received data. The sensing layer may also be called as perception layer [92, 93] or objects layer [80].

The network layer provides the interconnection between the sensing layer and the application layer. This layer normally is composed of multiple types of communication networks, which form the communication infrastructure used for the exchange of information between the different types of devices that are part of the IoT. An overview of relevant network standards is provided in the next subsection. This layer also handles other IoT tasks, such as data storage and cloud computing [92]. In this sense, several IoT cloud platforms [94] are currently available, as well as cloud computing platforms from major players that also provide IoT services, such as Amazon Web Services (AWS), Google Cloud Platform, Microsoft Azure, and IBM Bluemix.

The application layer is the higher level of the IoT architecture. This layer provides specific services for the users based on the data collected by the sensing layer. These services include the automation of processes, using application-specific control algorithms designed in the scope of this layer. In the context of vehicle electrification applications, one example is the EVBC control, inside a smart home, based on the measurement of the total instantaneous home current, in order to avoid the tripping of the main circuit breaker [95]. The services that may be performed by this layer include also the provision of a user interface through an IoT client device, to allow the user to interact with the IoT system [96]. This layer also includes data-mining algorithms [97, 98].

3.2 Network standards

The devices that are part of an IoT system may range from multiple distributed sensor nodes, at the lower level, to centralized cloud computing servers, at the higher level. These devices present different requirements and capabilities in terms of data rate, energy consumption, processing power, connectivity, etc. For example, many applications require the deployment of several low-cost wireless sensor nodes to collect relevant data [99]. Without cables, the sensor node has to resort to a battery as its power source; therefore, it is normally designed to operate with very low energy consumption, in order to maximize its lifetime. Typically, these nodes also require low data rate and offer low processing power. On the other hand, a cloud server normally requires a high data rate wired connection and machines with high processing power and high energy consumption to handle the data collected from multiple devices. Therefore, the network layer of the IoT architecture requires different network technologies, organized hierarchically from lower to higher levels, in order to satisfy the requirements of its different IoT devices.

Wireless networks may operate in unlicensed or licensed frequency bands. The unlicensed bands were reserved originally for radiofrequency (RF) emissions of industrial, scientific, and medical (ISM) equipment for purposes not associated with communications (e.g., microwave ovens). Nowadays, ISM bands are used by short range wireless networks such as ZigBee, Bluetooth, and Wi-Fi, as well as some low power wide area networks (LPWAN), such as LoRa. The main advantage of ISM bands is that they can be used without a government license. On the other hand, they may be subjected to interference from other wireless communication devices and ISM equipment. Normally, there are multiple channels in these bands, so the network devices may select channels with less interference for operation. The main ISM bands currently used by wireless networks are the 433 MHz, 900 MHz, 2.4 GHz, and 5 GHz bands, but the first two are not available worldwide. Higher frequency bands tend to have more bandwidth available, which means that the wireless networks may offer higher data rates. On the other hand, lower frequency bands allow longer range. The channels in licensed frequency bands are normally sold by the government to operators, which offer their services to their users (e.g.,

mobile cellular network operators). These channels suffer less interference due to exclusive allocation to a single operator. However, the use of these wireless networks normally has costs to the user.

Wireless networks may also be classified according to their range. In this sense, short-range networks include personal area networks (PAN) and local area networks (LAN), whereas long-range networks include wide area networks (WAN). Wireless PAN (WPAN) standards [100] that are suitable for IoT include ZigBee [101], Bluetooth Low Energy [102].

The two lower layers of the ZigBee protocol stack, physical (PHY) and medium access control (MAC), are defined by the IEEE 802.15.4 low power and low data rate WPAN standard [103]. The PHY layer uses direct sequence spread spectrum (DSSS) and offers PHY data rates up to 250 kbps. There are 16 channels in the 2.4 GHz ISM band, available worldwide, as well as 11 channels in the 868/915 MHz bands, but these are available only in some regions of the world. The MAC layer is based on a CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) algorithm. ZigBee defines three types of nodes: coordinator, router, and end-device. The ZigBee coordinator starts the network formation and selects the communication channel, among other tasks. It may also perform the same tasks of ZigBee routers, which include routing of packets between nodes and allowing other nodes to join the network. The ZigBee end devices are located at the extremities of the network, which means that they cannot route packets. On the other hand, the end devices may sleep to save energy, making them suitable for battery-operated sensor devices. Although the direct range of ZigBee devices is limited to dozens of meters, the support of multi-hop mesh topology (**Figure 4a**) allows increasing the network range. ZigBee can also operate in star topology (**Figure 4b**), which is the topology normally used also by most of the other wireless networks, such as Bluetooth, Wi-Fi, and mobile cellular networks. In [104], the authors discuss the use of ZigBee and other wireless technologies in the context of intelligent transportation systems (ITS).

Bluetooth low energy (BLE) was introduced in the Bluetooth 4.0 specification. It operates in the 2.4 GHz ISM band using frequency hopping spread spectrum (FHSS). The original standard provides a PHY data rate of 1 Mbps. The MAC protocol is based on a master-slave polling mechanism. BLE was developed for use in low power wireless devices, such as battery-operated sensor nodes. BLE is not

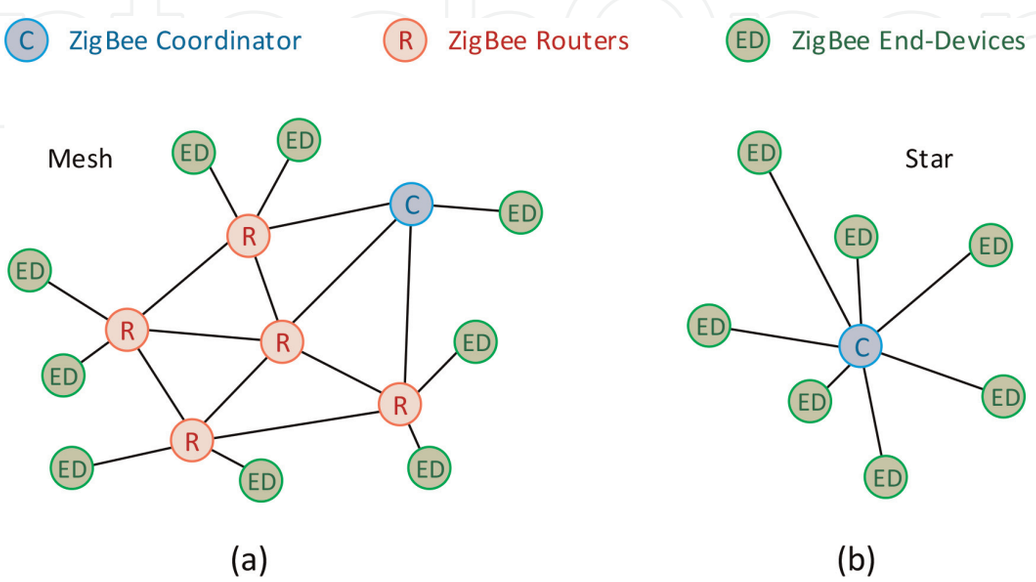


Figure 4.
Main ZigBee topologies: (a) mesh (multi-hop); (b) star (single-hop).

compatible with classic bluetooth, which continues to be offered for other applications (e.g., audio transmission). The new Bluetooth 5.0 specification introduces improvements in terms of data rate and range, among others [105]. BLE was designed to operate in star topology, but there are proposals to increase its range though the use of BLE mesh networks [106]. In [107], the authors present the development and test of a BLE network for wireless monitoring and control of parameters associated to the battery and traction systems of an EV.

WLAN technologies normally provide longer range and much higher data rate than WPANs, but they also tend to have higher power consumption. Although there were other WLAN alternatives in the past, such as high performance radio LAN type 2 (HIPERLAN/2), the WLAN market nowadays is dominated by Wi-Fi products. Similarly to ZigBee, the PHY and MAC layers of Wi-Fi networks are defined by IEEE standards, in this case, of the IEEE 802.11 family [108]. The original IEEE 802.11 standard defined PHY data rates of 1 and 2 Mbps in the 2.4 GHz ISM band. The IEEE 802.11b amendment increased the maximum data rate to 11 Mbps. IEEE 802.11a/g/n/ac/ax amendments extended the operation to the 5 GHz band and increased significantly the data rate, through the use of wider channels and higher-order modulation techniques. Several other amendments were specified, with improvements in other areas. For example, IEEE 802.11p defines enhancements to support vehicular networks [109], in the scope of ITS, including vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication and operating in specially allocated licensed ITS bands at 5.9 GHz.

Concerning wired network technologies, some alternatives available to provide local area communication in the context of IoT systems are IEEE 802.3/Ethernet [110, 111] standard and power line communication (PLC) technologies [112, 113].

When longer ranges than the ones provided by WPANs and WLANs are needed and the data rate requirements are low, the use of a low power wide area networks (LP-WAN) [114], such as LoRa [115], Sigfox [116], or Narrowband IoT (NB-IoT) [117] may be considered a better alternative. In [118], the authors propose an EV charging architecture based on the use of LoRa networks.

WPANs and WLANs are normally only suitable to provide local communication from sensor nodes to a nearby base station (e.g., Wi-Fi access point, ZigBee coordinator, or BLE master). One example is the use of these wireless network technologies for indoor communication inside a smart home. Therefore, it is also necessary to use other communication technologies to transfer the collected data from the base station to the IoT servers through the Internet, using appropriate wired and/or wireless wide area networks (WAN). Normally, this connection is provided by an Internet service provider (ISP) operator, using digital subscriber line (DSL) over twisted pair, coaxial cable, or fiber optic. An alternative is the use of cellular network technologies.

3.3 Higher layer protocols and gateways

Communication networks are normally structured into five protocol layers: physical, data link (or MAC, in wireless networks), network, transport, and application [119]. In order to communicate directly with other devices on the Internet, a sensor device needs to implement the higher layer protocols of the Internet protocol suite. This means that the device needs to implement Internet Protocol (IP), at the network layer (either IPv4 or IPv6). At the transport layer, there are two main options: transmission control protocol (TCP) or user datagram protocol (UDP). TCP provides error correction through retransmissions, whereas UDP is a lightweight transport protocol that provides only error detection, which means that error correction mechanisms have to be provided by other layers if required.

Application layer protocols include hypertext transfer protocol (HTTP), message queuing telemetry transport (MQTT), and constrained application protocol (CoAP) [120]. While HTTP is widely used on conventional Internet applications, MQTT and CoAP are lightweight protocols more suitable for IoT applications.

These higher layer (network, transport, and application) protocols are normally implemented in Wi-Fi devices, together with the specific PHY and MAC lower layer layers specified by the IEEE 802.11 standards [121], allowing seamless communication in IoT applications, as well as the sharing of the Wi-Fi network with the conventional Internet traffic. In contrast, IEEE 802.15.4/ZigBee and BLE implement their own higher layer protocols, which are optimized for low power devices and not directly compatible with the Internet protocol suite. The 6LoWPAN protocol, which compresses the IPv6 header to make it more suitable for low power wireless networks [122], was designed to enable direct connection of IEEE 802.15.4 networks to the Internet.

An alternative to allow the integration of these WPAN devices into the IoT is the use of a gateway device to translate the packets exchanged between the WPAN and the Internet. The same gateway may also be used to provide other functionalities, such as: a local database; a controller node, running automation algorithms associated to the IoT application; a security firewall, monitoring and controlling the communications in order to protect the WPAN devices from malicious attacks [96]; or a MQTT broker. An example of a BLE/Wi-Fi gateway implementation based on a Raspberry Pi 3, which also acts as local database, is provided in [123]. In some applications, it may also be interesting to use a smartphone as a gateway, especially in mobility scenarios. An example is described in [124], where a smartphone is used to provide connection between the nodes of a BLE-based intra-vehicular wireless sensor network (IVWSN) and a Google Firebase database using 4G and Wi-Fi.

3.4 Related work

As discussed before, there are many types of communication technologies that can be selected, based on their characteristics (such as communication range, transmission data rate, energy consumption, data transmission costs, mobility, etc.), to provide a suitable communication infrastructure for a particular application scenario. This section provides guidelines and examples of how these communication technologies can be used in the context of vehicle electrification applications.

The G2V/V2G collaboration for the smart grid reliability, analyzed in the perspective of communication is presented in [125], where an extension to the IEC 61850–7-420 standard is proposed as a support for coordinating the EV in G2V/V2G modes in terms of an information model.

In the perspective of the EV integration into smart grids, bidirectional communication between the EV and roadside units (V2I) is also fundamental. In this context, simulations and a comparative analysis in terms of communication performance between the EV and roadside units are conducted in [126], where wireless communications technologies as ZigBee, Wi-Fi, and Worldwide Interoperability for Microwave Access (WiMAX) [127], were considered. In the comparison, the results were mainly focused on the doppler effect and the end-to-end delay, taking into account the requirements of the IEC 61850 and the IEEE 1609 WAVE standards.

The integration of V2I and V2G communication with smart grid components such as CSs using different information models based on the IEEE 1609WAVE and IEC 61850 standards is investigated in [128]. The assessment is based on the evaluation of the end-to-end delay over diverse vehicular ad-hoc network protocols.

Simulation results show that the protocols with lower overhead are able to achieve better performance.

As demonstrated in [129], the IEC 61850 communication standard can also be used for the energy management (EM) of EVs in microgrids, based on smart algorithms for the G2V/V2G modes and distinct modes (as example, valley mode, steep hump mode, flat and low hump mode). The proposed method is based on the extensible messaging presence protocol (XMPP), and its mapping to the service models is demonstrated as a solution for the energy management problem, providing network security and scalability.

A IEC61850-based communication system, in the perspective of the power management within a smart home with an EV in G2V/V2G mode and with RES (PV in this case), is proposed in [130], where the management structure is supported by the estimation of the RES production and the EV battery state-of-charge. The communication messages were transmitted by means of different wired and wireless communication technologies, and the presented results demonstrate that the delays are within the limitations imposed by IEC 61850 standard.

4. Vehicle electrification: a comprehensive perspective of wireless charging systems

EVs need electricity to run their motors. This electricity either can be supplied by an on-board battery, which must be periodically recharged from the electrical grid, or can be directly obtained from a continuous over time connection to the power grid itself. Variations around this classification can be made, as electric energy can be generated, for instance, by a thermic engine installed on-board of a hybrid vehicle, or it can be delivered to the vehicle by an off-grid power plant. The point is that electricity either can be originated from an energy source or storage that is co-installed on board of the vehicle, or can be delivered by a stationary power plant, which is external to the vehicle, as shown in **Table 1**. In the first case lie almost all passenger cars so far seen in the market, whereas in the second case are trains and trams, which are energized either by rails or overhead wires and, commonly, ride on tracks. The tracks mechanically restrict the lateral displacement of the vehicle, what helps keeping the alignment of the vehicle to the electrified rail or the overhead line, an essential condition for the power transfer to occur. A vehicle with a self-contained energy storage will still normally need external electrification, at least during the stationary charging cycle.

Until very recently, the only way for an EV to get its battery recharged was by wired transference of electric energy, that is, by galvanic contact. If for some safety reason galvanic isolation, between the EV and the electrical grid is required, an isolating transformer should be employed in the charging station. After wireless power transfer (WPT) advances have entered the market of cell-phone recharging and small, low-power, home electrical appliances, the automotive industry is now the major target: The recent development of WPT technologies now make it possible to obtain stationary EV charging stations without cables or any galvanic

Vehicle kinematics	Self-contained energy storage	External electrification
Vehicle immobilized	Idle/standby charging	Stationary charging
Vehicle in movement	Discharging/in-march charging	Dynamic electrification/charging

Table 1.
Types of vehicle electrification.

electric contact between the EV and the charging unit, which can be hidden underneath the floor surface. This is now gaining commercial status and, in the near future, many units are expected to be seen (or more precisely, not seen, for they can be concealed in the floor) in garages and parking lots.

A novel WPT-based system for the vehicle electrification with an active power of 11 kW is presented in [131], where special reflections were considered for the misalignment between the WPT: primary coil (off-board the EV) and secondary coil (on-board the EV). A 10-kW WPT prototype dedicated for EVs is proposed and validated in [132], obtaining an efficiency of 94%. In a global perspective, an analysis of the state-of-the-art of WPT technologies, as well as a review of industrial projects under development, is presented in [133]. An overview about WPT technologies, as an influence for a sustainable mobility, is offered in [134], including sustainable performance, technical progresses, and applications of WPT. Complete overviews concerning WPT technologies focusing in electric mobility applications are presented in [135–137].

There are also multiple ongoing research efforts to make WPT a viable technology choice for dynamic electrification. Currently, built prototypes of electrified pathways are capable of sustaining 20 kW of electric power dynamically delivered to a moving vehicle on a 100 m long road segment [138]. However, even with the great advances in materials and power electronics, the technology is still expensive and not fully engineered to large-scale applications.

In this section, the principles of wireless power transfer and some of its automotive applications mostly focusing charging systems are reported, pointing out new achievements in the field.

4.1 Wireless power transfer

The application of WPT technology is reported to have been envisioned far behind, in late nineteenth century, by Nikola Tesla. WPT is based on two phenomena relating magnetism and electricity. The first was discovered by Hans Christian Ørsted in 1820 and theorized by André-Marie Ampère shortly after [139], and consists in the creation of magnetic field by electric currents. The second, the induction of electric by varying magnetic fields and the existence of mutual induction between two windings magnetically coupled, was later demonstrated by experimentation and theorized by Faraday [140], in a sequence of experiments starting in 1831. These results were later integrated in a treatise by Maxwell [141], which was later simplified by Oliver Heaviside to what is currently known as the Maxwell's Equations [142].

The applications of Maxwell's Equations to magnetically coupled coils lead to simplified models of transformers that were extensively proved by experimentation and that can effectively allow the calculation of energy transfer over these entities with circuit theory. In this way, the behavior of magnetically coupled coils, as shown in **Figure 5**, under harmonic excitation at a low enough frequency (so that the system can be considered not to irradiate energy) and negligible resistive losses, is well described by the simplified transformer model in **Figure 5** and the complex Eqs. (1) and (2).

$$V_1 = jwL_1.I_1 + jwM.I_2 \tag{1}$$

$$V_2 = jwL_2.I_2 + jwM.I_1 \tag{2}$$

The power P transferred over the two magnetically coupled coils is then given by (3):

$$P = V_{M_2}. - I_2^* = -jwM.I_1.I_2^*, \quad w = 2\pi f \tag{3}$$

From (3), it can be inferred that the power wirelessly transferred through the coils is proportional to the working frequency f, to the mutual inductance M, and the RMS currents $|I_1|$ and $|I_2|$. But, the power also depends on the relative phase between currents I_1 and I_2: If they are either in phase or in counter-phase (180° apart), no real power is exchanged between primary and secondary, only reactive power being involved. For I_1 and I_2 of fixed module, the transferred power from primary coil to secondary coil is maximized when these currents are 90° out of phase (4):

$$I_2 = -j.I_1 \tag{4}$$

In order to adjust the intensity of primary and secondary currents I_1 and I_2 and keep them as close as 90° as possible, so that condition (4) is observed, impedance compensation circuits should be added to the primary and secondary coils, as in **Figure 6a**. One of the possibly simplest compensation circuits, and the first to be used in Tesla's experiments, is the pure series capacitive compensation. The configuration derived when series capacitive compensation is employed in both primary and secondary, is called the series-series (SS) impedance compensation, shown in **Figure 6b**.

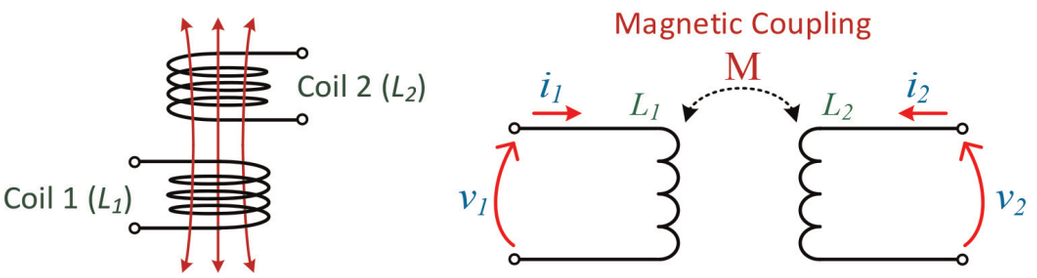


Figure 5.
Magnetically coupled coils and the equivalent transformer model in circuit theory.

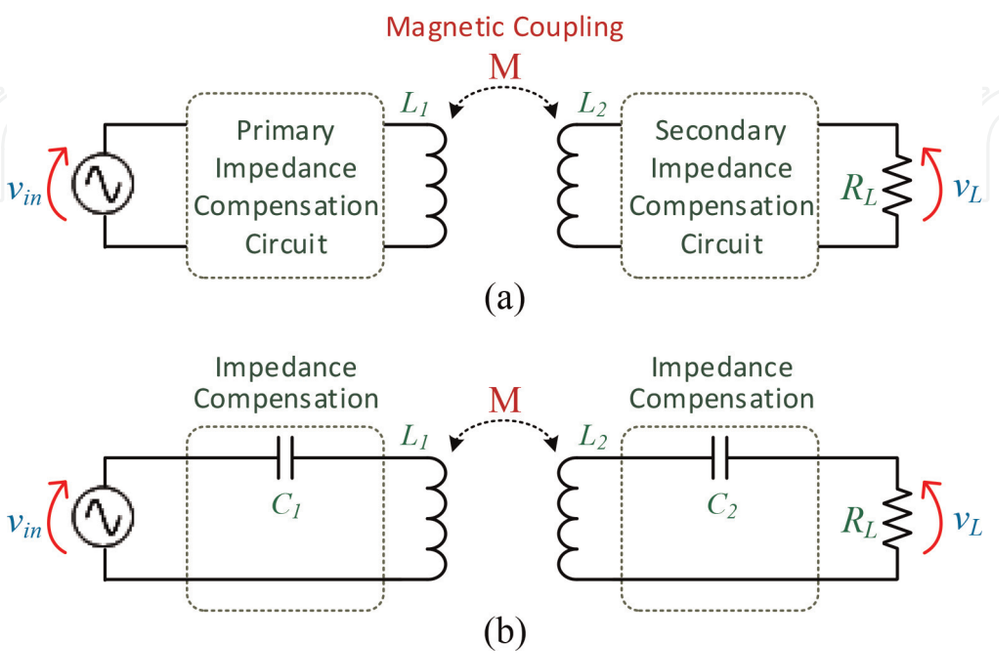


Figure 6.
Basic WPT configuration: (a) exemplified with the series-series (SS) impedance; (b) impedance compensation.

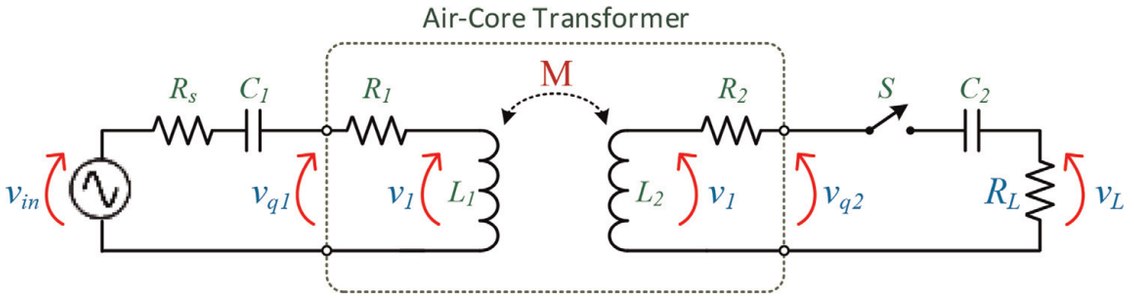


Figure 7.
Simplified circuit analysis for the SS-compensated WPT.

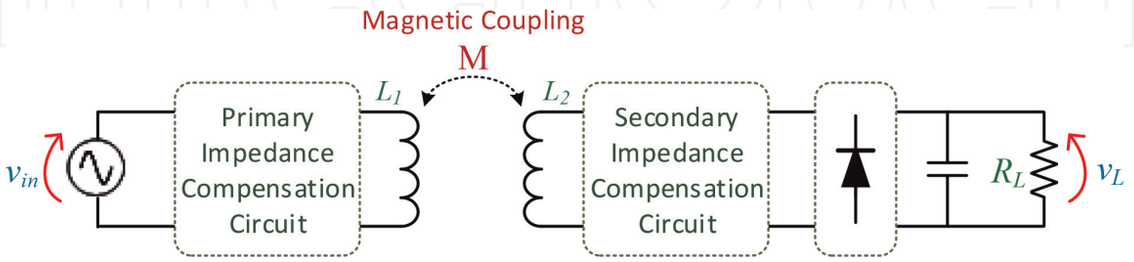


Figure 8.
Basic fixed gap WPT schema for dc load, with voltage rectification in the secondary.

The model in **Figure 5** is too simplified because no power losses in the winding or elsewhere are considered. When using the SS compensation in WPT the improved model that is still simple and is still able to represent the losses in windings of the primary and secondary coils is shown in **Figure 7**.

In this circuit, R_1 and R_2 are respectively the total series resistance of the capacitor and the inductor, in primary and secondary circuits, R_s is the impedance of the power source exciting the primary circuit and R_L is the load consuming the net power transferred to the secondary circuit. By circuit analysis, it can be derived that the electrical efficiency η of the power transfer scheme, from primary to secondary coils, at the resonance condition (5).

$$2\pi f_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \tag{5}$$

is given by (6) and (7):

$$\eta = \frac{1}{\left(1+\frac{R}{R_L}\right)\left(1+\frac{1}{k^2}\left(\frac{R_s+R_1}{w\,L_1}\right)\left(\frac{(R_2+R_L)}{w\,L_2}\right)\right)} = \frac{1}{\left(1+\frac{R}{R_L}\right)\left(1+\frac{1}{k^2 Q_1 Q_2}\right)} \tag{6}$$

where:

$$Q_i = \frac{w\,L_i}{r_i}, \qquad i \in \{1,2\}, \qquad r_1 = R_s + R_1, \qquad r_2 = R_2 + R_L \tag{7}$$

and f_0 is the frequency of the power source V_{in} exciting the primary circuit. An equivalent algebraic formulation for the efficiency η is given in [135]. The factors Q_i are called the quality factors of the primary and secondary coil windings. Commonly, the load connected to the secondary requires dc voltage, so a voltage rectification and stabilization circuit is required in the secondary, as exemplified in **Figure 8**.

Advances in the study of WPT models indicate the better adequacy of new impedance compensation topologies in automotive applications, such as the inductor-capacitor-capacitor (LCC) circuit, for both primary and secondary coils, as reported in more recent work [143, 144].

4.2 Stationary WPT charging

Based on so far available knowledge on WPT charging for light duty vehicles, the Society of Automobile Engineers (SAE) issued in 2016 a general recommendation for stationary WPT in automotive applications [145]. A simplified cross-section of a typical coil-to-coil WPT assembly is shown in **Figure 9**.

It can be seen in **Figure 9** that the coils are placed parallel and center-aligned to each other, with ferrite plates around them to increase the mutual inductance, as the amount of transferred power, according to (3), is proportional to this parameter. Parallel aluminum plates partially enclose the coils, as to function as a magnetic shield, reducing the magnetic field that spreads outside the gap in between the coils. A set of recommendations concerning the geometry of this assembly was also included in the same document [145], the SAE J2954 Report, and is concerned with the future interoperability of stationary recharging equipment for the automotive industry. This document, which is due to eventually evolve to an industry standard, also predefines three power levels classes and a frequency operation band for the WPT, as shown in **Table 2**.

The current available technology strongly limits the maximum distance in between the primary and secondary coils that can be achieved at a reasonable electric efficiency, for the given desired power levels. The SAE J2954 also establishes

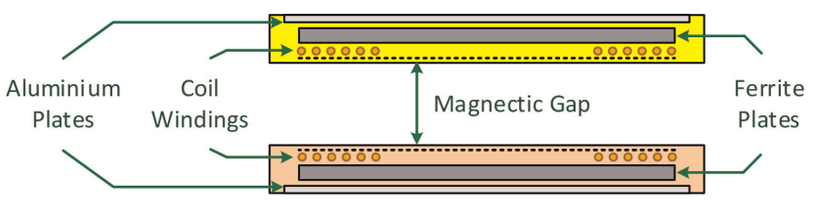


Figure 9.
Typical cross-section of the coil-to-coil WPT assembly of stationary chargers.

SAE J2954 recommended practice (as of Nov 2017)	WPT power classes		
	WPT1	WPT2	WPT3
Maximum input power	3.7 kW	7.7 kW	11 kW
Frequency band	81.38–90 kHz		
Transfer efficiency	>85% @ full alignment		

Table 2.
WPT power levels for stationary automotive charging according to SAE J2954 recommended practice.

SAE J2954 Z-class	Ground clearance range (mm)
Z1	100–150
Z2	140–210
Z3	170–250

Table 3.
SAE J2954 ground clearance range as per defined Z-classes.

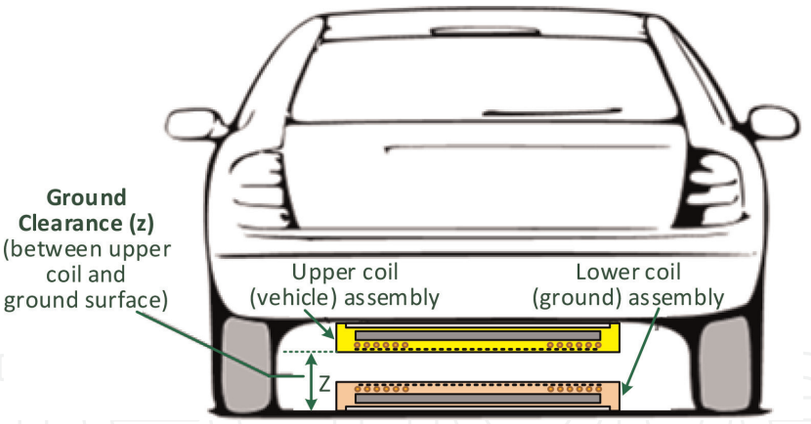


Figure 10.
Typical configuration for stationary WPT, showing coil in vehicle assembly (yellow) in alignment with coil in ground assembly (orange).

classes of possible clearances between the coil installed in the vehicle and the ground, what ultimately defines the gap between primary and secondary coils. SAE J2954 ground clearance range as per defined Z-Classes (**Table 3**). The ground clearance ranges by these named SAE classes, named Z1–Z3, are given in **Figure 10**.

4.3 Dynamic WPT electrification

The first automotive WPT designs targeted a means of dynamic electrification of vehicles, not stationary charging. The motivation was to minimize battery capacity requirements, not stationary charging: The subject was brought to light by George Babat, in Moscow, in the first half of the twentieth century [146, 147]. Due to many technical limitations of that time, however, the dynamic WPT remained forgotten for many decades.

In 1979, a conceptual project was charged by the University of California at Berkley to Systems Control Technology, Inc., Palo Alto, CA, USA [148]. The conception of a dynamic inductive WPT system was completed by 1986, when E.H. Lechner, S.E. Shladover, and K. Lashkari published two articles in the 8th International Electric Vehicle Symposium, Washington D.C. [149, 150], reporting the design of a Roadway Powered Electric Vehicle (RPEV). The final demonstration version of the system consisted of a 213 m long inductive road segment that could power an electric bus demanding 48 kw at an average electric efficiency in the order of 50–55%, and up 60% in peak conditions. In spite of the good qualities of the concept, practical limitations of power electronics components of the time influenced the design to be implemented at the low frequency of 400 Hz, with intensive use of iron alloy cores for the magnetic links in between the road and the vehicle, thus resulting in an unattractive cost level, so that the idea was abandoned [148].

In the 1990s, the interest on WPT for automotive applications was definitely recovered with the work of Covic and Boys [151] and, since then, many efforts in this direction have been pursued, with the most representative of them being the FABRIC project [138], as referred in [4]. In this design, a 100-m long track was built to deliver 20 kW of power, to up to two vehicles simultaneously running over it. The complexity and cost of enterprises like this are still too high for widespread adoption, but this is a topic of current research interest and it is believed that some kind of dynamic WPT will eventually become popular. In a general form of dynamic WPT implementation, the distance and relative orientations between primary and secondary coil are assumed to vary in a certain range. This relative

movement will cause dynamic variations in the magnetic coupling between the coils and, potentially, variable self-inductances of both primary and secondary coils as well, what will continuously change the transfer function of in between the coils, affecting the resonance frequencies exhibited by the whole assembly.

A possible solution to keep the power flow about constant is to allow both the excitation frequency and power level delivered to the primary coil to be also dynamically adjusted. In terms of circuit equivalence, dynamic WPT can then be modeled as in **Figure 11**. A generic wireless data channel is also illustrated, which is used to receive feedback from the secondary-side and to enable the control of the primary-side (i.e., the v_{in} voltage in terms of amplitude and frequency).

However, the dynamic WPT has also some disadvantages that must be viewed as challenges for future applications of this technology. A key challenge is the misalignment that can occur between the primary and secondary, which inevitably tends to deteriorate the transferred power. A homogeneous WPT technology targeting an effective dynamic WPT with moving objects is proposed in [152], where an experimental verification is demonstrated. A dynamic WPT containing numerous primary coils (stationary in the ground-side) and an EV with a secondary coil (moving EV) is proposed in [153], where a downscaled 3 kW prototype is presented allowing to confirm the dynamic WPT with its principle of operation.

4.4 Electromagnetic field exposure control

The use of electricity always brings some risks that should be carefully controlled at system design phase and further diminished by the elaboration of operational norms and procedures. In wired (galvanic) charging, for instance, careful dimensioning of cables and connectors should be done, for there is always the risk of overheating or sparks, which can cause a fire or, depending on the environmental conditions, even an explosion. Modern wired charging systems, for instance, avoid sparks by only switching a power circuit electrically after steady mechanical contact guarantees a stable galvanic connection. The risk of electrocution is one more issue, especially under mechanical failure of connectors, and it is aggravated when the contacts or the floor are wet.

In WPT systems, most of these risks involved in wired chargers are not present, because the user does not have direct contact with electric power cables, plugs, or receptacles. However, WPT systems are wireless only in the sense that there are no cables connecting the charger unit and the vehicle. Internally, these units are also replete of cables and wires, which should be well dimensioned, isolated, and constrained from direct human contact much in the same way wired systems are. Also, the strong EMF generated by the WPT coils can induce eddy currents in

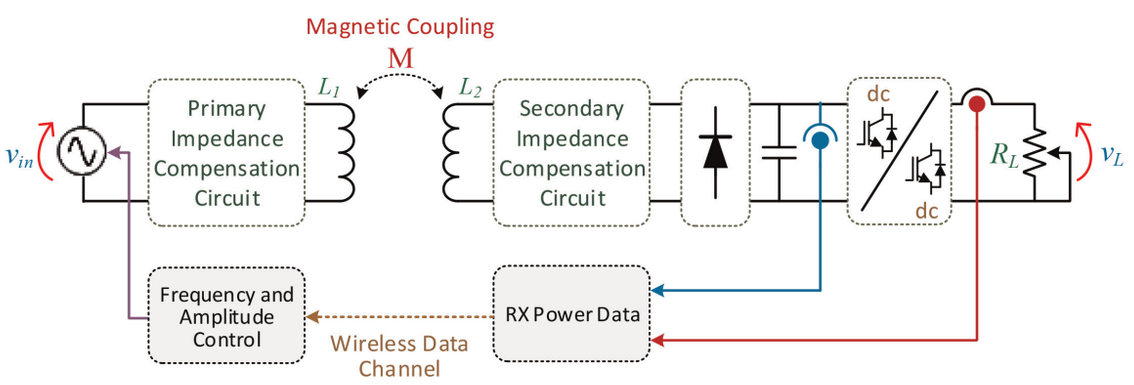


Figure 11.
Simplified dynamic WPT schema for dc load, with voltage rectification and stabilization in the secondary.

nearby resistive materials, which will heat and can start a fire. Similar happening with ferromagnetic materials, which can exhibit energy losses in the form of heat due to the alternating magnetic field. It is not enough to design for avoidance of such materials in the area exposed do the EMF. Monitoring the unexpected entrance in the WPT zone of objects made of such materials, the so-called "foreign objects," is also essential. A screw or nail stuck in a piece of wood left over a WPT transmitter can potentially start a fire. The system must then be able to automatically turn off an ongoing WPT and alarm, whenever foreign objects are detected. Additionally, the high intensity of EMF produced in the vicinity of both the transmitter and receiver coils can endanger human health. The level of human exposure to magnetic and electric fields tends to be much higher in WPT than in wired chargers. It is then necessary to carefully limit, by design, the maximum EMF in the area of human occupancy.

4.4.1 ICNIRP recommendations

As the knowledge regarding the long-term effects of EMF over human being progresses, the International Commission on Non-Ionizing Radiation Protection continually updates recommendations that are generally accepted by the society and the industry as de facto standards. This affects all engineered devices, including those in the automotive sector. The maximum International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommended electric and magnetic RMS field exposure levels are established as a function of the frequency of excitation. For the operation frequency band recommended in SAE J2954, which is from 81.38 to 90 kHz, the maximum exposure levels for the general public are given in **Table 4**.

4.4.2 Special EMF recommendations for automotive WPT applications

Beyond the generally worldwide accepted ICNIRP recommendation for maximum human exposure to EMF fields, the SAE J2954 extends the recommended safety levels by considering the case that humans in the automotive application may have an implanted medical device (IMD), such as cardiac pacemakers, in which case the AAMI/ISO 14117-2012 standard should also be applied. This requires the use of more tight limits for the magnetic field strength in regions 2b and 3, as depicted in **Figure 12**. In these regions, SAE J2954 further requires the RMS values of the magnetic field to be limited to 15 μT and the peak magnetic field to 21.2 μT, in the adopted bandwidth for the automotive stationary WPT.

SAE J2954 still admits that conformity may still be observed if this additional requirement is not met, but in this case, steps should be taken to warn pacemaker wearers to avoid this region, that is, to stay away from the car. Since notices on the laterals and panel of the vehicle, warning that IMD users are under life threatening conditions are not very appealing for most drivers and passengers, in practice, this additional requirement must be observed. In region 2a (**Figure 12**), the basic

	General public exposure	**Occupational exposure**
Maximum electrical field strength	83 V/m	170 V/m
Maximum magnetic flux density	27 μT	100 μT

Table 4.
Maximum ICNIRP recommended EMF maximum RMS exposure levels to non-irradiating magnetic fields in the 3–10 MHz band.

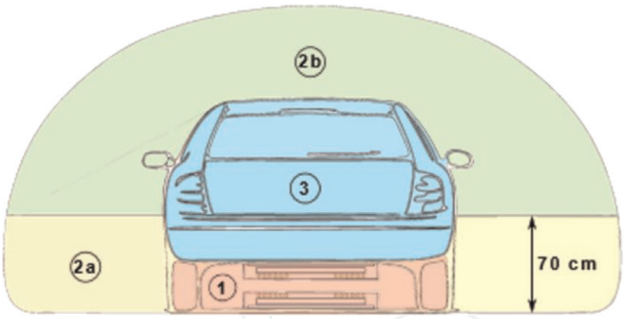


Figure 12.
EMF regions around a vehicle: 1. Space underneath the vehicle. 2a. Space outside the vehicle below the height of 70 cm from ground and excluding region 1. 2b. Space outside the vehicle above the height of 70 cm. 3. Space in the interior of the vehicle.

ICNIRP maximum recommended exposure level of upto 27 μT holds. In region 1, where the WPT phenomenon develops, no restrictions are posed – better not be there. As commented in [150], no conductive or magnetic debris should be left in that region as well, for the risk of overheating the parts and causing a fire. The recommendation and its referred norms are specific on the methods for measuring and verifying the field strength values.

4.5 New perspectives for WPT

In a future perspective, it is common sense that different types of EV will be available on market. In this sense, as previously demonstrated, with the possibility of the EV charging using WPT technologies, the main gains for the EV will be in terms of simplicity and comfort, since it is not necessary to use additional cables to maintain the EV plugged into the electrical grid. Moreover, it is an active approach to strength the market penetration of the vehicle electrification. A strategy to control the maximum power transfer points in WPT systems, based on arbitrary number of coils, is described in [154], where an experimental validation was performed at different modal frequencies and coils.

Many other innovative works have been accomplished in the last years: Compact dual-band WPT, constituted by two interlaced resonators, for instance, is proposed in [155]. It can operate in bidirectional mode, where a peak efficiency of 80% was obtained with an operating frequency of 300 MHz and considering a distance of 17 mm. In the perspective of WPT technologies framed in smart grids, a bidirectional WPT is of utmost importance, allowing to apply the G2V/V2G modes (for power transfer in both directions) with WPT [134]. An 1-kW bidirectional WPT prototype is proposed and validated in [156] focusing the resonant network in terms of active and reactive power control.

Since the efficiency is a key factor in WPT technologies, an innovative tracking method for guarantee maximum efficiency is proposed in [157], including aspects of: adjustment for coupling coefficient; variations of operating power; and controllability. Similarly, a system to guarantee optimum efficiency in WPT over a wide load range is proposed in [158].

Concerning the new technologies of WPT, the communication channels will also have a preponderant role. The main features concerning the communication protocols for WTP technologies, also based on wireless technologies, between the roadside controller and the on-board EV controller are discussed in [159]. The presented solution takes into consideration real-time aspects and the motion control. The combination of Internet of Things (IoT) communication networks with WPT technologies is explored in [160].

Besides the inductively-coupled WPT [161], other wireless power transfer technologies are also emerging, contributing for the fourth-generation of personal mobility [162]. As example, a dynamic via-wheel power transfer (V-WPT) is proposed in [163] as a trial solution for roadways.

The development of new electronic materials and devices allows continuous improvement in the electrical efficiency in converters used to implement WPT, simultaneously with significant decrease in costs. As the relative price of electricity with respect to fossil fuels reduces, more demand for electric vehicles and support technologies such as wireless power transfer is foreseen. While the advances in battery technology may eliminate the range anxiety of today's EV drivers, the batteries will always expectably need recharge. The WPT technology for stationary charging will be there for it.

Other grid and off-grid applications for the WPT stationary chargers and the electric vehicles themselves are expected to gain space among us, those related with vehicle-to-grid (V2G) and vehicle-to-home (V2H). In this sense, the new bidirectional WPT stationary charges will be able to dispose the electric vehicle as a mobile energy storage unit, extending by far its transportation functionality.

Last, it is worthwhile to mention that the lifecycle of batteries and the associated recycling issues, when projected at large scale, may perfectly justify the minimization of battery capacities by the widespread adoption of dynamic WPT on the roads as well.

5. Vehicle-to-vehicle: a power transfer perspective

As previously studied in this chapter, the EV interface with the electrical grid has a huge relevance for smart grids, considering the vast number of possible operation modes that the EV can allow. Besides the conventional modes G2V/V2G for exchanging active power with the electrical grid, there is a proposed operation mode in the literature termed as vehicle-to-vehicle (V2V). The V2V designation is mainly associated to communication systems between vehicles, either EVs or not. Nevertheless, a V2V operation mode considering power transfer between EVs was also proposed in the literature [164–167].

5.1 V2V power transfer using the front-end power stages

The V2V proposal intended to designate the power transfer between the batteries of different EVs connected to the same electrical grid, as a peer-to-peer power exchange method. Therefore, this operation mode is, in fact, the combination of G2V and V2G operation modes for two (or more) EVs connected to the same electrical grid, where the power provider operates in V2G and the power receiver operates in G2V. A practical implementation concerning a military environment was addressed in [168], where EVs would form a microgrid to replace diesel generators. Assuming that each on-board EVBC contains a front-end power stage and a back-end power stage, the power transfer from one EV battery to the other requires four power conversion stages. Thus, even if each power stage is highly efficient, the overall efficiency of the power transfer will always be lower than the least efficient converter. For instance, if all the converters have an efficiency of 90%, the overall efficiency of the power transfer would be 65.6%. Additionally, the power transfer between EV batteries is only possible if the EVs are connected to the same electrical grid. **Figure 13** illustrates this case of power transfer between EVs connected to the same electrical grid. Besides this possibility, where both EVs are plugged-in into the electrical grid and the front-end power stages are controlled by current feedback, other possibility consists in using one of the EVs as a voltage source and the other

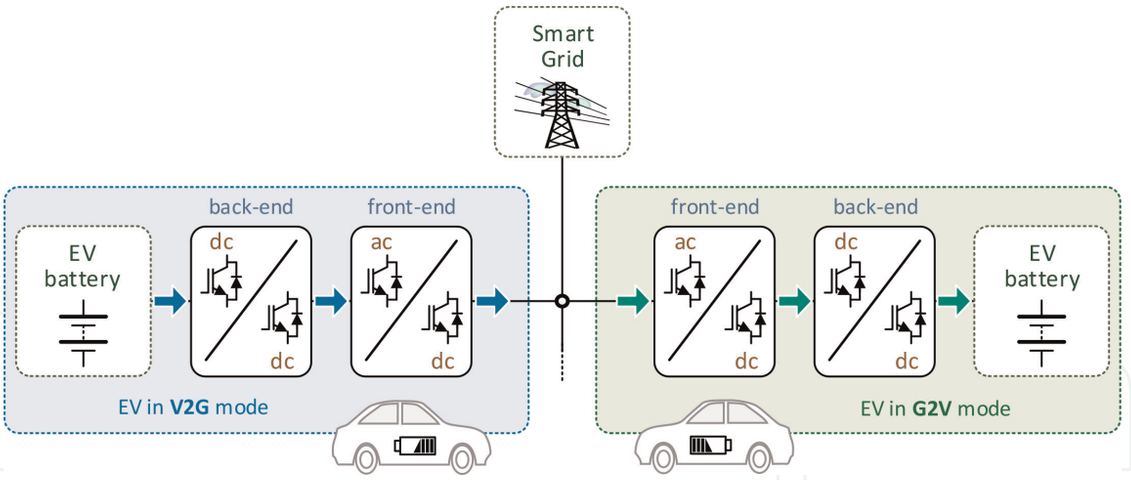


Figure 13.
Power transfer between EV batteries with EVs connected to the same electrical grid, one operating in G2V mode and the other in V2G mode.

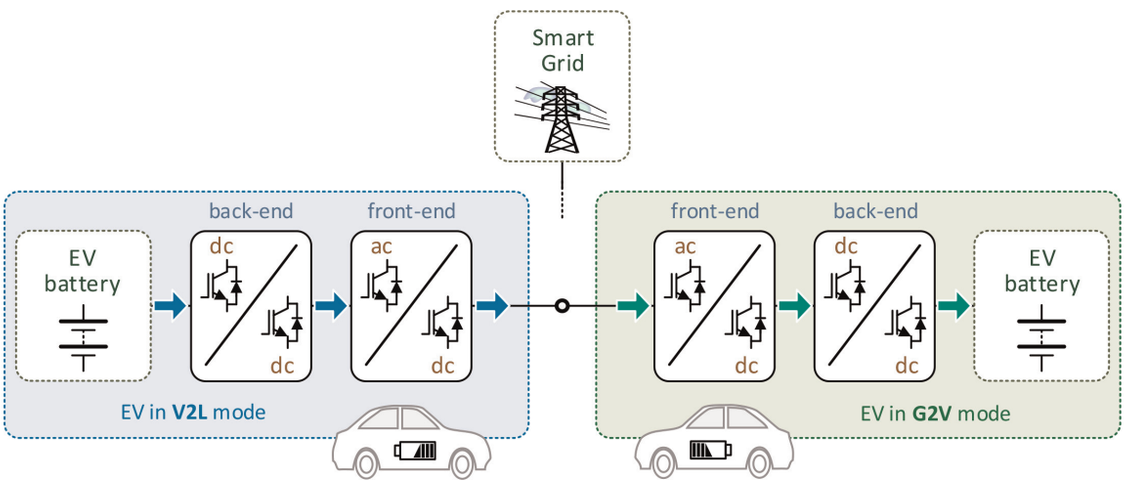


Figure 14.
Power transfer between EVs using both front-end and back-end power stages of both EVs, and without using electrical power grid interface.

in the G2V mode. The possibility of the EV operation as a voltage source is presented in more detail in Section 7 and is identified as vehicle-to-load (V2L). Contrarily to the previous case, this approach of V2V does not require the interface with the electrical grid, and the front-end power stage of the EV that operates as a voltage source is controlled by voltage feedback (operation that emulates the electrical grid). **Figure 14** illustrates this case of power transfer between EVs using both front-end and back-end power stages of both EVs and without the electrical grid interface.

5.2 V2V power transfer using the back-end power stages

A direct V2V power transfer without the need for the connection to an electrical grid was proposed and analyzed in [169] and developed in [170], with two EVs being connected by the ac-side of each on-board EVBC. With this approach, it is possible to provide power to an EV that has its batteries completely discharged and, therefore, cannot move to a charging station or to a power outlet to be charged. Despite the use of the ac-side converters, the power transfer is performed in dc. **Figure 15** illustrates this case of power transfer directly between EV batteries only using the back-end power stages. Accordingly, this V2V approach is more efficient than the previously referred combination of V2G and G2V and allows the power

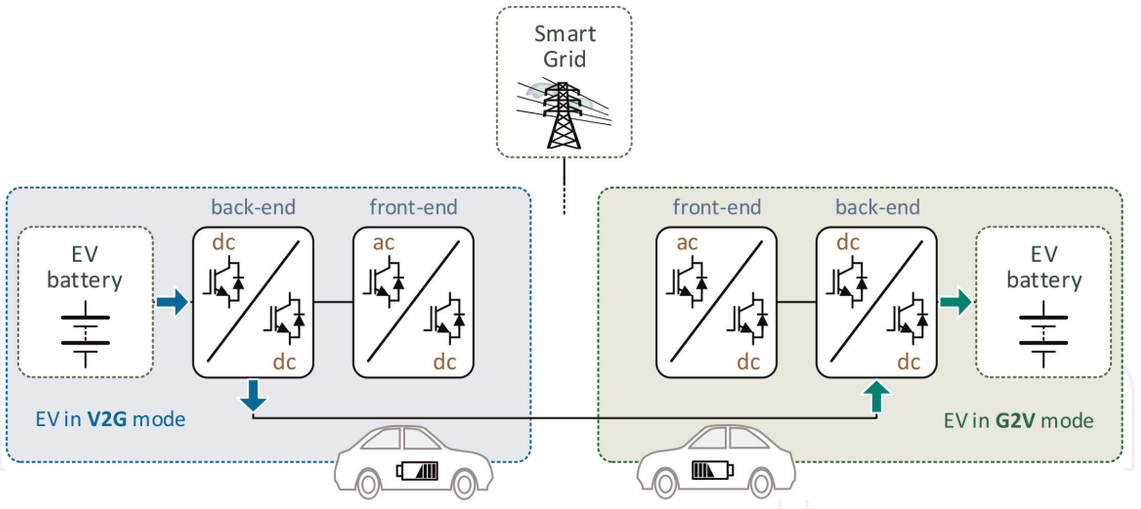


Figure 15.
Power transfer between EVs using only the back-end power stages of both EVs, and without using the electrical power grid interface.

transfer between EVs in remote areas, that is, without the need of the electrical grid. In [171], another topology was presented for V2V power transfer that uses two back-end dc-dc converters in each EV, plus a front-end ac-dc converter, whose dc-links represent the connection point of the two EVs. The main disadvantage of this topology is that each EV contains two dc-dc converters, with the first being a non-isolated topology to interface the battery and the latter a dual active bridge dc-dc converter. Moreover, these converters are on-board, with the ac-dc converter being the only off-board converter.

An efficiency comparison regarding different V2V approaches in a simulation environment was performed in [172], being compared power transfer approaches in ac and dc. A typical on-board EVBC was considered, with a two-quadrant buck-boost topology for the back-end power stage, and a four-quadrant full-bridge topology for the front-end power stage. The connection between the EVs was performed through the dc-links formed by the power stages, with the front-end power stage not being used. This connection formed a split-pi buck-boost converter, resulting in a dc-dc converter capable of operating in four-quadrants. This is advantageous, meaning that a given EV battery can provide power to another, regardless of its voltage being higher or lower than the supplying battery. Moreover, despite the connection forming two dc-dc converters, it is possible to perform a power transfer with only one converter activated. In this way, different control modes for performing the power transfer can be considered, namely by controlling the dc-link voltage or only controlling the battery current for each EV.

Besides the aforementioned wired V2V mode, wireless power transfer regarding V2V operation is also possible for two EVs [171, 173]. Wireless power transfer takes V2V power transfer a step further, allowing not only the power transfer between EVs in remote areas, but also the power transfer between EVs without the need of being stopped. The V2V concept is a relatively recent topic of research and it is expected that new developments would take place in the next few years.

6. Unified technologies for the vehicle electrification

The main purpose of an EV, as well as with any other type of vehicle, is to perform transportation. In order to perform this function in an EV, the electro-chemical energy stored in the EV batteries is controlled, via power electronics

converters, to drive the electric motor of the EV, which in turn transforms the supplied electrical energy into mechanical energy, making the EV able to move. Additionally, the reverse process, that is, regenerative braking, is also possible, since an electric motor can also behave as an electric generator. It should be noted that the power electronics converters responsible for the EV motor driver should be bidirectional in order to perform regenerative braking. On the other hand, an EV contains also an on-board EVBC, making it possible to charge the EV batteries with power from a domestic power outlet, for instance. Contrarily to an off-board EVBC, which operates with power levels classified as Level 3 (50–100 kW) and, hence, provide fast battery charging, the on-board EVBC are only framed in Level 1 (1.4–1.9 kW) and Level 2 (4–19.2 kW), offering slow battery charging operation [174]. Compared with the power electronics converters used for the EV motor driver, the EVBC has a substantially lower power rating, since the EV motor driver needs to be sized for a power level above (or equal to, in the limit) the electric motor nominal power. As happens with internal combustion engine vehicles, the range of available power values for EV motors is relatively large, ranging from dozens of kW, such as Renault Zoe (65 kW) [175] or the first generation Nissan Leaf (80 kW) [176], to several hundreds of kW, such as Tesla Model S (451 kW for the P100D model) [177]. Power levels of even MW can be also found, as in supercar Rimac C Two (1.048 MW) [178], for example. As it can be seen, even for lower powered EVs, the EV motor driver has a power rating several times higher than the on-board EVBC.

6.1 Integrated battery chargers for the vehicle electrification

Based on the previous analysis, an EV comprises two main groups of power electronics converters: the EV motor driver and the EVBC, with the first being used to perform the EV movement and the latter to supply power to the EV batteries. **Figure 16** illustrates this case. Accordingly, only one group of power electronics converters is used at a time: the EV either is being used for traveling, with the only possibility of charging its batteries being through regenerative braking, or is charging its batteries through the on-board (or an off-board) EVBC, with the EV being stopped in this situation. In both cases, there is no superposition of active groups of power electronics converters, attributing some redundancy to these converters. This redundancy gave rise to the concept of integrated battery chargers, that is, only one single group of power electronics converters is used to perform both the traction (motor driver) and the battery charging operations. Besides reducing the

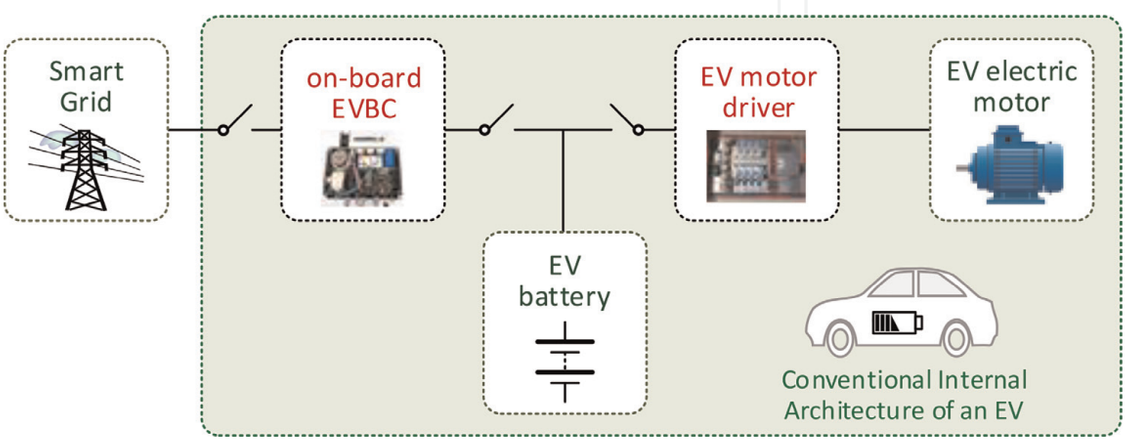


Figure 16.
Conventional internal architecture of an EV constituted by the on-board EVBC and the EV motor driver.

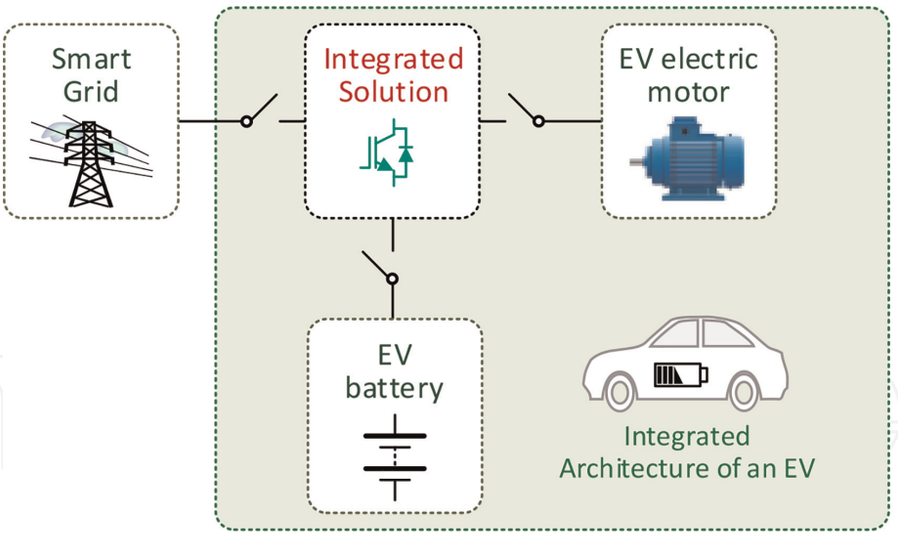


Figure 17.
Integrated architecture of an EV used for two purposes: On-board EVBC and EV motor driver.

required hardware, this approach furnishes the EV with a fast on-board EVBC, since the battery charging power level is established by the EV motor driver. **Figure 17** illustrates an integrated architecture of an EV used for both purposes: on-board EVBC and EV motor driver.

The first publication on integrated battery chargers dates back to 1983 with a USA Department of Energy/NASA report [179], followed by a journal publication of the same author 2 years later [180], when EVs were far from having the popularity of the twenty-first century second decade. In this approach, a 3.6-kW resonant inverter based on silicon-controlled rectifiers (SCRs) was used. A few years later, Rippel and Cocconi filled patents regarding integrated battery chargers [181–183] In the first of these patents [181], dating to 1990, a connection to a single-phase ac electrical grid was available through a diode full-bridge rectifier, with the traction inverter operating as a boost dc-dc converter to charge the EV batteries. Despite an external inductor being used for the boost operation, the authors referred that the leakage inductance of the motor windings could be used instead, although leading to a high ripple in the battery current. In Rippel and Cocconi [182], a scheme was proposed for two induction motors or, alternatively, a motor with two sets of windings. This system comprised two three-phase inverters and used the motor windings as the boost dc-dc converter inductors. Similarly to the previous proposal, this system considered the connection to a single-phase ac electrical grid. In Cocconi [183], the previous work was extended to single-phase and three-phase ac electrical grids. However, for these three cases, due to the boost operation of the traction inverter, the electrical grid peak voltage should be lower than the EV battery voltage. In 2001, an integrated battery charger for an electric scooter was proposed, with the traction inverter operating as a three-phase boost dc-dc converter to perform the battery charging [184]. Power factor correction (PFC) characteristics were added to a similar system in 2010, as well as a bidirectional dc-dc converter between the EV battery and the traction inverter, making it possible to charge the EV battery from a single-phase ac electrical grid with a higher or lower peak voltage than the battery voltage [185]. An innovative topology was proposed in 2013 [186], using an eight switch inverter to interface a three-phase induction motor and a single-phase ac electrical grid. An innovative topology termed as multi-source inverter was recently proposed for plug-in hybrid EVs, aiming to connect multiple dc sources to the same ac output though a single power conversion stage [187, 188].

6.2 Integrated battery chargers: the electric motor perspective

Concerning electric motors, switched reluctance motors have been gaining interest due to their constructive simplicity, low size and weight, and low cost. An integrated battery charger for two-phase switched reluctance motors with connection to a single-phase ac electrical grid was proposed in 2000 [189]. In this case, the integrated battery charger behaved as a flyback dc-dc converter, with an auxiliary coupled winding being used for the battery charging operation. In 2009, a similar system was proposed for three-phase switched reluctance motors, with the traction inverter forming a PFC topology [190]. Two motor windings were used as input filters of the diode bridge rectifier, while the third winding was used as the inductor of the boost dc-dc converter. Two years later, the same authors proposed a modification of this system, adding buck-boost PFC charging functionalities, by changing the traction inverter topology [191]. In both cases, the system was connected to a single-phase ac electrical grid. In 2014, an integrated battery charger for switched reluctance motors applicable to plug-in hybrid EVs was proposed, allowing the battery charging operation from the EV internal combustion engine or ac electrical grids, either single-phase or three-phase [192]. One year later, similar systems were proposed for four-phase switched reluctance machines, with [193] proposing increased functionalities, such as V2G and V2H, and [194] proposing a system based on a dual converter, supporting battery charging from both dc and single-phase ac electrical grids. In 2017, an integrated battery charger based on a four-level converter for a three-phase switched reluctance motor was proposed, for application in plug-in hybrid EVs [195, 196]. In both cases, the batteries could be charged from the internal combustion engine or from a three-phase ac electrical grid.

It is relevant to note that integrated battery chargers encompassing galvanic isolation are also possible. The previously referred system proposed in [189] for switched reluctance motors achieved galvanic isolation through a flyback dc-dc converter, but its battery charging efficiency was low (25%). Two galvanically isolated integrated battery chargers, to be used in industrial EVs, were proposed in 2005 [197]: one of the systems aimed for 1.5 kW dc motor powered pallet trucks, with galvanic isolation being accomplished with a Ćuk converter; the other aimed for 6 kW wound rotor induction motor powered forklift, in which galvanic isolation was accomplished by the motor itself (while the stator windings were connected to the inverter, the rotor windings were connected to a three-phase ac electrical grid). Integrated battery chargers for EVs using a motor/generator set and winding reconfiguration to achieve galvanic isolation were proposed in 2011 [198] and 2013 [199, 200]. Despite adding safety to the battery charging process, galvanically isolated integrated battery chargers are disadvantageous in terms of size, weight, cost, and efficiency compared to non-isolated topologies and, therefore, are less analyzed in the literature than the latter.

The interest for multiple motor powertrains has been increasing, as well as integrated battery chargers for such purpose. In fact, an integrated charger for a four in-wheel motor EV was proposed in 1995 [201]. Four inverters and four sets of three-phase windings were combined to achieve an interleaved operation, with two motors/inverters forming a single-phase ac-dc converter to interface the electrical grid and the other two motors/inverters forming a two-phase bidirectional interleaved buck-boost dc-dc converter to interface the EV battery. In 2015, a dual motor/generator set was proposed as an integrated battery charger to be connected to a single-phase ac electrical grid [202]. Integrated battery chargers based on a single motor and a dual inverter are also common, being proposed in 2015 [203] a topology for charging the secondary battery of EVs through the main battery, with the dual inverter and the motor windings interfacing both batteries. However, this

system required an additional on-board EVBC. In 2018 [204], a similar solution capable of charging both batteries simultaneously from a single-phase ac electrical grid was proposed, being necessary to add a diode-bridge rectifier to interface the electrical grid. A more complex solution comprising galvanic isolation was proposed in 2016 [205] for interfacing a three-phase ac electrical grid, using a diode bridge rectifier and a full-bridge inverter per phase to connect with each of the three primary windings of a magnetic combination transformer, with the only secondary winding being connected to a diode bridge rectifier which, in turn, was followed by the EV battery.

Besides multiple motor and multi-inverter topologies, integrated battery chargers based on multi-phase motors are also commonly found in the literature. An integrated battery charger for a powertrain based on a five-phase motor was presented in 2016 [206], which was capable of fast battery charging, that is, interfacing with a three-phase ac electrical grid. Slow [207] and fast [208] battery charging operations concerning integrated battery chargers with five-phase, six-phase, and nine-phase motors were analyzed in the same year by the same authors, and galvanic isolation was considered for six-phase motors the next year [209]. Further reading concerning multi-phase motors and integrated battery chargers for these can be found in [210–212].

7. Vehicle electrification: innovative modes contextualized with smart homes and smart homes

The possible structures that can be implemented for an EVBC were presented in Section 2 and the different technologies targeting the vehicle electrification in Sections 3–6. Using the previous sections as support, this section introduces new opportunities for the smart grids and smart homes arising from the EV flexible operation.

7.1 EV battery charger: on-board

The main operation modes of an on-board EVBC are presented considering the restrictions and also the offered opportunities when integrated in smart grids and smart homes scenarios. **Figure 18** illustrates a smart home with an on-board EVBC plugged-in. As shown, a bidirectional communication is necessary for establishing a power management control between the smart home, the smart grid, the electrical appliances, and the EV. In fact, the power management at the smart home level is used for communicating with the EVBC and with the controlled electrical appliances aiming to define control strategies based on schedules of operation. On the other hand, the power management at the smart home communicates with the power management of the smart grid.

7.1.1 Operation mode: grid-to-vehicle (G2V)

Nowadays, the G2V mode is the existing mode on commercial EVs, which is related with the EV battery charging. **Figure 19** illustrates an on-board EVBC plugged-in at a smart home. As shown, a unidirectional power flow is established with the electrical grid, but a bidirectional communication is established for communicating the charging status and for defining set-points of operation. In G2V, the value of the grid-side current is independent of the other electrical appliances. Since the current is limited by the home switch-breaker, if the consumed current exceeds the nominal value, then the switch-breaker will be triggered. In order to overcome

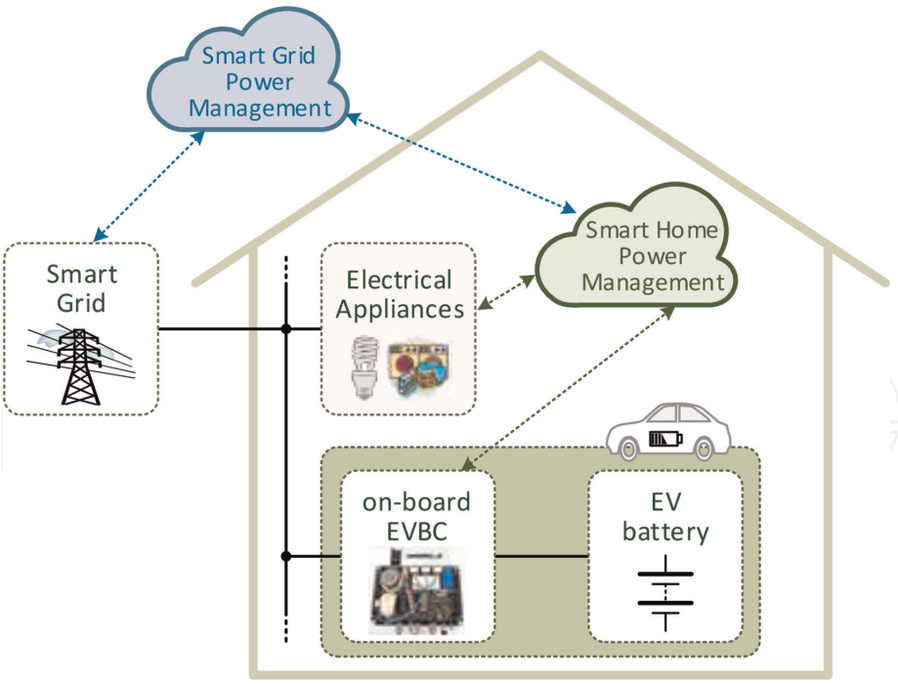


Figure 18.
An on-board EVBC plugged-in at a smart home.

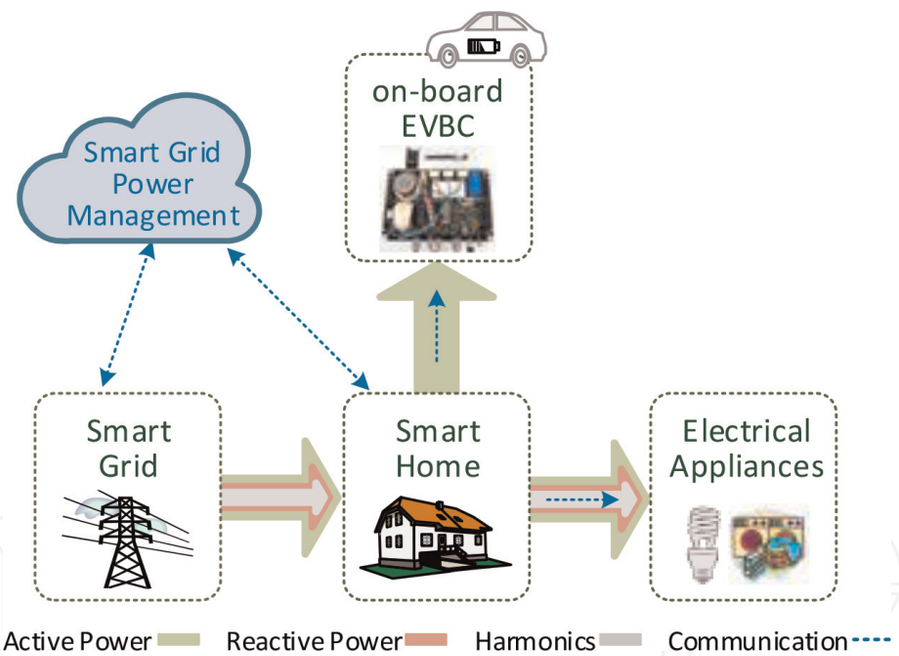


Figure 19.
On-board EVBC: G2V operation mode.

this situation, the smart home power management forces the EVBC to stop the G2V mode, representing a disadvantage of this mode.

Analogously to the aforementioned G2V mode, the flexible G2V mode refers to a situation when the EV charging power is adjusted according to the status of the other electrical appliances [95]. For example, the value of the charging power can be adjusted based on the injected power from RES as a contribution to balance the production/consumption from the smart home perspective. Moreover, it can be performed without harming power quality aspects. Also in this mode, it is fundamental to establish a bidirectional communication between the EVBC and the smart home power management.

7.1.2 Operation mode: vehicle-to-grid (V2G)

The V2G mode denotes a state related with the possibility of a bidirectional operation also in terms of power flow: the EV is used to return part of the stored energy back to the electrical grid. This mode is performed in convenience of the smart grid or smart home power management, as well as in the convenience of the EV user. Therefore, the EV is seen as a flexible ESS allowing a support for the grid stability. Furthermore, this mode entails communication with a smart grid aggregator targeting to outline schedules for the EVBC operation, as well as the quantity of power that must be returned back to the electrical grid. **Figure 20** illustrates this operation mode when the EV is plugged-in at the smart home, permitting a dual opportunity: the flexible operation in V2G mode for the smart home and/or for the smart grid.

7.1.3 Operation mode: vehicle-to-load (V2L) - as voltage source

In the G2V/V2G modes, the controllability of the EVBC is performed, respectively, only in relation to absorb/inject active power. In both G2V/V2G case, a current feedback control is applied. Instead, a new opportunity for the EV operation is associated with the EVBC controllability as a voltage source for supplying electrical appliances (loads). This operation is only valid while the EV is not plugged-in to the electrical grid, which is denominated as V2L (where a voltage feedback control is applied, meaning that the voltage waveform is forced by the EVBC and the current waveform by the electrical appliances) [213]. **Figure 21** illustrates the principle of operation of the V2L mode. The relevance of the V2L mode is linked with the option to use the EV in isolated locations from the electrical grid (for instance, in extreme circumstances of catastrophic events when the electrical grid is unavailable or in campsites). This operation is very applicable and represents a new support offered by the EV, however, since it requires to use the energy stored in the battery, the battery state-of-charge is obligatory managed with the EV owner agreement (for instance, conserving an acceptable state-of-charge for the next travel). Similar opportunity was before recognized by Nissan (the

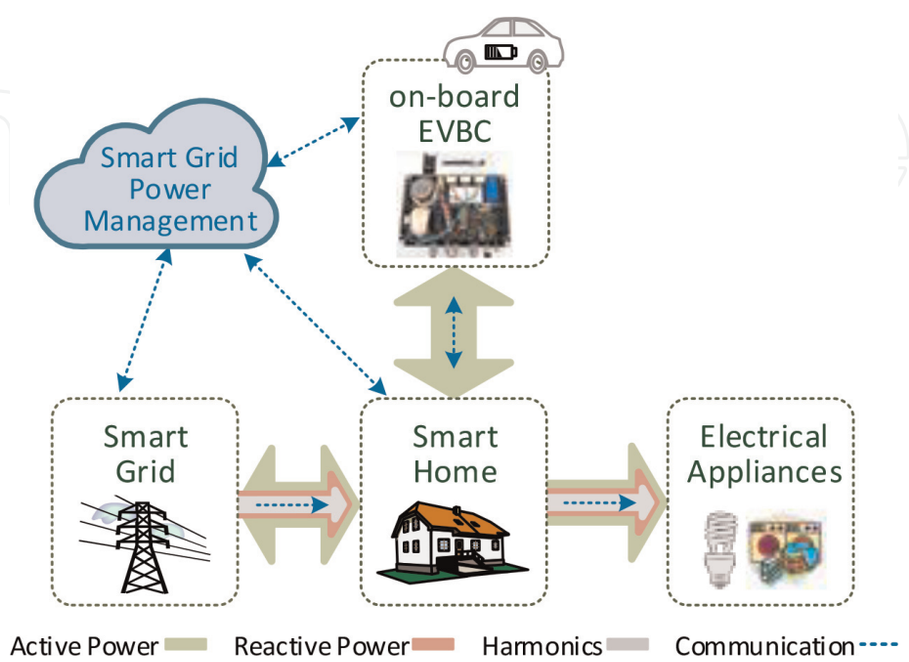


Figure 20.
On-board EVBC: V2G operation mode.

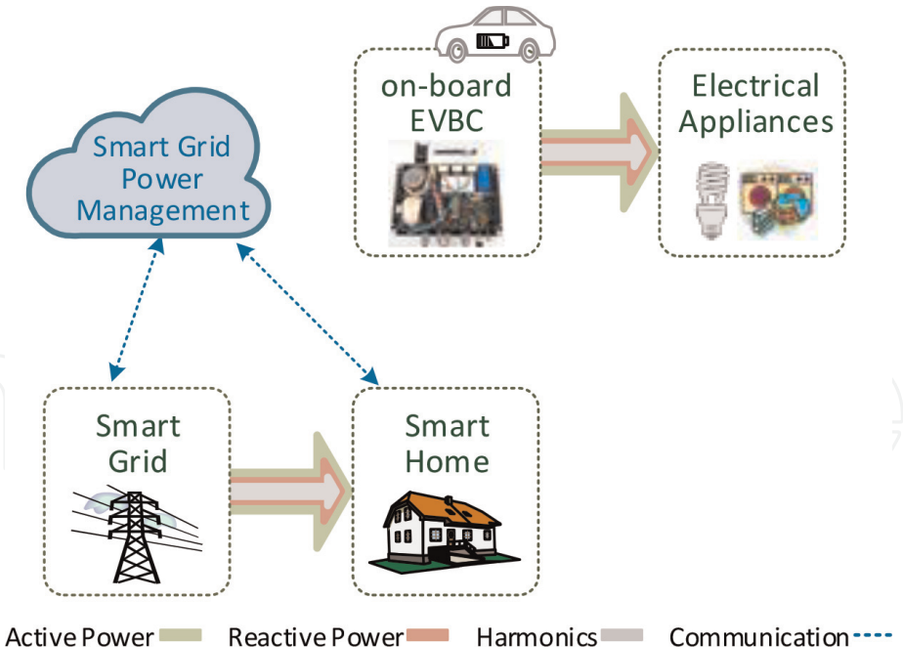


Figure 21.
On-board EVBC: V2L operation mode (as a voltage source).

"LEAF-to-Home" project), but requiring an external "EV Power Station," limiting the application of this concept to the location where the system is permanently installed [214]. Consequently, the presented V2L mode assumes a greater field of application, since it can be used generically with the EV in the place where it is parked.

7.1.4 Operation mode: vehicle-to-home (V2H) - as uninterruptible power supply (UPS)

As a sequence of V2L mode, emerges the possibility of the EVBC operation with features based on an off-line uninterruptible power supply (UPS) [215]. This is especially dedicated for smart homes in the existence of a power failure, where the EVBC starts to operate as a voltage source practically instantaneously. In this mode, it is required a communication from the smart home to the EVBC notifying about the power outage and a communication from the EVBC to the smart home to inform about the battery state-of-charge (for instance, permitting to establish a control based on selecting priority electrical appliances). **Figure 22** illustrates the V2H mode as a UPS contextualized into a smart home, which evidently recognizes the operation disconnected from the electrical grid. As in the previous mode, the grid-side converter (front-end power stage) is controlled with a voltage feedback, however, it is obligatory to measure the electrical grid voltage for noticing the power failure (in this event, the smart home is disconnected from the electrical grid almost instantaneously and the EVBC starts its process). When the voltage is restored, such situation is identified by the EVBC and, subsequently, it starts the synchronization with the phase of the voltage targeting the transition to the normal mode, when the electrical grid supplies power for the smart home. Posteriorly, the EVBC can stay in an idle state or it can return to a G2V/V2G mode.

7.2 EV battery charger: off-board

The foremost opportunities for an off-board EVBC are addressed in this section targeting a contextualization with smart grids. It must be highlighted that the identified opportunities are independent from the off-board EVBC classification as

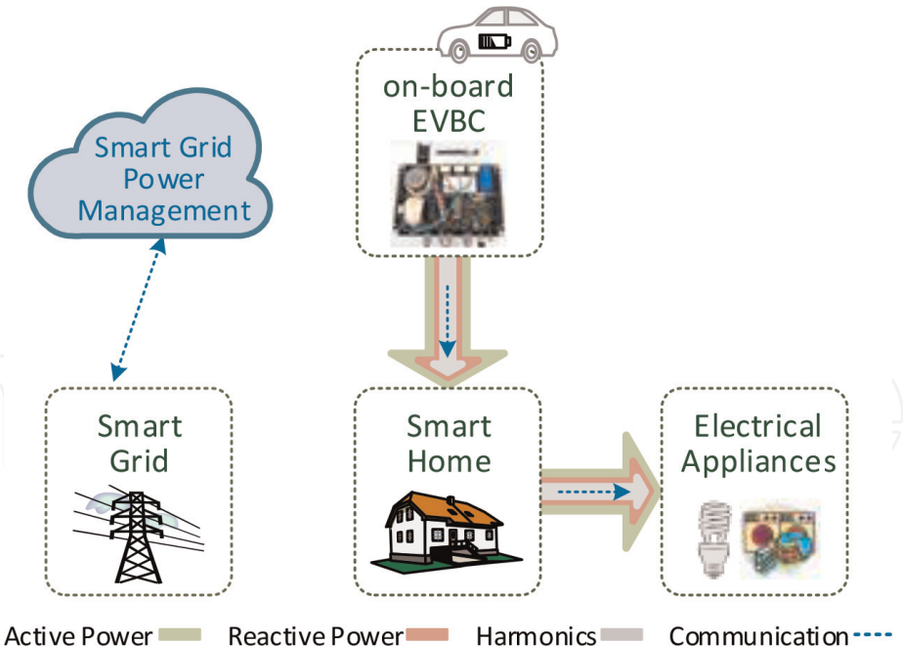


Figure 22.
On-board EVBC: V2H operation mode (as an off-line uninterruptible power supply).

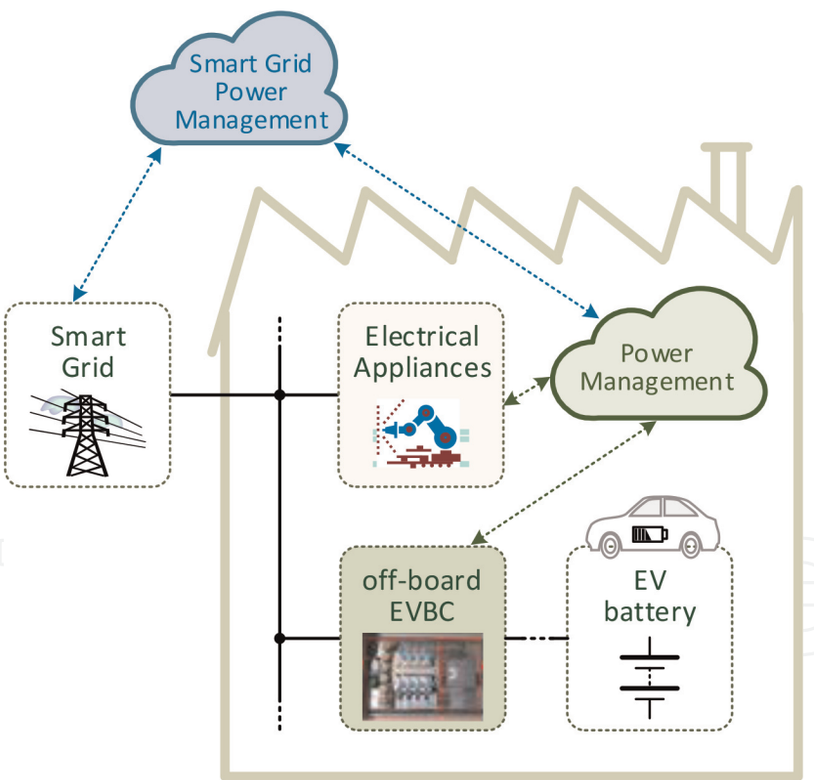


Figure 23.
An off-board EVBC and an EV plugged-in at an industry.

slow, semi-fast, fast, or ultra-fast (in single-phase or three-phase interfaces). **Figure 23** illustrates an off-board EVBC into an industry. Since it is an off-board EVBC, it is always connected to the electrical grid even without any plugged-in EV. Also in an off-board EVBC, it is fundamental a bidirectional communication, allowing to transmit data from the off-board EVBC (for instance, the information of the battery state-of-charger) and transmit set-points of operation to the off-board EVBC. This communication is indispensable for the smart grid contextualization.

7.2.1 Operation mode: grid-to-vehicle and vehicle-to-grid

An off-board EVBC also enables the G2V/V2G modes, but the core variance, when compared with an on-board EVBC, is the operating power, which is significantly higher (the power is higher, but it is used for shorter periods of time). **Figure 24** illustrates an off-board EVBC operating in G2V/V2G modes, where a

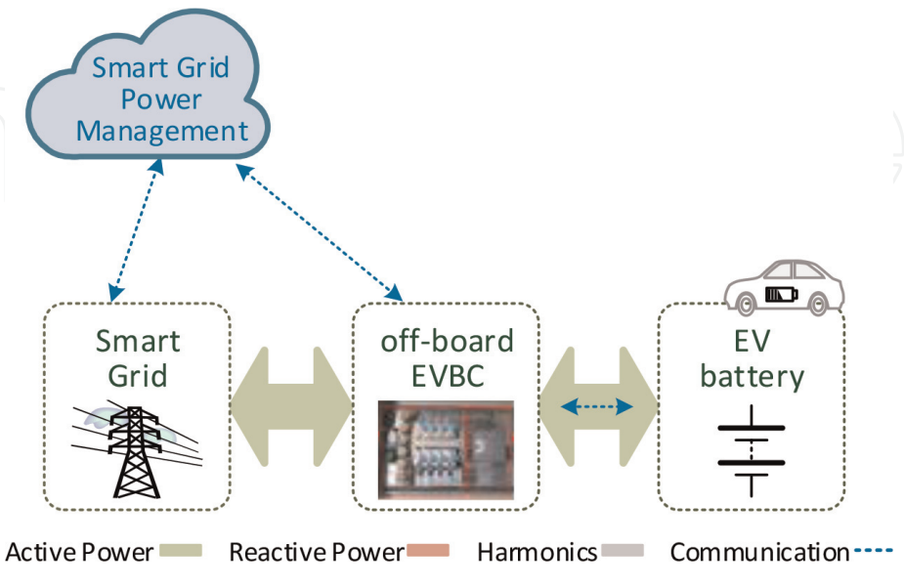


Figure 24.
An off-board EVBC with an EV plugged-in into the electrical power grid: G2V/V2G modes.

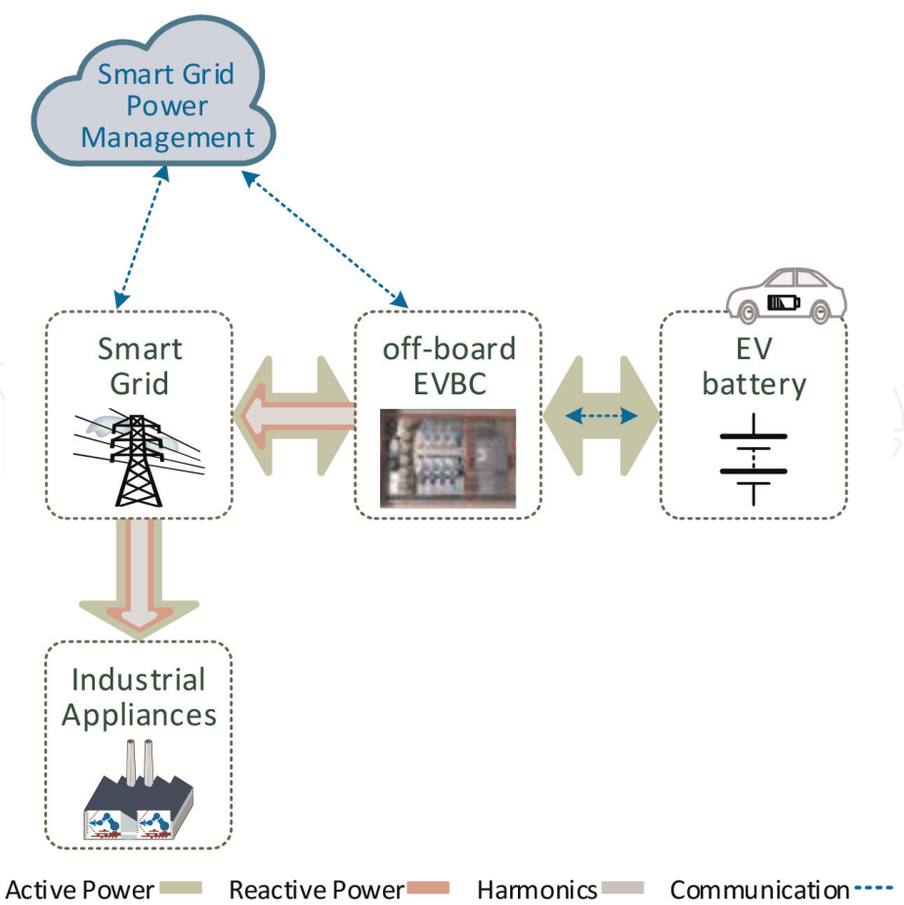


Figure 25.
An off-board EVBC with an EV plugged-in into the electrical power grid: operation as a power quality compensator.

bidirectional power flow and a bidirectional communication is identified. The V2G mode is interesting, but in the case of an off-board EVBC, its use is very particular, because when the EV is parked and plugged-in the goal is to charge the battery as fast as possible, so if the process is interrupted for the V2G mode, the charging will take longer.

7.2.2 Operation mode: power quality compensator

As previously identified, an off-board EVBC can be used in G2V/V2G modes, a situation that occurs as fast as possible (where a high power value in a short period of time is necessary). Therefore, after the EV charging, the off-board EVBCs may be out of operation throughout some periods, that is, until another EV arrives to charge. Accordingly, a new opportunity is recognized for the off-board EVBC when the EV is not plugged-in, which is linked with the support to the smart grid in terms of power quality (mainly, the issues corresponding to low power factor, current imbalances in three-phase systems, and harmonic current). Furthermore, the existing opportunity of this mode is additionally attractive, by the reason that it can be accomplished while the EV plugged-in (for instance, without jeopardizing the off-board EVBC or without using the stored energy in the EV battery, the G2V/V2G modes can also be performed) or without any EV plugged-in. This means that it is not necessary to transfer active power from the electrical grid to the EV or vice-versa. Additionally, it is not required extra hardware for this additional mode of operation related with power quality coverage. **Figure 25** illustrates an off-board EVBC,

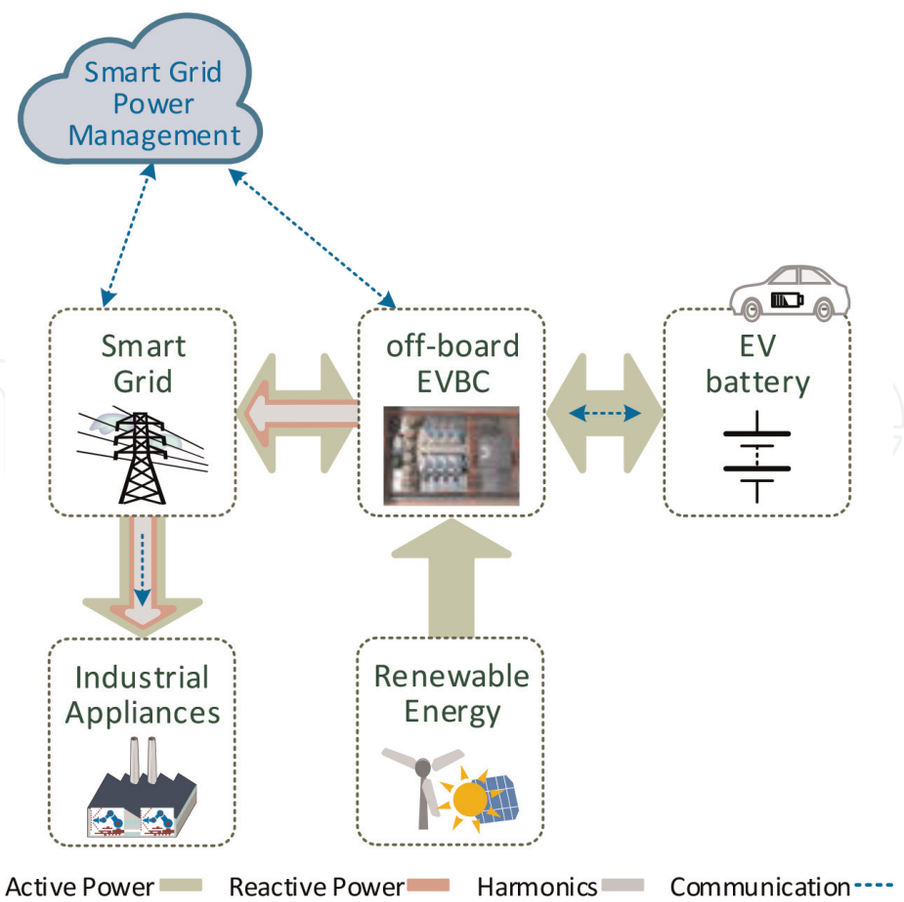


Figure 26.
An off-board EVBC with an EV plugged-in into the electrical power grid: unified operation with RES and as a power quality compensator.

where is highlighted this opportunity. In this case, the power quality problems are determined by the linear and nonlinear electrical appliances within the industry.

7.2.3 Unified operation: power quality compensator and interface of renewable energy sources

The possibility for exchanging power with the electrical grid and for compensating power quality issues was previously presented. Moreover, knowing the stimulus of RES for the progress of smart grids, also to mitigate the impact of the EV required power from the electrical grid, their installation close to the off-board EVBC is of pertinent importance. As the most pertinent example of RES, solar photovoltaic panels can be mounted in EV charging stations, as well as in industries. This is an advantage for solutions as described in this section. Since the off-board EVBC and RES require similar front-end power stages, the identified opportunity consists of unifying both systems targeting a single interface with the electrical grid. **Figure 26** illustrates this opportunity, requiring a common dc-link for both EV and RES. The utmost advantage of this opportunity is about the efficiency. In this condition, as the EV establishes a direct interface with the RES for the charging (over the dc-link and requiring less power stages), it is conceivable to boost the efficiency when compared to customary solutions (based on various front-end and back-end power stages).

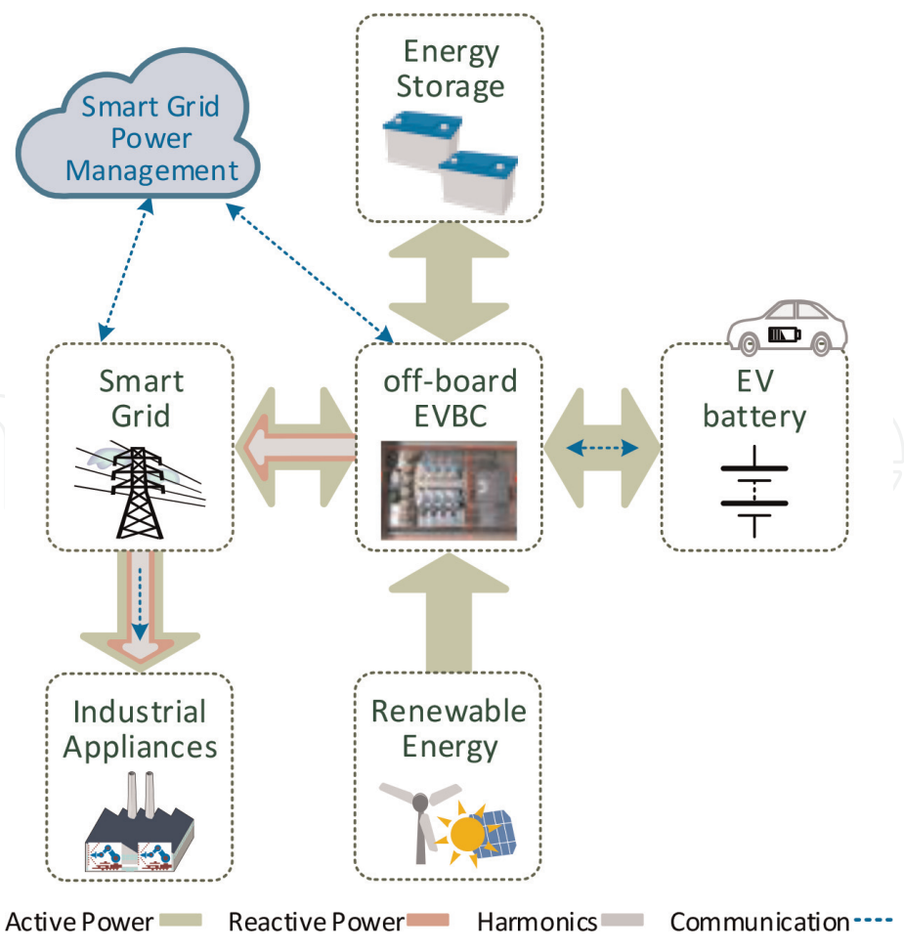


Figure 27.
An off-board EVBC with an EV plugged-in into the electrical power grid: unified operation with RES, ESS, and as a power quality compensator.

7.2.4 Unified operation: power quality compensator and interface of energy storage systems and renewable energy sources

Based on the previously identified opportunity, adding a bidirectional dc interface to the off-board EVBC results in a new opportunity for interfacing an ESS (bidirectional power transfer, charging or discharging, with the dc-link). Consequently, in this circumstance, based on the off-board EVBC, a whole system is offered for the smart grid: interface of G2V/V2G modes; interface of a RES; and interface of a flexible ESS. **Figure 27** illustrates this new opportunity (based on the common dc-link, a single interface with the electrical grid is considered). In this approach, for instance, the power from the RES can be injected directly into the EV (as well as to the ESS), avoiding the electrical grid. Consequently, in this process, fewer power stages are required, allowing to improve the efficiency of the process. A pertinent aspect is also associated when the EV is plugged-in. Since it requires a high value of power in a short period of time, therefore, the ESS is an important influence to avoid power fluctuations in the electrical grid side (in this occasion, the power for the EV can be provided by the ESS). On the other hand, in a situation where the EV is not plugged-in, the RES and the ESS are integrated through the same system, permitting the operation similar to a load shift system (basically, the power production from RES can be stored in the ESS for a posterior use, when convenient for the electrical installation). Moreover, even in a case where the EV is not plugged-in, the RES is not producing, and the ESS is not required, the off-board EVBC can operate for compensating the aforementioned problems of power quality (directly caused by the industrial appliances or in a selective strategy for the smart grid).

8. Conclusions

In this book chapter, technologies, challenges, and a global perspective for the vehicle electrification in smart grids are presented. The new reality of shifting the transportation sector targeting the vehicle electrification, mainly with plug-in electric vehicles (EV), is boosted by climate concerns. However, this new paradigm also promotes a set of emergent technologies, such as: power electronics for on-board and off-board battery charging systems; communication technologies; wireless power transfer for charging processes; bidirectional power transfer in vehicle-to-vehicle mode; unified technologies combining the battery charging system and the motor driver based on a single system; and operation modes of the EV, both on-board and off-board, in smart homes and smart grids. The importance of these emergent technologies for the vehicle electrification is described along this book chapter, as well as the relation among them. The identified EV battery charging operation modes can be performed independently of the charging system structure (i.e., the number and types of power stages for the on-board and off-board charging system). Moreover, since some operation modes only require the front-end power stage (ac-dc converter), technologies of wireless power transfer can also be considered. Similarly, unified technologies of battery charging and motor driver can also be considered for the implementation of the presented operation modes. Furthermore, combined technologies of wireless power transfer and unified systems are also possible in the implementation of some operation modes. Despite the relevance of these technologies in terms of power transfer, communication technologies are absolutely indispensable for defining the operation modes, establishing a bidirectional link for data transfer and power management between the smart grid or smart home, the user, and the EV. This book chapter covers these technologies,

demonstrating the relevance of the vehicle electrification, not only as a new paradigm for the transportation sector, but also as a promoter of smart grids.

Conflict of interest

The authors declare no conflict of interest.

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