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Chapter 3

The Role of Off-Board EV Battery Chargers in Smart Homes and Smart Grids: Operation with Renewables and Energy Storage Systems

Vitor Monteiro

ALGORITMI Research Centre
Department of Industrial Electronics, University of Minho, Portugal.
Email: vmonteiro@dei.uminho.pt

Jose Afonso

CMEMS-UMinho Center
Department of Industrial Electronics, University of Minho, Portugal.
Email: jose.afonso@dei.uminho.pt

Tiago Sousa

ALGORITMI Research Centre
Department of Industrial Electronics, University of Minho, Portugal.
Email: tsousa@dei.uminho.pt

Joao L. Afonso

ALGORITMI Research Centre
Department of Industrial Electronics, University of Minho, Portugal.
Email: jla@dei.uminho.pt

Abstract

Concerns about climate changes and environmental air pollution are leading to the adoption of new technologies for transportation, mainly based on vehicle electrification and the interaction with smart grids, and also with the introduction of renewable energy sources (RES) accompanied by energy storage systems (ESS). For these three fundamental pillars, new power electronics technologies are emerging to transform the electrical power grid, targeting a flexible and collaborative operation. As a distinctive factor, the vehicle electrification has stimulated the presence of new technologies in terms of power management, both for smart homes and smart grids. As the title indicates, this book chapter focuses on the role of off-board EV battery chargers in terms of operation modes and contextualization for smart homes and smart grids in terms of opportunities. Based on a review of on-board and off-board EV battery charging systems (EV-BCS), this chapter focus on the off-board EV-BCS framed with RES and ESS as a dominant system in future smart homes. Contextualizing these aspects, three distinct cases are considered: (1) An ac smart home using separate power converters, according to the considered technologies; (2) A hybrid ac and dc smart home with an off-board EV-BCS interfacing RES and ESS, and with the electrical appliances plugged-in to the ac power grid; (3) A dc smart home using a unified off-board EV-BCS with a single interface for the electrical power grid, and with multiple dc interfaces (RES, ESS, and electrical appliances). The results for each case are obtained in terms of efficiency and power quality, demonstrating that the off-board EV-BCS, as a unified structure for smart homes, presents better results. Besides, the off-board EV-BCS can also be used as an important asset for the smart grid, even when the EV is not plugged-in at the smart home.

Keywords: Vehicle Electrification, On-Board EV Battery Charger, Off-Board EV Battery Charger, Renewable Energy Sources, Energy Storage Systems, Power Quality, Smart Grids, Smart Homes.

3.1 Introduction

The spread of electric mobility is experiencing a steady growth worldwide, in special concerning the private-level contribution, where its participation in the transportation sector is identified as a key paradigm for substituting conventional vehicles based on internal combustion engines. In this context, varied technologies are available, demonstrating an appropriate contribution to sustainability. The issues, challenges, and opportunities of vehicle electrification are investigated in [1] and [2], and a survey about this topic in the context of the smart grid is offered in [3]. Among the different technologies, the most representative is the pure plug-in battery electric vehicle (EV) and the hybrid plug-in EV. From the power grid point of view, both two types of EVs are plugged-in to absorb power through EV battery charging, where the main difference is the required time for the charging since the capacity of their energy storage system (ESS) is very different. Therefore, for simplicity, in the scope of this book chapter, the designation "EV" is used for both types of vehicles. In this context, it is important to note that the use of hybrid ESS is conceivable for both cases, mainly based on batteries and ultra-capacitors as support for sudden requirements of power [4]. The number of plug-in EVs available for purchase is growing, especially along the last two decades, all of them equipped with an on-board EV battery charging system (EV-BCS) and some also permitting external charging using equipment designated as off-board EV-BCS.

Concerning the power transfer interaction between most of the commercially available EVs and the power grid, only the EV battery charging, i.e., the unidirectional power transfer from the power grid to the EV, is possible [5][6]. This unidirectional operation is designated in the literature as grid-to-vehicle (G2V), and it is common for both on-board and off-board EV-BCS. Nevertheless, since the power flows from the power grid to the EV, the latter can be understood in two distinct functions: (1) As a normal electrical appliance for the power grid, consuming power randomly in terms of schedules and charging point (independently of the power quality matters, in terms of harmonic current and power factor); or (2) As an electrical appliance with the possibility of flexible control schedules.

In this scenario, the EV introduction into the power grid is of utmost importance, since the EV is identified not only as a key element to mitigate the emission of greenhouse gases, but may also enable a useful power transfer collaboration with the power grid. In this perspective, for the power grid, the presence of the EV becomes even more relevant when it is controlled in a flexible way, allowing accomplishing three main features: (1) The EV operation can be controlled for absorbing power from the power grid in specific schedules, controlled by the smart grid, according to the power limits of the EV-BCS, independently of the place where it is plugged-in (e.g., at a smart home); (2) The EV can be set up for storing energy in a specific place where it is plugged-in, and, due to its natural mobility, transport the stored energy for a different place in the power grid (e.g., it can be interesting for power management between different smart homes); (3) The EV can be controlled for injecting power into the power grid, conferring the necessities of the electrical installation of the place where it is plugged-in, or the necessities of the smart grid (e.g., the EV can be plugged-in to the smart home, but injecting power as a service for the smart grid, independently of the smart home power management). Within this context, as an example, an admission and scheduling mechanism for EV charging is proposed in [7], and a scheduling strategy for the EV, framed in residential demand response programs, is proposed in [8].

Based on the possibilities of the EV interaction with the power grid, together with the G2V mode arises the vehicle-to-grid (V2G) mode, which is a bidirectional mode, permitting a power flow from the power grid (smart grid or smart home) to the EV and vice-versa [9][10][11]. The G2V/V2G power interaction may be investigated also from the perspective of coordinated controllability [12][13][14]. Contextualizing this scenario, an on-board EV-BCS incorporated into a smart home is illustrated in Fig. 1, where the G2V/V2G modes are identified. As it can be seen, since a smart home is considered, the smart home power management can communicate with the EV-BCS, with the smart grid, with the electrical switch-board, and with the controlled smart electrical appliances. As represented in Fig. 1, the EV can either consume power from the grid (G2V) or deliver power (V2G) for the smart home, the smart grid, or both at the same time (i.e., a parcel of the power injected by the EV is consumed by the electrical appliances of the smart home and another parcel is injected into the power grid). Besides the G2V/V2G controllability, particularly along the last decade, novel paradigms of operation were proposed targeting power quality improved features (e.g., in the presence of unpredictable power outages, in islanded power grids, in situations of compensating harmonics, and in circumstances of producing reactive power).

Concerning all of the aforementioned aspects, the main contributions of this book chapter are: (1) A complete investigation about technologies of on-board and off-board EV-BCS and advanced operation modes outlined in smart homes and smart grids; (2) A comprehensive explanation about upcoming perspectives of operation for on-board and off-board EV-BCS, and their innovative association with renewable energy sources (RES) and ESS, when framed with smart grids and with ac, dc or hybrid smart homes; (3) A validation taking into account the upcoming perspectives, addressed in the previous point, for the off-board EV-BCS operation in smart homes and smart grids.

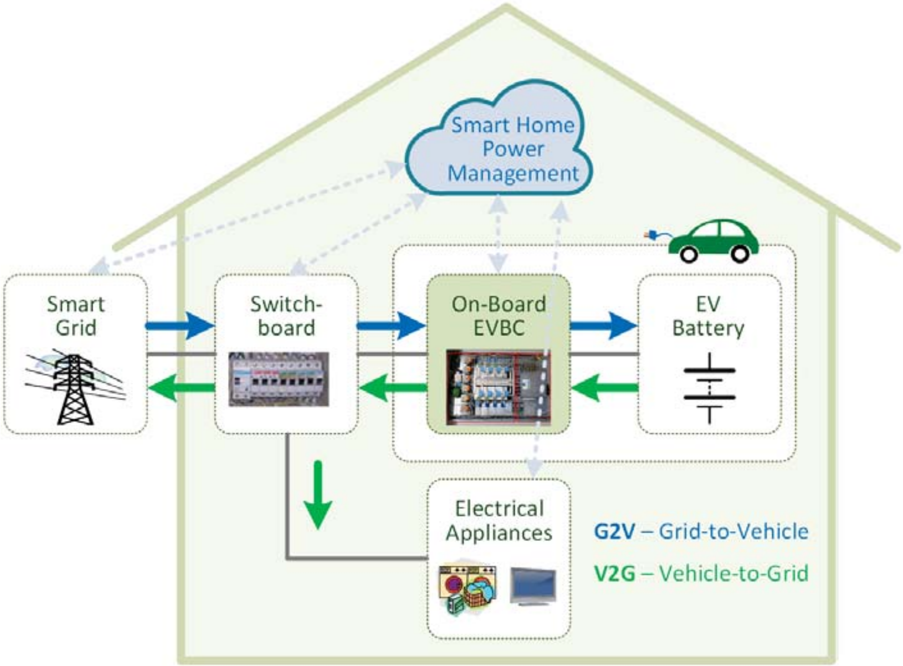


Fig. 1. On-board EV-BCS in a smart home scenario: G2V/V2G modes.

3.2 EV Operation Modes: An Overview

As described in the introductory section, there is a bidirectional opportunity associated with the EV interaction with the power grid through the G2V/V2G modes. In fact, the G2V/V2G modes are already a reality and an encouraging factor for enhancing the interaction with smart homes and smart grids. Nevertheless, these modes are only used for exchanging active power according to the necessities of the smart grid or smart home, i.e., the EV is controlled based on an on/off strategy. In this way, the schedules for the charging (G2V) or discharging (V2G) processes are defined by the management system, but the value of active power to be exchanged is defined neglecting relevant factors, for instance, other constraints of the smart home. This influence is very pertinent, allowing the use of the plugged-in EVs to improve the efficiency and the power quality aspects for the power grid side [15][16][17][18]. From this point of view, despite the increased wear of the EV battery and the consequent reduction of the battery lifetime due to the G2V/V2G operation, the EV driver can also benefit from this interaction, since interesting tariffs for programs of G2V/V2G are emerging, permitting to establish collective schedules for charging (G2V) and discharging (V2G) [19][20][21].

Since the EV can be plugged-in in distinct places, the control complexity increases for the smart grid, even with the flexibility in terms of operation modes. This is also valid for scenarios of microgrids [22][23]. A specific case is related to the possibility of the EV to operate in V2G or vehicle-to-vehicle (V2V) mode in microgrid scenarios [24]. A smart microgrid with optimal joint scheduling for the EV and the electrical appliances of a smart home is proposed in [25]. Besides the conventional G2V/V2G validations [26][27], emerging G2V/V2G future interfaces are also identified [28]. When considering the intermittency of the power produced from RES, the G2V/V2G flexibility is even more relevant, since the EV can be used as a power compensation system, i.e., similar to an energy buffer, capable of consuming, storing, or delivering power as a function of the RES intermittence. In this context, a strategy of accommodating the EV operation into the power grid, as a function of the power production from RES, is available in [29]. Considering the EV operation in G2V/V2G modes, a specific control algorithm based on RES production for demand-side management is presented in [30]. A specific cooperative combination between the EV and RES in terms of controllability, with the main objective of reducing emissions and costs, is offered in [31]. An optimal cost minimization about the EV charging with operation modes for the smart grid and smart home is presented in [32].

The associated operation of the EV with RES is not only limited to a smart grid perspective. In fact, this mixed operation is also very applicable for smart homes, as demonstrated in [33], since smart homes are a strategic contribution to smart grids. Therefore, technologies and foresight for the EV integration in smart homes are discussed in [34], and an EV optimization in a smart home from the customer point of view is analyzed in [35]. All the aforementioned technologies (in the context of smart grids and smart homes), as well as the cooperative operation with RES, are considered in the perspective of EV-BCS only in the G2V/V2G modes. Nevertheless, other opportunities are identified in the literature with relevant potential prospecting smart grids and smart homes.

The home-to-vehicle (H2V) is interesting in the smart home perspective, requiring a plugged-in EV. In fact, the H2V mode is similar to the G2V mode. Nevertheless, as a distinctive characteristic, the H2V mode offers the possibility of power controllability in opposite to the conventional on/off approach. This is predominantly relevant, since it involves the EV in the smart home management more effectively, offering more flexibility of controllability together with the controlled electrical appliances. In the H2V mode, the value of the operating power can range from zero to the nominal power. Moreover, for both the EV and the electrical appliances, strategic levels of precedence can be planned. For instance, through a mobile app, the EV user can outline their preferences. Considering the context of the H2V mode in the smart home, three main cases can be highlighted. In the first case (a), maximum priority is defined to the EV. In this way, the EV has more priority than the electrical appliances, and then it is charged with maximum power, where, in this circumstance, the electrical appliances are turned-off if necessary (this occurs when some electrical appliances can be turned-off and it is indispensable, as fast as possible, the EV charging). In a second case (b), the EV is defined to have priority only over some specific electrical appliances. In this way, the EV is charged with fixed power, but different from the maximum power that is permitted by the EV-BCS. In such circumstance, it is guaranteed a fixed value of power for the EV charging, and to avoid the circuit breaker tripping, the electrical appliances are programmed in different schedules. In a third case (c), a minimum priority is established to the EV, where the value of power results from the difference between the smart home nominal power and the instantaneous power consumed. If the electrical appliances are turned off, then the EV is charged with maximum power (similar to the case (a)). Instead, if the electrical appliances are turned on and turned off, then the EV is charged with variable power. Summarizing, the H2V mode is comparable to the G2V, but permitting the adjustable charging power. Instead, it is also important to note that the H2V strategy can also be used during the discharging process. In this way, the EV can inject power to the smart home or the smart grid, but as a function of the electrical appliances. A specific case occurs when the power consumed by the electrical appliances exceeds the nominal power of the smart home. In this circumstance, the EV can be controlled just to provide the difference of power (between the nominal value and the required by the electrical appliances).

3.3 Operation Modes: Future Perspectives

Future viewpoints for the EV are discussed in this section, highlighting the relation with the G2V/V2G/H2V modes, but establishing new opportunities for the EV-BCS, involving the requirements of the smart grids and the smart homes (with ac, dc, or hybrid electrical installations [36]).

3.3.1 On-Board EV BCS

Fig. 2 illustrates an on-board EV-BCS in a smart home considering the G2V/V2G/H2V modes, as well as a new mode for its operation, which is related to power quality. Although the demonstration is for a smart home, this new operation mode can be also framed with smart grids, contributing to define new control strategies and energy policies under the smart grid scope.

Based on the analysis of Fig. 2, three different cases are identified: (a) the on-board EV-BCS can be controlled for exchanging power with the smart home, providing power only in accordance with the requirements of the smart home management system, i.e., the G2V/V2G/H2V operation is limited to the smart home scope; (b) the on-board EV-BCS can be controlled for exchanging power with the smart grid, providing power only in accordance with the requirements of the smart grid management system, i.e., the G2V/V2G operation is limited to the smart grid scope, and the H2V is not considered in this control strategy; (c) the on-board EV-BCS can be controlled, at the same time, with the smart home and with the smart grid, i.e., the three G2V/V2G/H2V modes are adjusted within the smart home and smart grid scope.

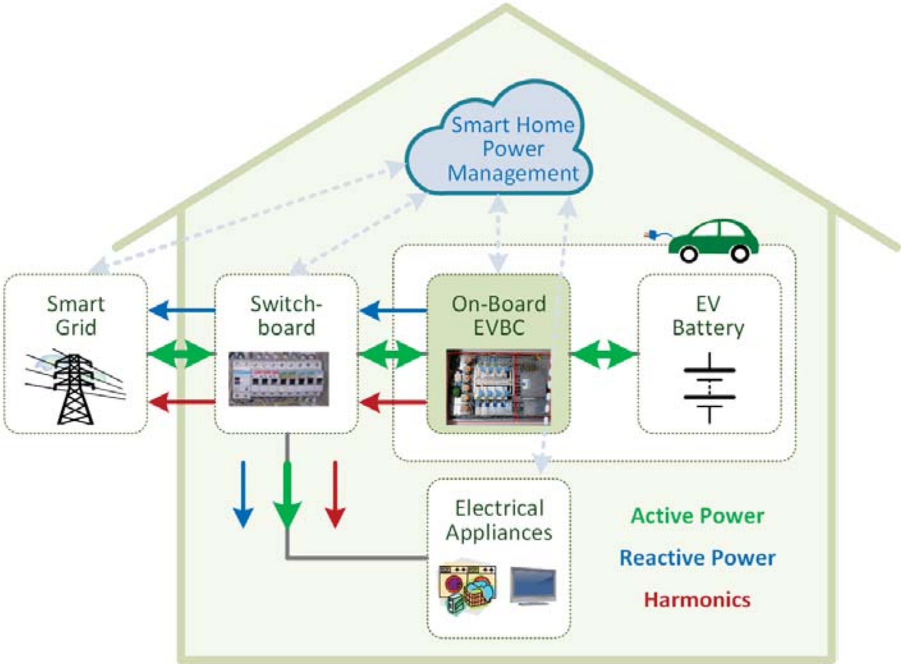


Fig. 2. On-board EV-BCS in a smart home scenario: Operation in G2V/V2G modes and compensating problems of power quality, both for smart home and smart grid (harmonic currents and low power factor).

Besides the G2V/V2G/H2V modes, the on-board EV-BCS can also be controlled in a perspective of compensating power quality problems. This mode is identified as vehicle-for-grid (V4G) since the on-board EV-BCS is used to provide additional services for the grid. This mode is exceptionally relevant since it does not interfere with the G2V/V2G/H2V modes, i.e., the V4G mode can be combined with each of the G2V/V2G/H2V modes. Moreover, it does not require to use the EV battery, since only the front-end converter of the on-board EV-BCS is used. Using the EV in this mode, independently or not of the G2V/V2G/H2V modes, almost all the harmonic currents and the power factor of the smart home can be compensated. However, in the smart grid perspective, when the EV is plugged-in at the smart home, the on-board EV-BCS can be used only to produce specific harmonic currents and a specific value of reactive power for compensating the power factor (e.g., other EV plugged-in neighboring smart homes can operate with the same functionalities to compensate all the current harmonics and power factor of a specific part of the smart grid). This is particularly relevant, making emerge another perspective for the EV in smart homes, which is associated with the selective harmonic current compensation. In this strategy, each EV is controlled to produce a specific harmonic current for the smart grid. Notwithstanding the strong benefits of the on-board EV-BCS operating in G2V/V2G/H2V/V4G modes for the smart home and the smart grid, a crucial drawback is notorious: these modes are only conceivable if the EV is plugged-in at the smart home (since the on-board EV-BCS is used). However, from the power grid point of view, a new important benefit is recognized: the EV can operate in the G2V/V2G/H2V/V4G modes where it is plugged-in, representing a dynamic system conferring an important asset for smart grids. As previously demonstrated, the EV can be controlled in the G2V/V2G/H2V/V4G modes, where the specific V4G mode is linked to the compensation of harmonic currents and power factor.

This new opportunity is also relevant taking into account that the derived costs caused by power quality problems are substantially high around the world [37][38][39]. Therefore, the EV can be used as a dispersed and dynamic active power filter within the power grid, demonstrating that it can be an added value for supporting power quality. Equivalent opportunities are obtainable based on computer simulations in [40] and [41], but in the perspective of the EV powertrain. The option just for producing reactive power, as a requirement of the power grid, is investigated in [42], [43], [44], [45], and in [46], but neglecting the capability of harmonic current compensation. The option for compensating harmonics and reactive power only during the G2V mode is assumed in [47], which is a pertinent drawback since the EV manufacturers are presenting the V2G mode and this option is independent of the G2V/V2G mode. The exploitation of the V2G mode for power quality improvement is proposed in [48] for a smart grid perspective. The possibility to use an on-board EV-BCS in four quadrants is offered in [49], which is based on an experimental validation in G2V/V2G modes, but only considering the production of reactive power, i.e., neglecting the harmonic current compensation. In [50] is proposed an external system, only validated by computer simulations, where the necessary coupling passive filters are installed, limiting the option of linking the EV to any outlet. In [51] is presented a three-phase off-board EV-BCS offering the capability of harmonic current and reactive power compensation. Another three-phase off-board EV-BCS is proposed in [52], but only for harmonic current compensation, neglecting the power factor compensation, as well as the possibility of a combined operation in G2V/V2G modes.

Nevertheless, also within the V4G mode, the on-board EV-BCS can be controlled to compensate other power quality problem: power outages of short duration at the smart home level. Taking into account this scenario, besides the G2V/V2G modes, the operation of the EV as a power source for the electrical installation, when it is not plugged-in to the power grid, is considered in [53]. Correspondingly, the possibility of using the EV as a backup generator at the residential level is proposed in [54]. This particular concept is denominated as vehicle-to-home (V2H), since, when required, the EV can be used to feed the electrical appliances in the smart home. A more convenient situation is related to the possibility of using the EV as an off-line uninterruptible power supply (UPS). This possibility was initially considered in [55], based on preliminary results used to validate the operation mode when considering linear electrical appliances (representing an unrealistic condition). In this context, it must be highlighted that, sometimes, the designation of V2H is also considered for aggregating the G2V/V2G modes for the EV at residential level [56][57], but without the possibility of operation as an off-line UPS. The possibility of operation in V2H mode is particularly committed to smart homes during the occurrence of power outages, representing a relevant contribution for improving reliability and security against failures at the power grid level. These methodologies comprise the operation of the EV in smart homes as an ESS [33], the flexibility for managing the power consumption and user comfort at the smart home [58][59], and an optimal control scheduling considering the electrical appliances power consumption [60]. Nissan proposed the EV operation through the “LEAF to Home” [61], and Mitsubishi and Toyota have also similar platforms [62]. Nevertheless, in such platforms, the EV does not allow the operation as an off-line UPS.

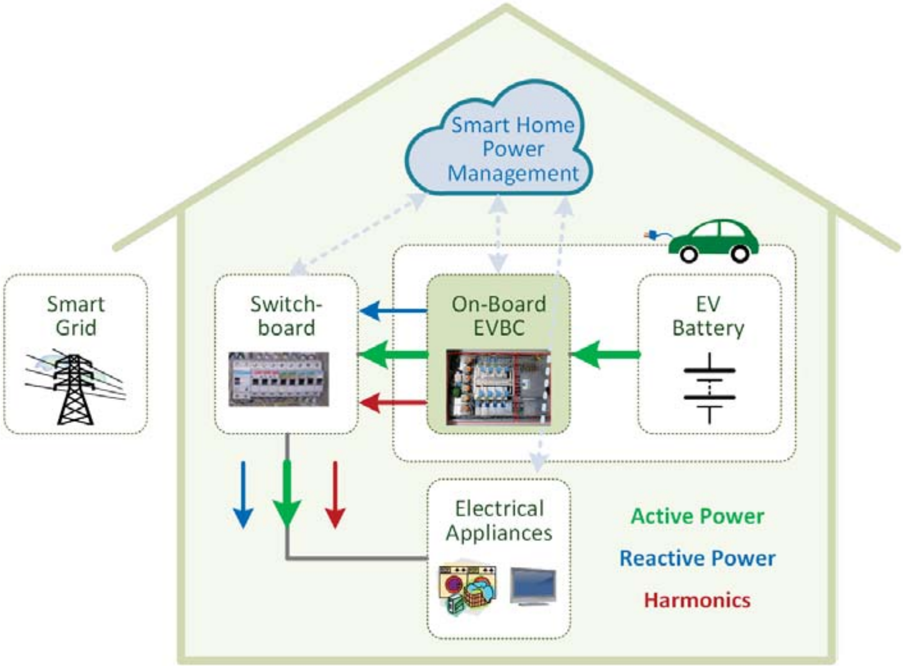


Fig. 3. On-board EV-BCS in a smart home scenario: Operation in G2V/V2G modes and compensating problems of power quality for the smart home (power outages using the EV as a power supply).

Fig. 3 illustrates this case, where the EV battery is the power source of the smart home, the on-board EV-BCS is controlled as an inverter, and the smart home is not connected to the smart grid. In this particular case, the on-board EV-BCS is controlled with voltage feedback to guarantee a stable voltage, both in terms of amplitude and frequency, even with sudden variations of the electrical appliances (which will define the current waveform). Since the EV battery is the power source of the smart home, the management of the battery state-of-charge must be determined with maximum accuracy [63]. More specifically, when the EV is forced to operate in this mode, the power management of the smart home can control some of the non-priority electrical appliances to be turned-off, contributing to preserving the EV battery.

3.3.2 Off-Board EV BCS

Besides the application of the G2V/V2G/H2V/V4G modes for on-board EV-BCS, these modes can also be applied to off-board EV-BCS. Therefore, the previous descriptions of these modes are also valid when considering off-board EV-BCS. Fig. 4 illustrates an off-board EV-BCS and an EV plugged-in at a smart home. Taking into account the use of an off-board EV-BCS at the smart home level, the existing opportunities are even more appropriate, since the off-board EV-BCS is permanently connected to the smart home. Consequently, independently of the EV presence at the smart home, some of the previous operation modes are also available, representing an added value for the smart home. As an example, the off-board EV-BCS can offer power quality functionalities, both for the smart home and for the smart grid, precisely as the on-board EV-BCS. Nevertheless, as a vital differencing factor, the functionalities offered by the V4G can be provided independently of the EV presence, while the G2V/V2G/H2V modes are only accessible when the EV is present (a situation that also occurs for on-board EV-BCS). Fig. 5 illustrates a vision of an off-board EV-BCS in a smart home, but without an EV plugged-in. As shown, the V4G mode is possible in terms of compensation of harmonic currents and power factor, but, since the EV is not plugged-in, the possibility of operation during power outages is not possible.

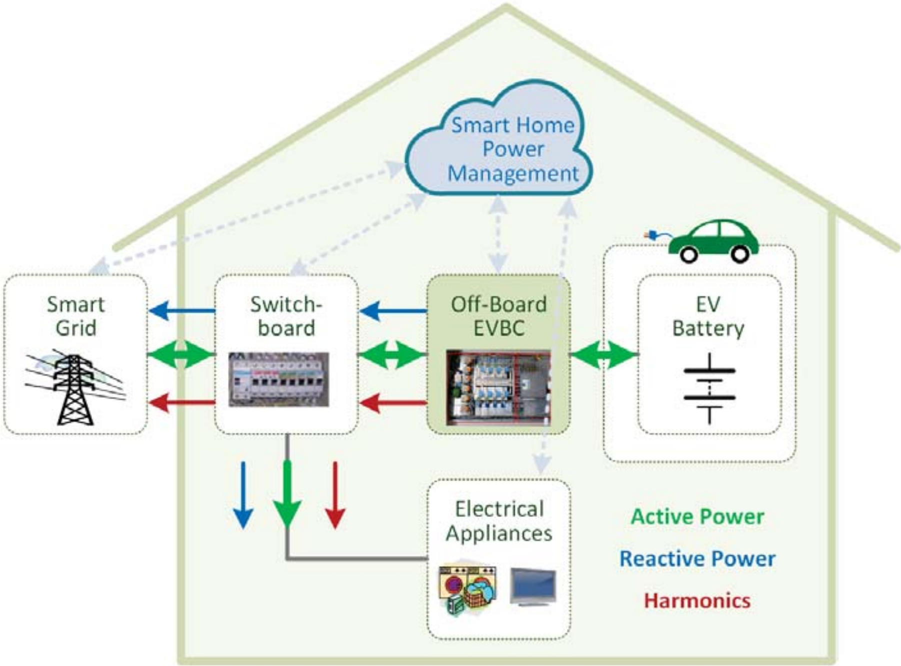


Fig. 4. Off-board EV-BCS in a smart home scenario with an EV plugged-in:
Operation in G2V/V2G modes and compensating problems of power quality, both for smart home and smart grid (harmonic currents and low power factor).

Despite the relevance of the aforementioned modes, the foremost future opportunity associated with off-board EV-BCS is about the interfacing of other technologies for smart grids and smart homes, namely the technologies of ESS and RES [64]. In this way, the main objective consists of using the same off-board EV-BCS to interface a dc-dc converter for RES (unidirectional mode), as well as a dc-dc converter for ESS (bidirectional mode), where a shared dc-link is used for such purpose. This is distinct from the conventional solutions based on multiple power stages for encompassing the EV, the RES, and the ESS [65].

It must be highlighted that the integration of an off-board EV-BCS encompassing this opportunity denotes a complete solution involving the smart home three key technologies: EV in bidirectional mode, ESS, and RES. This opportunity is different from the conventional cooperation between the EV and the ESS using independent systems [66]. Fig. 6 illustrates this specific situation, where the single interface for the power grid is highlighted, avoiding the necessity of additional ac-dc converters to interface RES and ESS (i.e., this solution requires less two ac-dc converters). Furthermore, this opportunity is even more relevant when considering the migration from ac grids to dc grids, where the requirements of ac-dc converters are severely reduced. Moreover, since the majority of the electrical appliances include a front-end ac-dc converter that is only used to interface the ac grid, this opportunity gains new relevance to avoid the use of multiple ac-dc power converters.

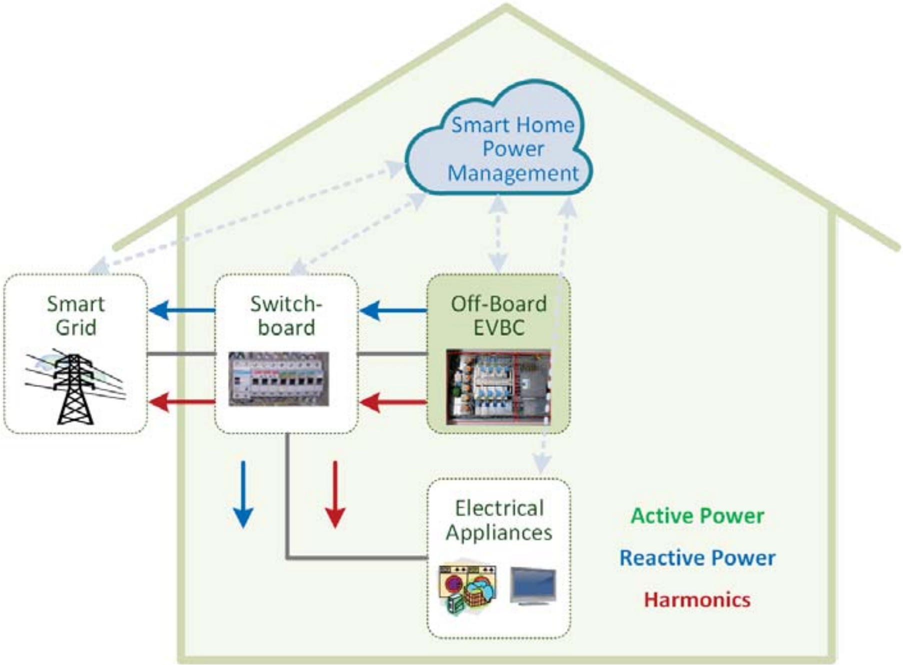


Fig. 5. Off-board EV-BCS in a smart home scenario without an EV plugged-in: Operation in G2V/V2G modes and compensating problems of power quality, both for smart home and smart grid (harmonic currents and low power factor).

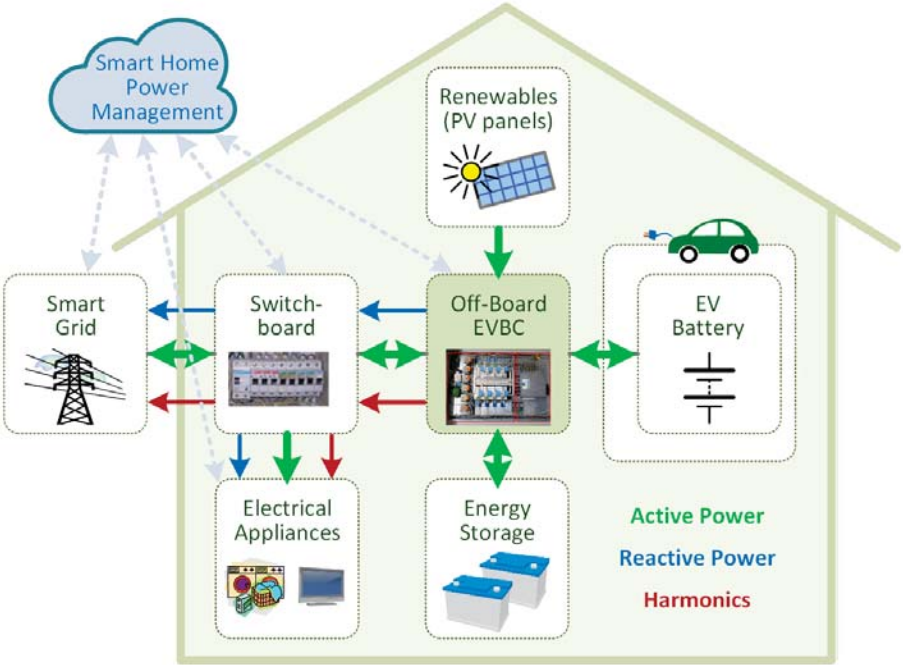


Fig. 6. Off-board EV-BCS in a hybrid smart home scenario with an EV plugged-in: Operation in G2V/V2G modes and compensating problems of power quality, both for smart home and smart grid (harmonic currents and low power factor). The RES (solar photovoltaic panels) and the ESS (batteries) are interfaced through a shared dc-link, while the electrical appliances are directly connected to the ac grid.

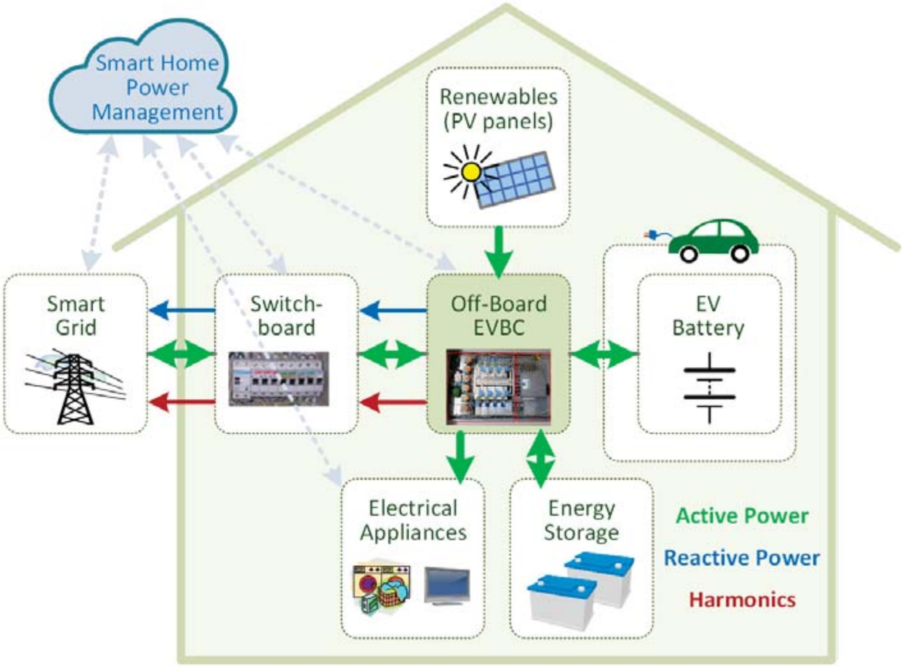
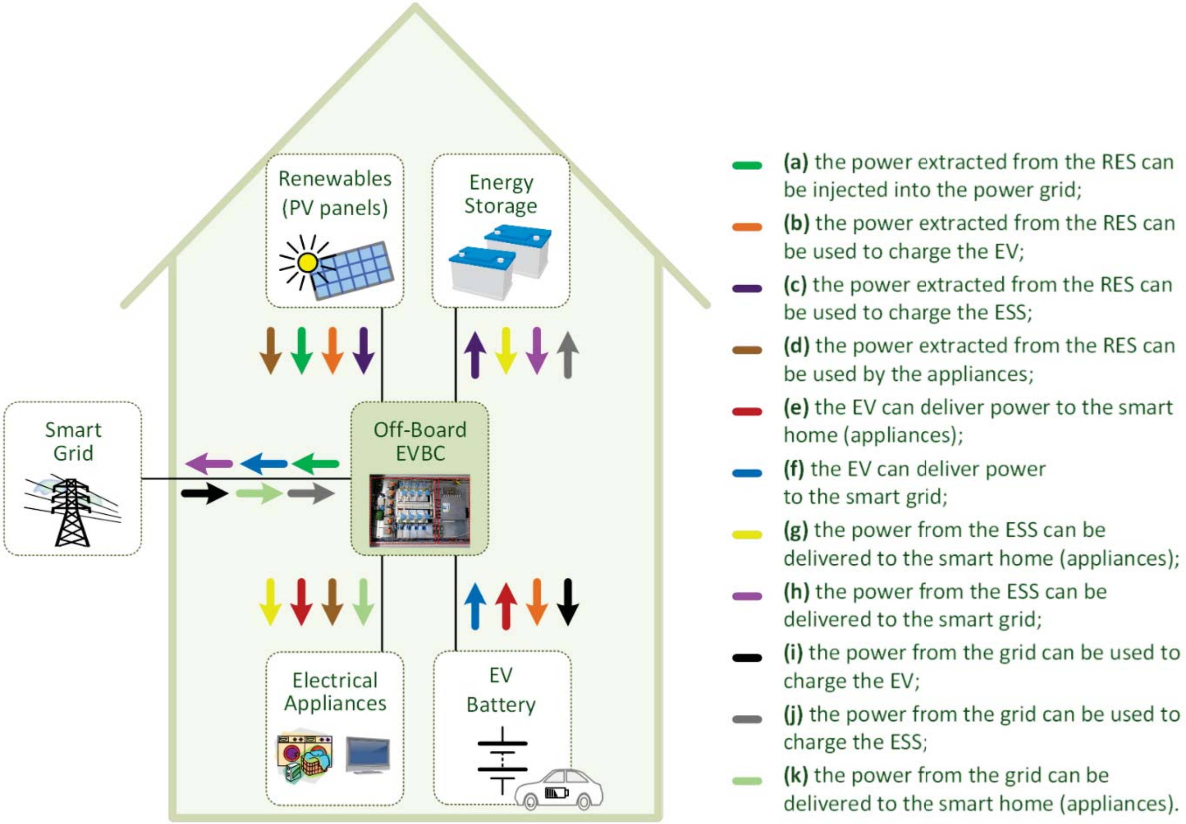


Fig. 7. Off-board EV-BCS in a dc smart home scenario with an EV plugged-in: Operation in G2V/V2G modes and compensating problems of power quality, both for smart home and smart grid (harmonic currents and low power factor). The RES (solar photovoltaic panels), the ESS (batteries), and the electrical appliances are interfaced through a shared dc-link.



- 🟩 **(a)** the power extracted from the RES can be injected into the power grid;
- 🟧 **(b)** the power extracted from the RES can be used to charge the EV;
- 🟪 **(c)** the power extracted from the RES can be used to charge the ESS;
- 🟫 **(d)** the power extracted from the RES can be used by the appliances;
- 🟥 **(e)** the EV can deliver power to the smart home (appliances);
- 🟦 **(f)** the EV can deliver power to the smart grid;
- 🟨 **(g)** the power from the ESS can be delivered to the smart home (appliances);
- 🟪 **(h)** the power from the ESS can be delivered to the smart grid;
- ⬛ **(i)** the power from the grid can be used to charge the EV;
- ◼ **(j)** the power from the grid can be used to charge the ESS;
- 🟩 **(k)** the power from the grid can be delivered to the smart home (appliances).

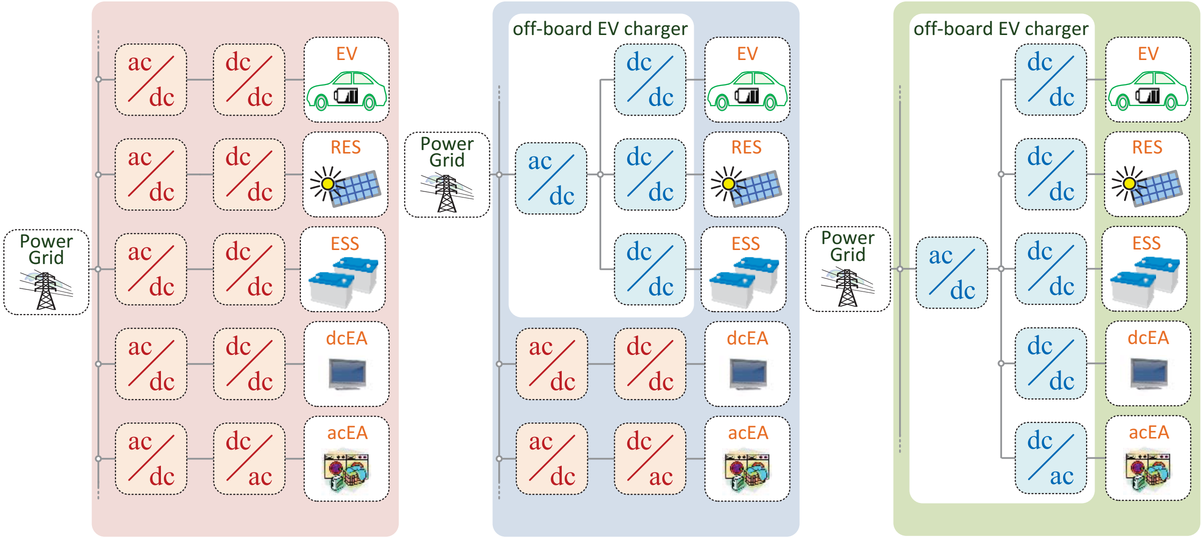
Fig. 8. Operation of the off-board EVBC within the smart home.

3.4 Validation of Off-Board EV Battery Chargers when Contextualized in Smart Homes and Smart Grids

Taking into attention the possibilities offered by the integrated solutions based on the off-board EV-BCS for smart homes and smart grids, this section introduces an analysis that was performed considering three distinct cases of a smart home.

In the first case (a), a conventional ac smart home was considered, where the electrical appliances are coupled to the ac power grid, as well as an on-board EV-BCS, a power converter to interface RES, and a power converter to interface ESS. In this case, independent power converters for each technology are used, which are based on front-end (ac-dc) and back-end (dc-dc) power stages. In the second case (b), a hybrid ac/dc smart home was considered, where the electrical appliances are coupled to the ac power grid (as in the conventional case), but an off-board EV-BCS is used to interface RES and ESS (sharing a common dc-link and avoiding the necessity of ac-dc converters for interfacing these technologies). In the third case (c), a dc smart home was considered as a future perspective, including an off-board EV-BCS as main equipment. Therefore, for interfacing the technologies, dc-dc and dc-ac converters were considered. Fig. 9 illustrates these three cases.

Dedicated simulation models were developed for each case based on the PSIM software. Considering the different technologies, the following situations were addressed: (a) a set of solar photovoltaic (PV) panels was considered as an example of RES, for a maximum power of 1.5 kW; (b) a set of lithium batteries was considered as an example of ESS, with nominal voltage of 200 V and capacity of 10 Ah; (c) a set of resistive loads was selected (dc electrical appliances); (d) an electric motor (induction) was selected (ac electrical appliances). On the other hand, for the power converters, the following conditions were addressed: (a) full-bridge converters as example of ac-dc converters to interface the power grid (voltage source converters controlled with current feedback); (b) half-bridge converters as example of dc-dc converters (also with current or voltage feedback); (c) full-bridge converters as example of dc-ac converters (also with voltage feedback).



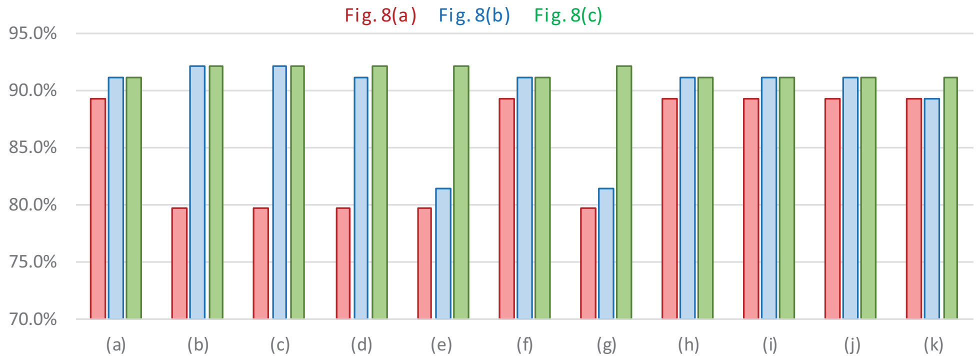
(a) (b) (c)

Fig. 9. Considered cases for analysis: (a) A conventional ac smart home (using ac-dc power converters for each technology); (b) A hybrid ac and dc smart home, where the electrical appliances are directly connected to the ac power grid, but an off-board EV-BCS interfaces RES and ESS; (c) A dc smart home, where an off-board EV-BCS is the only interface with the power grid equipment.

3.4.1 Comparative Analysis: Efficiency of the Different Cases

Taking into account the innovative modes allowed by the future off-board EV-BCS (used in a dc smart home to interface the EV, RES, ESS, ac electrical appliances, and dc electrical appliances), as presented in section 3 and based on the structures of Fig. 9, a comparative analysis was performed based on the efficiency of the different possibilities. Fig. 10 presents the estimated efficiency for each mode of operation that was defined for the off-board EV-BCS and considering the three cases for the smart home (a conventional ac smart home, a hybrid ac/dc smart home, and a dc smart home). By analyzing the obtained results, it is clear that the dc smart home is the case that presents better results, independently of the operation mode defined for the off-board EV-BCS. These results makes sense, since a single ac interface is used, and, when it is necessary to exchange power between technologies, only the dc-dc converters are used (i.e., the quantity of power stages is considerably reduced). By analyzing the worst case in terms of efficiency, it is clear that the first case presents the worst results since ac-dc converters are always required for the power grid interface, even when it is necessary to exchange power between dc technologies, as, for instance, between the ESS and the EV. It must be noted that similar values of efficiency, sometimes, were achieved, since some operation modes are equal, independently of the case in consideration.

Aiming to obtain results as comprehensive as possible, the operation of the off-board EV-BCS was considered in the different modes according to the cases identified in Fig. 9: (a) a conventional ac smart home with ac-dc power converters for each technology; (b) a hybrid ac and dc smart home, where only a RES and an ESS are interfaced by the off-board EV-BCS; (c) a future dc smart home, where the off-board EV-BCS interfaces the RES and the ESS, as well as the dc or ac electrical appliances. The values of reference for the operation in each mode (i.e., the power for the EV charging, the power extracted from the RES, the power of the ESS, and the power of the electrical appliances) were selected as exemplification situations of a real scenario of the application. It is important to note that the development of a power management algorithm, for the smart home or the smart grid, is out of the scope of this book chapter, as well as the communication strategies.



(a) The power extracted from the RES can be injected into the power grid;

(b) The power extracted from the RES can be used to charge the EV;

(c) The power extracted from the RES can be used to charge the ESS;

(d) The power extracted from the RES can be used by the appliances;

(e) The EV can deliver power to the smart home (appliances);

(f) The EV can deliver power to the smart grid;

(g) The power from the ESS can be delivered to the smart home (appliances);

(h) The power from the ESS can be delivered to the smart grid;

(i) The power from the grid can be used to charge the EV;

(j) The power from the grid can be used to charge the ESS;

(k) The power from the grid can be delivered to the smart home (appliances).

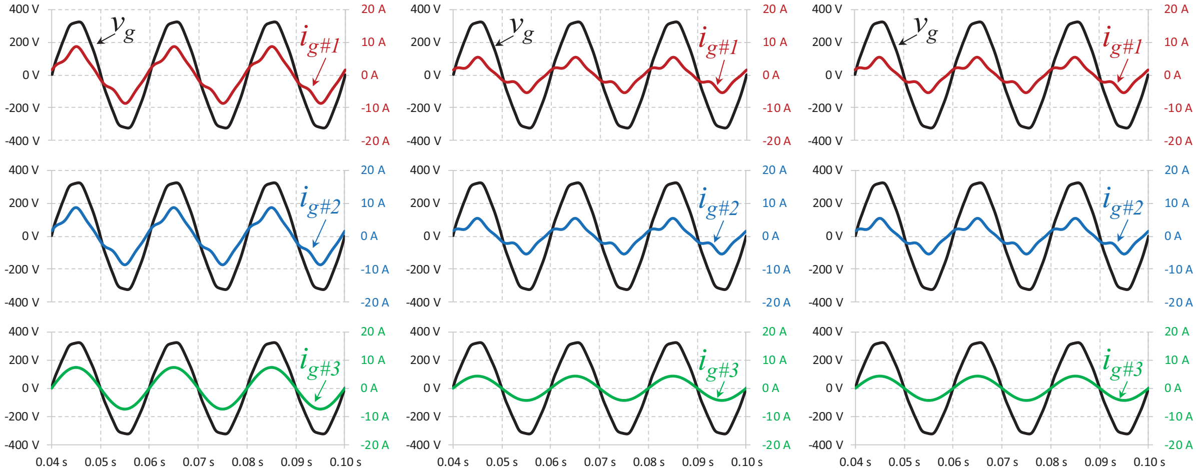
Fig. 10. Estimated efficiency for each case under analysis, where for each case were considered diverse perspectives of operation modes.

3.4.2 Comparative Analysis: Operation of the Different Cases

Fig. 11(a) shows the obtained results for the three cases when it is considered that only the electrical appliances are connected to the power grid, i.e., the power produced by the RES is zero, the EV is not plugged-in, and the ESS is not operating. For the electrical appliances, an active power of 1.2 kW and a reactive power of 225 VAr were measured. For the first and second cases, the current in the power grid ($i_{g\#1}$ and $i_{g\#2}$) is defined by the current consumption of the electrical appliances. Therefore, since the electrical appliances are categorized by linear and non-linear characteristics, the power grid presents harmonic distortion. In this case, the measured THD was 15.2% and the power factor was 0.97. In the third case, since an ac-dc converter is used to interface the power grid, the current in the power grid ($i_{g\#3}$) is sinusoidal, with a measured THD of 1.1% and with a unitary power factor. In this third case, the same electrical appliances were considered (i.e., the same active power), but removing the ac-dc converters to interface the power grid, since they are connected to the common dc-link through the dc-dc and dc-ac converters.

Fig. 11(b) also shows the obtained results for the three cases considering that the same electrical appliances are connected to the power grid (an active power of 1.2 kW and a reactive power of 225 VAr were measured), but with a power production from the RES (with a power about of 550 W), while the EV is not plugged-in and the ESS is not operating. In this circumstance, for both cases #1 and #2, the power produced by the RES is injected into the power grid with a sinusoidal waveform. However, since the power required by the electrical appliances is greater than the power produced by the RES, a parcel of power is absorbed from the power grid, resulting in a non-sinusoidal current in the power grid side, as demonstrated by the waveforms of the currents $i_{g\#1}$ and $i_{g\#2}$. In these cases, when compared with the situation reported in Fig. 11(a), the measured active power was 660 W and the reactive power was 225 VAr. For both cases, the measured THD of the current was 26.9%. In the third case, similar to the situation reported in Fig. 11(a), the current in the power grid ($i_{g\#3}$) is sinusoidal, with a measured THD of 1.2% and with a unitary power factor. However, since the power produced by the RES is consumed by the electrical appliance, the power absorbed from the power grid is reduced, also meaning that the amplitude of the power grid current ($i_{g\#3}$) is reduced. In this case, the power from the RES is directly used by the electrical appliance through the dc-dc converters.

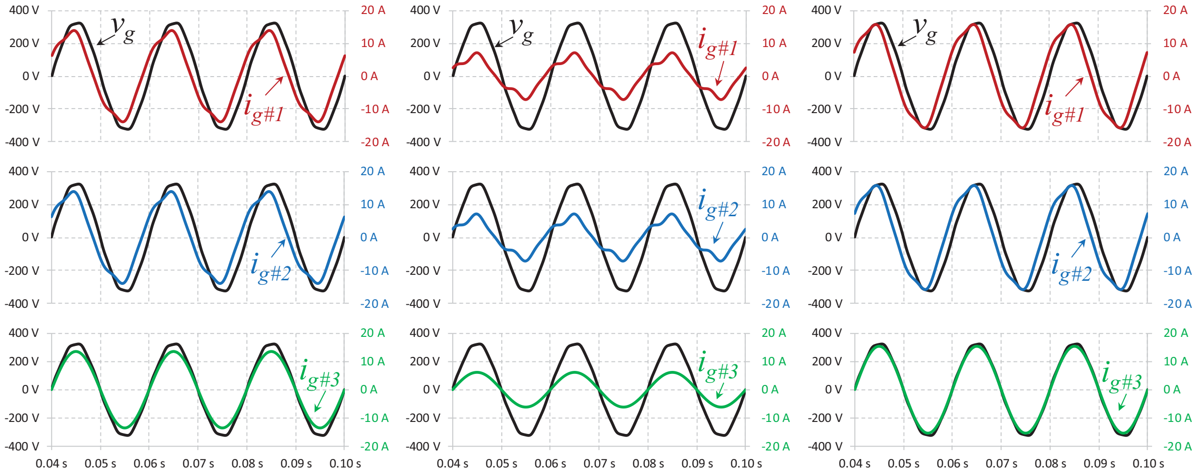
Finally, Fig. 11(c) shows the obtained results for the three cases considering that the same electrical appliances are connected to the power grid (an active power of 1.2 kW and a reactive power of 225 VAr were measured), with a power production from the RES (with a power about of 1 kW) and the ESS storing energy (with a power about of 450 W), while the EV is not plugged-in. Also, in this case, a parcel of power is absorbed from the power grid, resulting in a non-sinusoidal current in the power grid side, as demonstrated by the waveforms of the currents $i_{g\#1}$ and $i_{g\#2}$. For the first case, when compared with the situation reported in Fig. 11(b), the increased power production from the RES was stored in the ESS, therefore, from the power grid point of view, the waveform of the current is the same. This is valid since the current from the RES is sinusoidal (injected into the power grid) and the current absorbed from the ESS is also sinusoidal. For the second case, the situation is different, since a unified topology is considered for RES and ESS. In this case, the parcel of the power produced by the RES is directly stored by the ESS through the dc-dc converters. For the first case, the measured active power was 660 W and the reactive power was 225 VAr, and, for the second case, the measured active power and reactive power were similar. For both cases, the measured THD of the current was about 26.9%. In the third case, which is similar to the situation reported in Fig. 11(b), the current in the power grid ($i_{g\#3}$) is sinusoidal, with a measured THD of 1.2% and with a unitary power factor. When compared with the situation reported in Fig. 11(b), the increment of the power production from the RES does not influence the current in the power grid side since it was directly stored by the ESS through the dc-dc converters.



(a) (b) (c)

Fig. 11. Results concerning the three cases identified in Fig. 8:
(a) When the power grid provides power exclusively to the electrical appliances;
(b) When the power grid and the RES provide power to the electrical appliances;
(c) When the power grid and the RES provide power to the electrical appliances and to the ESS.

Similarly to Fig. 11, Fig. 12 shows some results where the off-board EV-BCS operates in different modes according to the different cases identified in Fig. 9. Fig. 12(a) shows the obtained results for the three cases when it is considered that the necessary power for the electrical appliances and for the EV charging is provided by the RES and by the power grid, i.e., analyzing all the technologies, only the ESS is not operating. For the electrical appliances, an active power of 1.2 kW and a reactive power of 225 VAr were measured. To perform the EV charging, a power of 2 kW was established, while the power production from RES was about 1 kW. Therefore, the power extracted from the RES is used for the electrical appliances, but a parcel of power is required from the power grid, both for the electrical appliances and for the EV charging. In the first case, since a parcel of power absorbed from the power grid is used for the electrical appliances, the waveform of the power grid current ($i_{g\#1}$) is distorted, even with the presence of the EV consuming a sinusoidal current. In this case, the measured THD of the power grid current ($i_{g\#1}$) was 8.3% and the power factor was 0.91. The on-board EV-BCS presents a sinusoidal current with a THD of 1.1% and a unitary power factor. In the second case, since a unified topology is considered, the power extracted from the RES is directly used by the EV through the dc-dc converters. In this circumstance, the power required by the EV is greater than the power extracted from the RES, meaning that a parcel of power must be absorbed from the power grid for the EV charging, added by the necessary power for the electrical appliances. Therefore, the measured THD of the power grid current ($i_{g\#2}$) was 8.3% and the power factor was 0.91. In the third case, due to the presence of a unified topology with a single ac-dc converter used to interface the power grid, the current in the power grid ($i_{g\#3}$) is sinusoidal, with a measured THD of 1.1% and with a unitary power factor. Again, it must be noted that the same electrical appliances were considered (i.e., the same active power), but removing the ac-dc converters to interface the power grid, since they are connected to the common dc-link through the dc-dc and dc-ac converters.



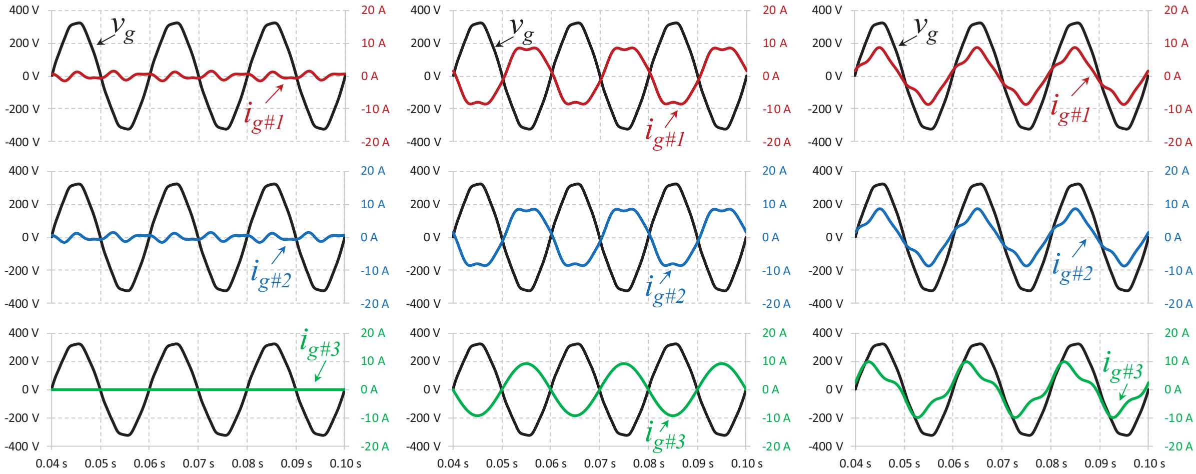
(a) (b) (c)

Fig. 12. Results concerning the three cases identified in Fig. 8:
(a) When the power grid and the RES provide power to the electrical appliances and to the EV;
(b) When the power grid and the ESS provide power to the electrical appliances;
(c) When the power grid and the ESS provide power to the electrical appliances and to the EV.

Fig. 12(b) shows the obtained results for the three cases when it is considered that the necessary power for the electrical appliances is provided by the ESS and by the power grid, i.e., the RES is not operating and the EV is not plugged-in. In this situation, the active power required by the electrical appliances is 1.5 kW and the power injected by the ESS is 500 W, meaning that the power grid must provide a power of 1 kW. In the first case, the ESS injects a sinusoidal current into the power grid (with a THD of 1.2% and in phase opposition with the voltage); however, taking into account the linear and non-linear characteristics of the electrical appliances, the current in the power grid side ($i_{g\#1}$) presents a THD of 18.4% and a power factor of 0.93. In the second case, a unified topology is used, but taking into account that the RES is not producing power and the EV is not plugged-in. This case is very similar to the situation reported in the previous case, where the current in the power grid side ($i_{g\#2}$) presents a THD of 18.4% and a power factor of 0.93. In the third case, the unified topology is considered, but the situation is very different from the situations reported in the previous case since the power from the ESS is directly used by the electrical appliances through the dc-dc and dc-ac converters. In this circumstance, power must be also absorbed from the power grid, but the current presents a sinusoidal waveform with a THD of 1% and a unitary power factor.

Fig. 12(c) shows the obtained results for the three cases when it is considered that the necessary power for the electrical appliances and the EV charging is provided by the ESS and by the power grid, i.e., analyzing all the technologies, only the RES is not operating. In this situation, the EV requires a power of 2 kW, the ESS provides a power of 1 kW, and the electrical appliances require a power of 1.5 kW. Therefore, the power grid must provide a power of 2.5 kW. In the first case, a parcel of power is absorbed from the power grid, since the power injected by the ESS is not enough for the requirements of the EV and the electrical appliances. Therefore, the current waveform presents harmonic distortion, with a measured THD of 7.3%, and a power factor of 0.9. In this case, the EV operates with a sinusoidal current and with a unitary power factor, similar to the ESS (but with a current in phase opposition with the voltage), but the current of the electrical appliances presents harmonic distortion. In the second case, a unified topology is considered, where the power from the ESS is directly used for the EV charging, meaning that only the dc-dc converters are used for such purpose. However, in this situation, the power required by the EV is greater than the power provided by the ESS, meaning that a parcel of power must be absorbed from the power grid, added by the necessary power for the electrical appliances. In this case, the current in the power grid side presents a THD of 7.3% and a power factor of 0.9. In the third case, it is also necessary to absorb a parcel of power from the power grid, since the power provided by the ESS is not enough for the requirements of the EV and the electrical appliances. In this case, due to the presence of a unified topology, the current in the power grid ($i_{g\#3}$) is sinusoidal, with a measured THD of 1.1% and with a unitary power factor. Also, in this case, the same electrical appliances were considered.

Similarly to the previous situation, Fig. 13 shows some results where the off-board EV-BCS operates in different modes according to the different cases identified in Fig. 9. Fig. 13(a) shows the obtained results for the three cases when it is considered that the necessary power for the electrical appliances is provided only by the ESS, meaning that the production from RES is zero and that the EV is not plugged-in. Moreover, as the ESS provides the necessary power for the electrical appliances, it is not necessary to absorb power from the power grid. In the first case, the necessary active power for electrical appliances is injected into the power grid by the ESS. However, the injected current is sinusoidal (in phase opposition with the voltage), but the consumed current by the electrical appliances is non-sinusoidal, meaning that a parcel of non-sinusoidal current is absorbed from the power grid. This situation is shown in the obtained waveforms of the currents. For the electrical appliances, an active power of 980 W and a reactive power of 172 VAr were measured, where the current has a THD of 18.6%. In this case, it is important to reinforce that the active power necessary for the electrical appliances is exclusively provided by the ESS, therefore, the current in the power grid ($i_{g\#1}$) is only responsible for providing the necessary harmonic currents. In the second case, a similar operation occurs. Despite the unified topology, in this case, when only the ESS is used, the power stages are the same. Therefore, the current in the power grid ($i_{g\#2}$) is very similar to the current in the power grid ($i_{g\#1}$) during the first case. In the third case, the operation is completely different, since the power is directly provided by the ESS to the electrical appliances through the dc-dc and dc-ac converters. In this way, it is not necessary to use the power grid, meaning that the current in the power grid ($i_{g\#3}$) is zero.

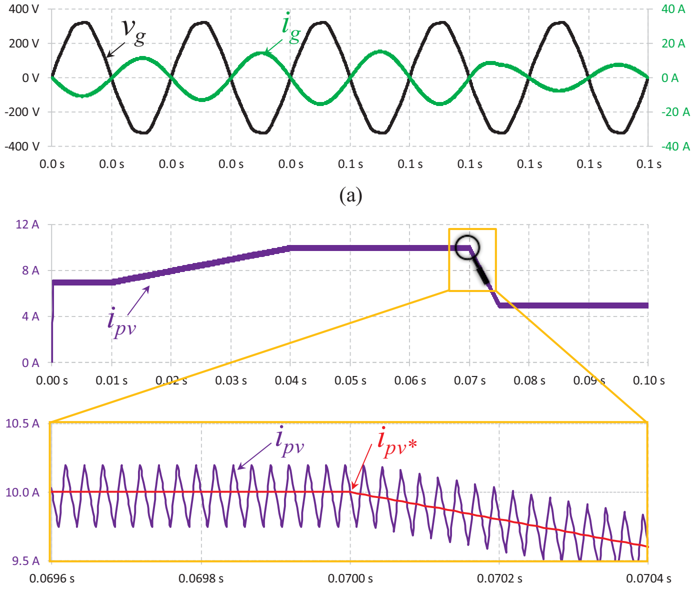


(a) (b) (c)

Fig. 13. Results concerning the three cases identified in Fig. 8:
(a) When the ESS provides power to the electrical appliances;
(b) When the RES and the EV provides power to the electrical appliances and to the smart grid;
(c) When the power grid provides power to the electrical appliances
and the off-board EV-BCS provides power quality services to the smart grid.

Fig. 13(b) shows the obtained results for the three cases when it is considered that the off-board EV-BCS is used to provide services for the smart grid. In this case, the power extracted by the RES is injected into the power grid and the EV is also injecting power into the power grid. However, the power consumption from the electrical appliances is inferior to the injected power, meaning that the difference is used by the smart grid for power management control. In the first case, the necessary active power for the electrical appliances is a parcel of the power injected by the RES and by the EV. However, the electrical appliances are categorized by linear and non-linear characteristics, meaning that the current in the power grid side ($i_{g\#1}$) has harmonic distortion with a THD of 11.8%, as well as a power factor of 0.98. This situation occurs because the converters of the RES and EV are controlled only to inject active power into the power grid. In a second case, a quite similar operation is observed, since the unified topology is controlled to inject a sinusoidal current into the power grid, but the current consumption of the electrical appliances has harmonic distortion. Therefore, harmonic currents are observed in the current of the power grid side ($i_{g\#2}$). The main difference from the previous case is the reduced number of necessary power converters, which only influence in the global efficiency. In the third case, the operation is completely different, since the necessary power for the electrical appliances is provided by the RES through the dc-dc and dc-ac converters. Therefore, a current with a sinusoidal waveform is injected into the power grid with a THD of 1.1% and in phase opposition with the voltage.

Fig. 13(c) shows the obtained results for the three cases when considering that only the electrical appliances are connected to the power grid (i.e., the power produced by the RES is zero, the EV is not plugged-in) and that the ESS is not operating. For the electrical appliances, an active power of 1.2 kW and a reactive power of 225 VAr were measured. This situation was considered only to highlight the opportunities offered by the off-board EV-BCS for the smart grid. Therefore, the first two cases are equal to the reported cases in Fig. 11(a). Therefore, in the third case, the current in the power grid side ($i_{g\#3}$) is composed of two parts: a fundamental component (corresponding to the active power necessary for the electrical appliances) and a selected harmonic current that is injected into the power grid tor compensating the harmonic currents as requested by the smart grid. In this case, a third-order harmonic current was considered with an amplitude of 2 A and a phase of 143 degrees. Moreover, the off-board EV-BCS is also controlled to produce reactive power for the smart grid, where a measured value of 600 VAr was considered. These values (harmonic order, amplitude, phase, and reactive power) were selected as exemplification since other values can be selected without jeopardizing the operation of the off-board EV-BCS. In these circumstances, the smart grid is responsible to establish a selective harmonic compensation control algorithm and to inform the different off-board EV-BCS about the required values. Moreover, the same off-board EV-BCS can be controlled for compensating more than one harmonic current (e.g., an off-board EV-BCS can produce the third-order and fifth-order harmonics and other off-board EV-BCS can produce the seventh-order harmonic).



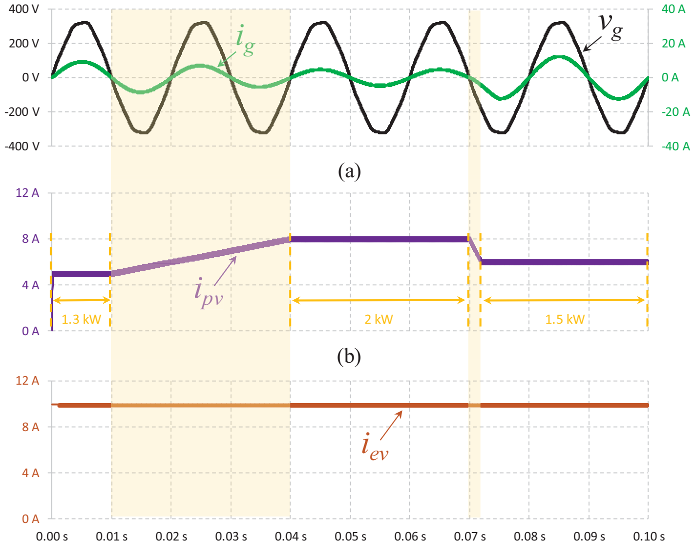
(a)

(b)

Fig. 14. Results considering that the power from the RES is injected into the power grid:
(a) Power grid current (i_g) and voltage (v_g); (b) Current in the RES and its reference (i_{pv} and i_{pv}*).

Differently from the previous case, Fig. 14 shows a case when the RES (PV panels) deliver power to the power grid, i.e., it is directly injected into the power grid. In the figure, it is possible to visualize that the grid current ($i_{g\#3}$) is sinusoidal, but in opposition with the waveform of the voltage, meaning that the power grid is absorbing power. Since the control of the dc-dc converter, used to interface the RES, is based on a maximum power point tracking (MPPT) algorithm, it is possible to extract the maximum power from the RES at each instant. Due to this control algorithm, the extracted power can change, also forcing to change the reference current for the power grid side (assuming that the extracted power is injected into the power grid). Fig. 14 shows this case for different levels of extracted power.

Besides the previous cases, Fig. 15 shows the results where the power for the EV charging is delivered by the RES and by the power grid. This is a combined situation that can be necessary if the power from the RES is not enough for charging the EV battery. Therefore, a parcel of power was absorbed from the power grid. In this figure are also shown the current (i_g) and the voltage (v_g) in the power grid side, as well as the currents in the dc-side, namely, the EV battery current (i_{ev}) and the RES current (i_{pv}). Since the EV battery is charged with constant current and the current in the RES is changing according to the MPPT algorithm, the current (i_g) in the power grid side is also changing, accordingly. Despite the observed variations, the current (i_g) in the power grid side does not present sudden variations capable of causing power quality problems.



(c)

Fig. 15. Results considering that the EV is charged with power from the RES and the power grid: (a) Power grid current (i_g) and voltage (v_g); (b) Current in the RES (i_{pv}); (c) Current in the EV (i_{ev}).

3.5 Conclusion

The dissemination of electric mobility has encouraged the appearance of new technologies and opportunities in terms of power management for smart homes and for smart grids, where the electric vehicle (EV) has emerged with a set of relevant valences for such purposes. Based on this background, this book chapter deals with the role of off-board EV battery chargers in terms of operation modes and new opportunities for smart homes and smart grids. Therefore, an analysis of the state-of-the-art is presented and used as a support for launching a relation with future perspectives. On-board and off-board EV battery charging systems (EV-BCS) are analyzed in the scope of this book chapter, but special focus is given to the off-board EV-BCS, particularly when interfacing renewable energy sources (RES) and energy storage systems (ESS). Moreover, as demonstrated throughout the chapter, an off-board EV-BCS can also be a central element in a future dc smart home, allowing to interface with electrical appliances. Based on this perspective, three distinct cases were considered: (1) A conventional ac smart home (using ac-dc power converters for each technology); (2) A hybrid ac and dc smart home, where the electrical appliances are directly connected to the ac power grid, but an off-board EV-BCS interfaces the RES and the ESS; (3) A dc smart home, where an off-board EV-BCS is the only interface with the electrical power grid. The results were obtained focusing on the efficiency and the power quality for each case when the off-board EV-BCS is operating in different modes. In terms of efficiency, the results show that the off-board EV-BCS in dc smart homes have better results, mainly due to the reduced number of required power stages. In terms of power quality, the off-board EV-BCS in dc smart homes also presents better results than the other cases, since the interface with the power grid is performed by a front-end ac-dc converter operating with a sinusoidal current, in phase or phase opposition with the power grid voltage. Moreover, for this case it was also demonstrated that the off-board EV-BCS can be used for providing power quality services for the smart grid, i.e., producing reactive power and operating in strategies of control based on selective harmonic compensation. By analyzing the obtained results, it is possible to infer that unified structures of off-board EV-BCS have several advantages when framed with hybrid or dc smart homes, as well as with smart grids.

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