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The Electric Vehicle in Smart Homes: A Review and Future Perspectives

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Abstract. The electric mobility dissemination is forcing the adoption of new technologies and operation paradigms, not only focusing on smart grids, but also on smart homes. In fact, the emerging technologies for smart homes are also altering the conventional grids toward smart grids. By combining the key pillars of electric mobility and smart homes, this paper characterizes the paradigms of the electric vehicle (EV) in smart homes, presenting a review about the state-of-the-art and establishing a relation with future perspectives. Since the smart home must be prepared to deal with the necessities of the EV, the analysis of both on-board and off-board battery charging systems are considered in the paper. Moreover, the inclusion of renewable energy sources, energy storage systems, and dc electrical appliances in smart homes towards sustainability is also considered in this paper, but framed in the perspective of an EV off-board battery charging system. As a pertinent contribution, this paper offers future perspectives for the EV in smart homes, including the possibility of ac, dc, and hybrid smart homes. Covering all of these aspects, exemplificative and key results are presented based on numerical simulations and experimental results obtained with a proof-of-concept prototype.

Keywords: Electric Vehicle, Smart Home, Smart Grid, Renewable Energy Source, Energy Storage Systems, Power Quality.

1 Introduction

The electric mobility is increasing its involvement in the transportation sector, where diverse technologies are available as a contribution for sustainability [1][2]. Among the different technologies, the most emblematic is the plug-in battery electric vehicle, simply designated as electric vehicle (EV) in the scope of this paper. Along the last decades, the number of commercially available EVs is increasing, all of them including on-board EV battery charging systems (EV-BCS) and some of them also including an interface for an off-board EV-BCS [3][4][5][6]. Nevertheless, in terms of the EV operation for battery charging, only the possibility of charging directly from the grid is available [7][8]. This operation mode, common for both on-board and off-board

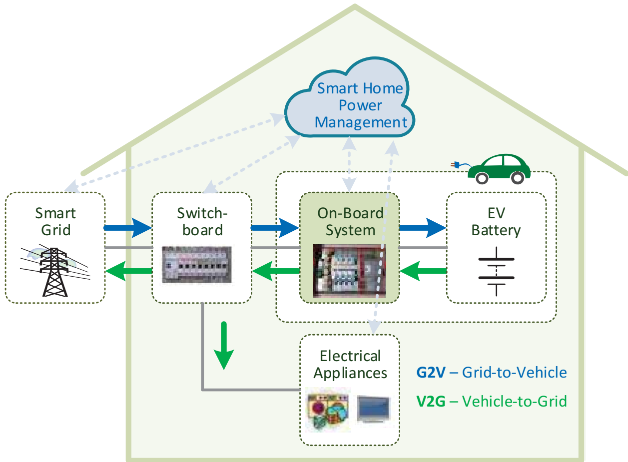


Fig. 1. On-board EV BCS integrated into a smart home, encompassing G2V and V2G (for the smart grid and/or for the smart home) modes.

EV-BCS, is denominated as grid-to-vehicle (G2V), since the power flows from the power grid to the EV. However, from the power grid viewpoint, the EV can be understood not only as an additional load for the system, but also as an energy storage. Therefore, in the perspective of the power grid, the inclusion of the EV will be even more relevant if it can be used as a flexible system capable of three key actions: (a) Absorbing controlled power from the power grid in the place where it is plugged-in; (b) Storing energy and transport it between different places in the power grid; (c) Injecting controlled power into the power grid in the place where it is plugged-in. Thus, alongside the G2V mode, arises the vehicle-to-grid (V2G) mode, where the power flows from the EV to the power grid [9][10][11]. The different possibilities of interaction between the EV and the power grid through the G2V/V2G modes are the main scope of several studies, as demonstrated in [12][13][14]. It is important to note that, in a progressive way, the V2G mode is being seen as a new reality; therefore, some manufacturers in the automotive sector have technological solutions for this possibility based on on-board EV-BCS.

Fig. 1 illustrates an on-board EV-BCS integrated into a smart home, encompassing the G2V/V2G modes. This is the conventional approach, where the on-board EV-BCS can be controlled by the smart home power management. As illustrated, the EV can consume power from the grid or can deliver power for the smart home or for the smart grid (or even for both).

More recently, new operation paradigms are emerging, not only supported by the controllability of the G2V/V2G modes, as in this figure, but also in the perspective of power quality, for instance, during power outages, during the integration in islanded grids, or during compensation of reactive power [15]. Therefore, the main contributions of this paper are: (a) A more comprehensive review about the state-of-the-art operation modes and technologies for the EV in smart homes and smart grids; (b) A description about future perspectives of operation paradigms; (c) Validation based on numerical simulation and on a proof-of-concept prototype.

2 EV in Smart Homes and Smart Grids: Overview of Operation Modes and Technologies

In the introduction section, the possibility of the EV interacting with the power grid in bidirectional mode was introduced. The G2V/V2G modes are already a reality; however, only for exchanging active power between the EV and the power grid, targeting smart grids in a perspective of an on/off control, without neglecting the grid constraints. This contribution is extremely relevant, allowing to use the plugged-in EVs to overcome problems of efficiency and power quality [16][17][18][19][20][21]. In this perspective, with the permission and for the benefit of the EV driver (e.g., different tariffs for programs of G2V/V2G), the EV is controlled by an algorithm of power management of the smart grid, which defines the schedules for charging (G2V) and, eventually, for discharging (V2G) [22].

Given the flexibility of the EV to be plugged-in in the power grid (i.e., it can be plugged-in in different places), the controllability offered by the smart grid gains new complexity. Besides, as presented in [23] and [24], the flexibility offered by the EV operation is also important in microgrid scenarios. In [25] and [26], experimental considerations for the EV in G2V/V2G scenarios are presented, and, in a future perspective, innovative G2V/V2G interactions are offered in [27]. The flexibility offered by these modes is even more applicable as a compensation for the intermittence of the energy obtained from renewable energy sources (RES). In this perspective, the EV can be seen as an energy buffer for the power grid, consuming, storing, or delivering power as a function of the RES intermittence. A perspective of accommodating the EV charging, targeting the RES production as a contribution for mitigating greenhouse gases emissions, is accessible in [28]. Another perspective combining also the EV and RES, targeting to reduce costs and emissions, is considered in [29], and the G2V/V2G operation based on RES for a demand-side management is offered in [30]. Correlating the miscellaneous operation of the EV with RES arises new perspectives, not only for smart grids, but also for smart homes, since, as demonstrated in [31], smart homes have a boost effect for the future innovation in smart grids. In this scenario, technologies and foresights for assimilating the EV in smart homes are discussed in [32], while an optimized EV interaction is presented in [33] from the customer perspective. The aforementioned discussed technologies only involve an on-board EV-BCS in G2V/V2G modes. However, other possibilities of operation are emerging as viable solutions for the EV in smart homes, but prospecting smart grids.

The home-to-vehicle (H2V) is a particular mode of operation for the EV, when it is plugged-in at home. In fact, this mode is comparable to the G2V mode, since the power flows from the power grid to the EV (plugged-in in the home). The differentiating factor resides in the controllability of this mode, more convenient than the on/off G2V mode. With the H2V mode, the charging power can vary dynamically between zero and the maximum power, i.e., it can assume any value of power between the range of operating power.

Similar to the controlled G2V mode, in the H2V mode, the on-board EV-BCS can also be remotely controlled according to the set-points received by the algorithm of power management. This mode is particularly relevant for a smart home management in combination with controlled electrical appliances. In this context, the management algorithm can establish different levels of priority for the EV and for the electrical appliances in accordance with the user preferences (e.g., through a mobile app). From the EV point of view, three main situations can be highlighted: (a) The EV is defined to have maximum priority; therefore, it is charged with maximum power, while the electrical appliances can be turned-off to prevent the circuit breaker trip. This situation corresponds to a critical case when it is fundamental to charge the EV as fast as possible, and the operation of the other electrical appliances is not relevant. (b) The EV is defined to have priority over some specific electrical appliances; therefore, a maximum charging power is defined (e.g., corresponding to 75% of the full power) and the turn-on and turn-off of the electrical appliances is controlled in order to avoid the circuit breaker trip. In this case, the EV is charged with a fixed power and the electrical appliances are controlled avoiding exceeding the maximum power allowed by the circuit breaker. (c) The EV is defined to have minimum priority; therefore, the charging power is defined with a value that corresponds to the difference between the maximum (i.e., allowed by the circuit breaker) and the instantaneous power consumed by the electrical appliances. In this case, the power for the EV charging is directly influenced by the power consumption of the electrical appliances; therefore, the charging process will be extended for a longer period. As mentioned, the H2V is similar to the G2V mode; however, during the discharging process (V2G), the same strategy of controlling the EV operation as a function of the electrical appliances can also be implemented.

3 Future Perspectives of Operation Paradigms

In this section, future perspectives for the EV in smart homes are presented. Therefore, besides the operation paradigms described in the previous section (G2V/V2G/H2V), new challenges in terms of infrastructures are presented, involving the requirements of smart homes.

In Fig. 2 is presented a vision of an on-board EV-BCS in smart homes, contemplating the abovementioned operation modes and a new one related with power quality. As it can be seen, these operation modes are relevant and extremely useful for the smart home, also contributing for new energy policies for smart grids. As an example, in bidirectional mode, three distinct cases can be considered for the on-board EV-BCS: (a) Exchange power with the smart home, where the EV can provide power according to the requirements of the home management system; (b) Exchange power with the smart grid, where the EV can provide power according to the requirements of the smart grid; (c) Exchange power, at the same time, with the smart home and with the smart grid. This example is directly related with the G2V/V2G modes, however, a similar case is for the vehicle-for-grid (V4G) mode, where the on-board EV-BCS can compensate power quality problems, both in the smart home and in the smart grid. It is important to note that, in this case, the on-board EV-BCS can compensate almost all the current harmonics and the power factor of the smart home, but in the smart grid perspective, it only contributes to mitigate part of such problems. In this case, a new perspective for the smart grid arises, which is related with selective harmonic current compensation

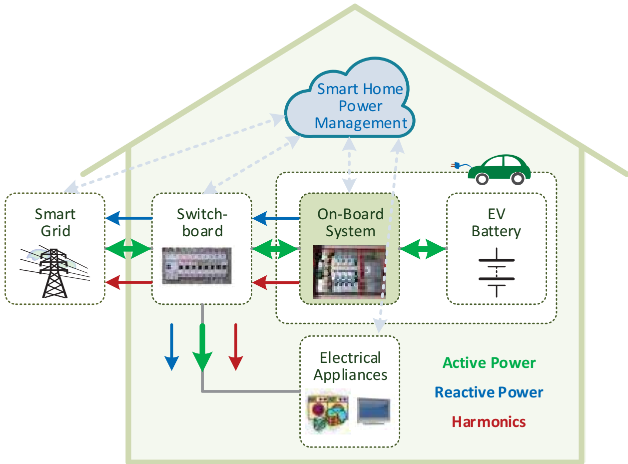


Fig. 2. On-board EV BCS integrated into a smart home, encompassing the G2V and V2G modes, as well as the possibility of compensating power quality problems related with harmonic currents and low power factor (producing reactive power for the smart home or for the smart grid).

(where each EV can be controlled to produce a specific harmonic current) and controlled reactive power (where each EV is responsible to produce a small amount of reactive power to compensate a specific value of power factor in the smart grid). Despite the clear benefits of these operation modes for the smart home and for the smart grid, a key disadvantage is identified: these operation modes are only possible when the on-board EV-BCS is available, i.e., when the EV is parked at the smart home. On the other hand, if analyzed from the power grid point of view, in terms of exchanging power and in terms of controllability, a new key advantage is identified: these operation modes are available in the place where the EV is parked, i.e., the EV is a dynamic system in the smart grid, capable of operating in different modes according to the necessities.

Besides the compensation of power quality problems related with harmonic currents and reactive power, the on-board EV-BCS can also be used during power outages. In this case, illustrated in Fig. 3, the on-board EV-BCS provides power for the smart home, but the current waveform is defined by the electrical appliances (i.e., the on-board EV-BCS can operate with a non-sinusoidal current and low power factor). In this case, the energy source is the EV battery; therefore, it should be used with the convenience of the EV driver. For instance, in this mode, the on-board EV-BCS system can be used only to provide power for priority electrical appliances in the smart home (to be defined and reconfigurable by the user). Moreover, this mode is more convenient for short periods of time. Concerning EV off-board battery charging systems, the abovementioned operation modes can also be applied. In Fig. 4 is presented a vision of an EV off-board battery charging system in smart homes when the EV is parked at home. Using an EV off-board battery charging system, the offered possibilities are even more relevant, since the equipment is always installed at the smart home. Therefore, some operation modes are available independently of the EV being parked. For instance, the EV off-board battery charging system can provide power quality services,

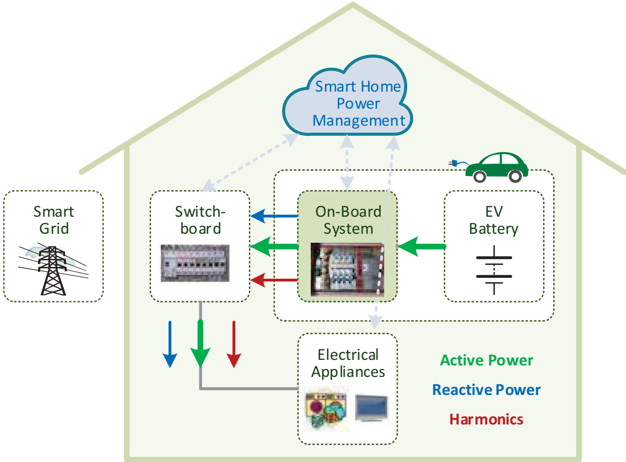


Fig. 3. On-board EV BCS integrated into a smart home, encompassing the G2V and V2G modes, as well as the possibility of compensating power quality problems related to power outages (where the EV is used as power supply with the EV batteries as energy source).

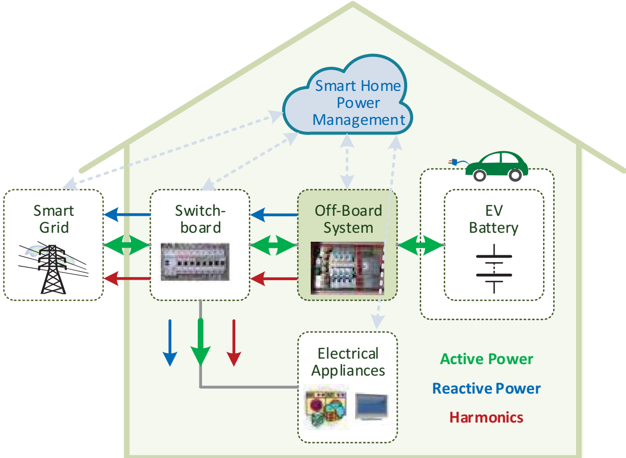


Fig. 4. Off-board EV BCS integrated into a smart home, with a parked EV, encompassing the G2V and V2G modes, as well as the possibility of compensating power quality problems related with harmonic currents and low power factor (producing reactive power for the smart home or for the smart grid).

exactly as the on-board EV-BCS, for both the smart home and for the smart grid; however, such services can be provided independently of the EV presence. On the other hand, G2V/V2G modes are only available, as for on-board EV-BCS, when the EV is present (with the batteries as the energy source). In Fig. 5 is presented a vision of an EV off-board battery charging system in smart homes when the EV is not parked at home. As illustrated, the same operation modes are available (i.e., G2V/V2G and compensation of harmonic currents and power factor), except the possibility of using the

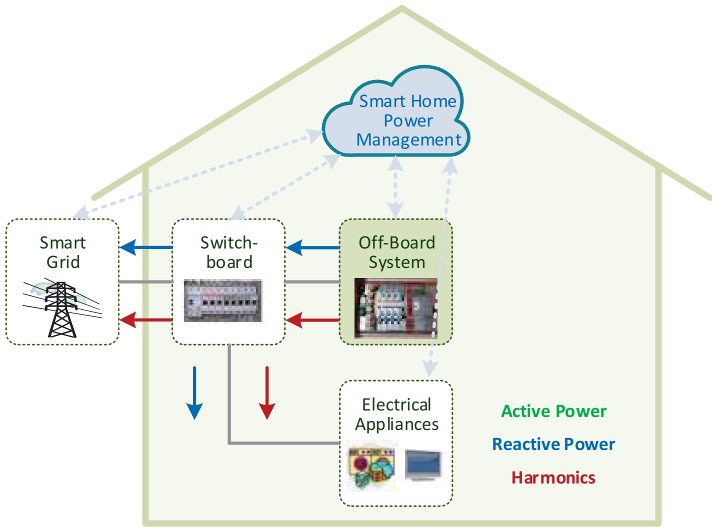


Fig. 5. Off-board EV BCS integrated into a smart home, without a parked EV, but with the possibility of compensating power quality problems related with harmonic currents and low power factor (producing reactive power for the smart home or for the smart grid).

EV battery as power supply during power outages. Nevertheless, the main future perspectives are related with EV off-board battery charging systems and, more precisely, with the possibility of interfacing other technologies for smart homes as RES or as auxiliary energy storage systems (ESS). Thus, the future perspectives are based on the possibility of using the same EV off-board battery charging system to interface, through a shared dc-link, a unidirectional dc-dc converter for RES and a bidirectional dc-dc converter for an auxiliary ESS [34]. It is important to note that the integration of an EV off-board battery charging system with this possibility is a complete solution to encompass in the smart home: electric mobility; RES; ESS. This situation is illustrated in Fig. 6, where the single interface with the power grid is a relevant key feature [35][36]. Moreover, with the migration from ac grids to dc grids, this is even more relevant, since the necessities of power converters are drastically reduced (it is important to take into account that the majority of the electrical appliances at home level are composed by a front-end ac-dc converter used only to interface the ac grid). Therefore, a complete future perspective of integrating an EV off-board battery charging system in a smart home, mainly focusing in an internal dc grid, is illustrated in Fig. 7. Within this scenario, the following modes can be considered: (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 batteries; (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 electrical appliances; (e) The EV can deliver power for the smart home (electrical appliances); (f) The EV can deliver power for the smart grid; (g) The power from the ESS can be delivered to the smart home (electrical 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

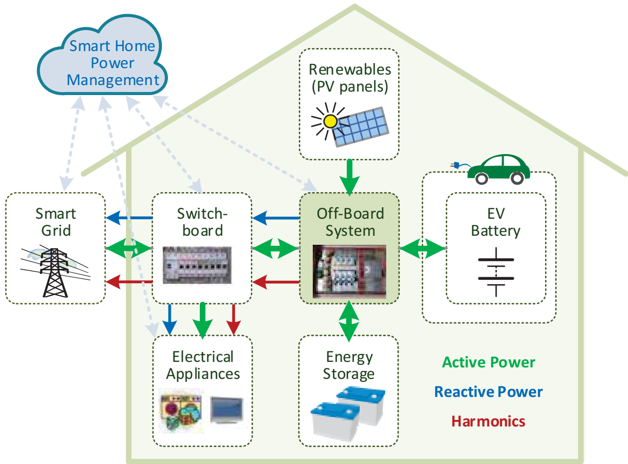


Fig. 6. Off-board EV BCS integrated into a hybrid ac and dc smart home, with a parked EV and interfacing a RES (solar photovoltaic panels) and an ESS (batteries) through a shared dc-link. The electrical appliances are directly connected to the ac grid. The G2V/V2G modes are contemplated, as well as the possibility of compensating power quality problems related with harmonic currents and low power factor (producing reactive power for the smart home or for the smart grid).

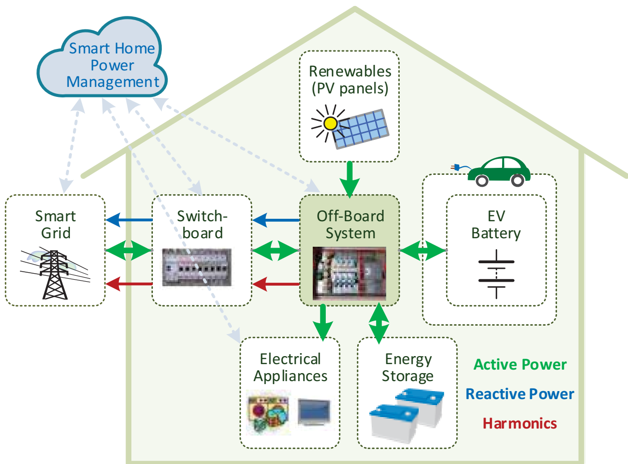


Fig. 7. Off-board EV BCS integrated into a dc smart home, with the EV parked and interfacing a RES (solar photovoltaic panels), an ESS (batteries), and electrical appliances through a shared dc-link. The G2V and V2G operation modes are contemplated, as well as the possibility of compensating power quality problems related with harmonic currents and low power factor (producing reactive power for the smart grid).

from the grid can be used to charge the ESS; (k) The power from the grid can be delivered to the smart home (electrical appliances). It is important to note that the EV off-board battery charging system can include a dc-dc converter with a direct interface with the EV battery, or an additional dc-dc converter (within the on-board EV-BCS) can be used between the EV off-board battery charging system and the EV battery.

4 Computational and Experimental Validation

In this section, a comparison between three main cases was considered: (a) A conventional ac smart home with independent power converters for each technology (on-board EV-BCS, RES, ESS, dc electrical appliances, and ac electrical appliances); (b) A hybrid ac/dc smart home with an integrated off-board EV-BCS for a RES and for an ESS, sharing a common dc-link; (c) A dc smart home with an integrated off-board EV-BCS, based on a single interface with the grid and with dc-dc or dc-ac converters for interfacing each technology (on-board EV-BCS, RES, ESS, dc electrical appliances, and ac electrical appliances). These three cases, illustrated in Fig. 8, were simulated using a model developed in PSIM software, where: (a) as RES, a set of photovoltaic (PV) panels was considered; (b) as ESS, a set of lithium batteries was considered; (c) as dc electrical appliances (dcEA), resistive loads were considered; (d) as ac electrical appliances (acEA), an induction motor was considered. In terms of the power converters: (a) for the ac-dc, full-bridge three-level converters were considered; (b) for the dc-dc, unidirectional and bidirectional half-bridge two-level converters were considered; (c) for the dc-ac, full-bridge three-level converters were considered.

According to the different possibilities of operation modes (cf. section 3 and Fig. 7), the estimated efficiency was determined. These operation modes are: (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 electrical appliances; (e) The EV can deliver power for the smart home (electrical appliances); (f) The EV can deliver power for the smart grid; (g) The power from the ESS can be delivered to the smart home (electrical 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 (electrical appliances).

The estimated efficiency for each mode, considering the three cases under study, is presented in Fig. 9 (for the case #1 the ac-dc with an efficiency of 94% and for the dc-dc with an efficiency of 95%, for the case #2 the ac-dc with an efficiency of 95% and for the dc-dc with an efficiency of 96%, for the case #3 the ac-dc with an efficiency of 95% and for the dc-dc with an efficiency of 96%). As it can be seen, the most efficient solution is obtained with the dc smart home, where a single ac interface with the power grid is considered. This is in accordance with the expectable, since the number of power stages is substantially reduced (as well as the required number of power converters). Taking into account that some operation modes are equal for some cases, very similar values of efficiency were obtained. On the other hand, the first case is the worst in terms of efficiency, since several power stages are required, where the power grid is always needed for each operation mode. Concerning the contributions of the future perspective of EV off-board battery charging systems for power quality, some results were

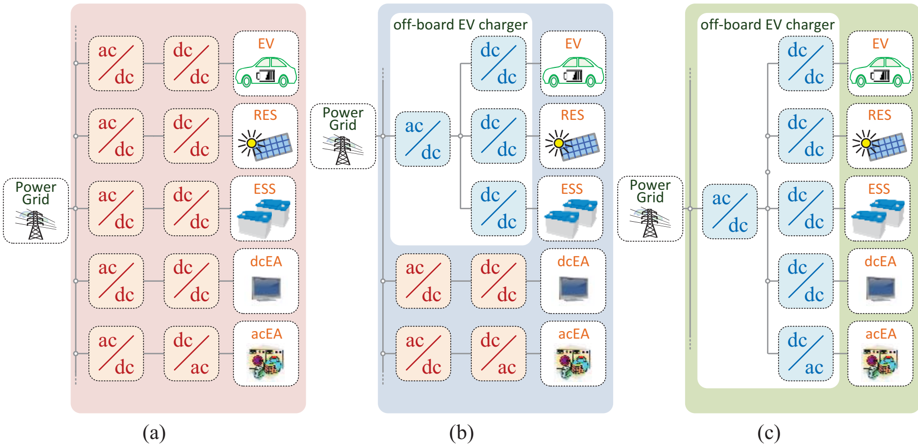


Fig. 8. Considered cases: (a) A conventional ac smart home with independent power converters for each technology; (b) A hybrid ac and dc smart home with an integrated EV off-board battery charging system for interfacing a RES and for an ESS, sharing a common dc-link; (c) A dc smart home with an integrated off-board EV BCS, based on a single interface with the grid and with dc-dc or dc-ac converters for interfacing each technology.

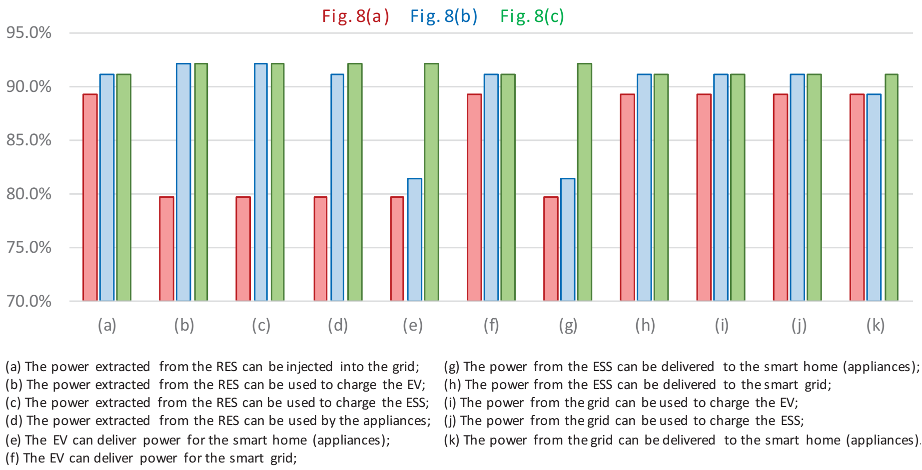


Fig. 9. Estimated efficiency for each case under study and considering all the possibilities of operation modes.

obtained, mainly focusing in the ac-dc converter used to interface the power grid. **Fig. 10** shows the power grid voltage (v_g), the grid current (i_g), and the voltage of the ac-dc converter (v_{ac}) when the EV batteries are charged from the power grid. Besides, a comparative detail of the grid current (i_g) with its reference (i_g*) is also presented. In this case, a power of 3.6 kW was considered. As expected, the grid current (i_g) is sinusoidal and the converter operates with unitary power factor. On the other hand, Fig. 10 shows a case when the power grid receives energy from the PV panels. This figure

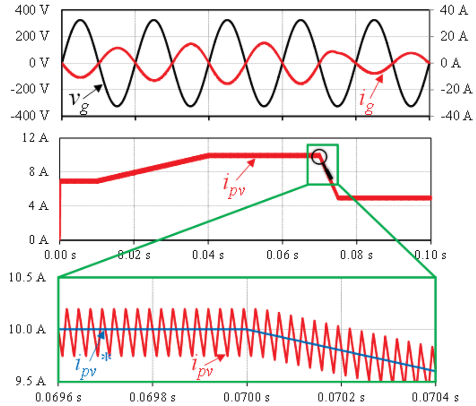


Fig. 10. Simulation results when the power grid receives energy from the PV panels: Power grid voltage (v_g); Grid current (i_g); Current in the PV panels (i_{pv}); Reference current for the PV panels (i_{pv}*).

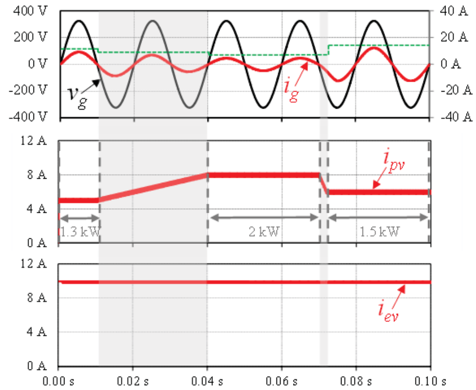
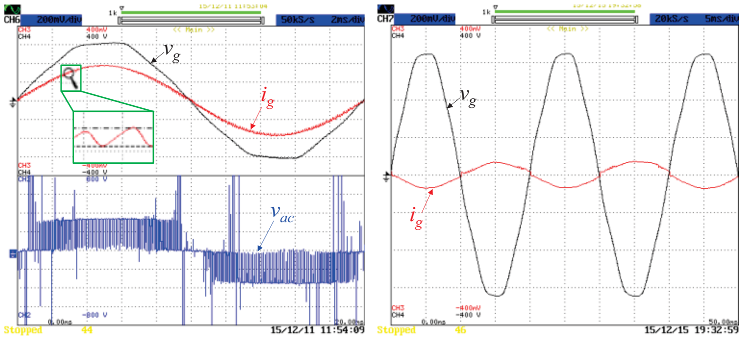


Fig. 11. Simulation results when the EV batteries are charged with energy from the power grid and from the PV panels: Power grid voltage (v_g); Grid current (i_g); Current in the PV panels (i_{pv}); Current in the EV batteries (i_{ev}).

shows the power grid voltage (v_g), the grid current (i_g), and the current in the PV panels (i_{pv}). A detail of the current i_{pv} is also presented. The dc-dc converter used to interface the PV panels is controlled in order to extract, at each instant, the maximum power from the PV panels. Therefore, the reference current changes in accordance with the maximum power point tracking (MPPT) algorithm and, due to the current control scheme, the current follows its reference. In Fig. 11 is shown a case when the EV batteries are charged with energy from the power grid and from the PV panels. This figure shows the power grid voltage (v_g), the grid current (i_g) and its maximum value to show the variation (in green), the current in the PV panels (i_{pv}), and the current in the EV batteries (i_{ev}). In this operation mode, the EV batteries are charged with constant current; therefore, the grid current changes in accordance with the current in the PV panels, i.e., in accordance with the MPPT algorithm. As it can be seen, the grid current changes without sudden variations, allowing to prevent power quality problems. A prototype was



(a) (b)

Fig. 12. Experimental results when the EV batteries are charged (a) or discharged (b): Power grid voltage (v_g: 100 V/div); Grid current (i_g: 10 A/div); Voltage produced by the ac-dc converter (v_{ac}: 200 V/div).

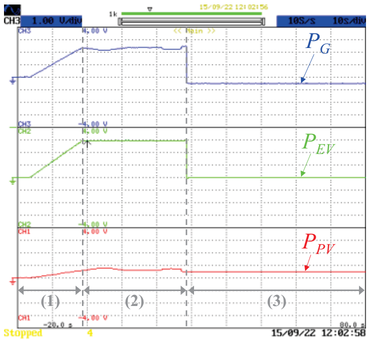


Fig. 13. Experimental results when the EV batteries are charged with energy from the power grid and from the PV panels: Power in the grid (P_G: 1 kW/div); Power in the EV (P_{EV}: 1 kW/div); Power in the PV panels (P_{PV}: 1 kW/div).

considered for experimental results. In Fig. 12(a) are presented some experimental results when the EV batteries are charged with energy from the power grid. As expected, the grid current (i_g) is sinusoidal (THD = 1.4%), even with a power grid voltage (v_g) with harmonic distortion (THD = 3.5%). With this strategy, the integrated topology does not contribute to the harmonic distortion of the power grid voltage. During the injection of power into the grid, Fig. 12(b) shows, in a time interval of 50 ms, the power grid voltage (v_g) and the grid current (i_g) for an operating power of 800 W. As expected, the grid current is in phase opposition with the power grid voltage, meaning that the power grid receives energy from the PV panels. In Fig. 13 is presented a case when the EV batteries are charged with energy from the power grid and from the PV panels. During this case are presented, the power in the grid (P_G), the power in the EV (P_{EV}) and the power in the PV panels (P_{PV}). As it can be seen, the power in the grid (P_G) is the difference between the power in the EV (P_{EV}) and the power in the PV panels (P_{PV}).

5 Conclusions

New technologies for smart homes and smart grids are emerging due to the electric mobility dissemination. Therefore, knowing the relevance of the electric vehicle (EV) as a contribution for smart homes, this paper deals with its characterization in smart homes, where an analysis of the state-of-the-art operation modes is used as a support for establishing a relation with the future perspectives. Aiming to establish an ample study, on-board and off-board battery charging systems are considered, as well as ac smart homes, dc smart homes, and hybrid smart homes. Moreover, the integration of ac and dc electrical appliances, renewable energy sources based on solar photovoltaic panels, and energy storage systems based on batteries is also considered in the perspective of future smart homes. The obtained results are based on three distinct cases of smart homes, where a study of energy efficiency was considered. With the obtained results, it was verified that the first case is the worst in terms of efficiency, since all the equipment are connected to the power grid, therefore, to exchange power between systems the power grid is always used. Some exemplificative experimental results are shown, obtained with a proof-of-concept prototype.

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