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Vehicle-to-Anything:
A Power Transfer Perspective for Vehicle Electrification

Vítor Monteiro,[1*] Tiago J. C. Sousa[1], Paula Ferreira[2], Júlio S. Martins[1], João L. Afonso[1]

[1] Department of Industrial Electronics, University of Minho, Portugal
[2] Department of Production and Systems, University of Minho, Portugal

* Corresponding author: vmonteiro@dei.uminho.pt, University of Minho, Campus de Azurem, 4800-058, Portugal

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ABSTRACT

The concept of vehicle-to-anything (V2X) is mainly focused on the bidirectional communication between any technology of vehicle and any external system that can contribute for its operation. However, prospecting the vehicle electrification, this concept can also be associated with the power transfer between an electric vehicle (EV) and any external system, where bidirectional communication is absolutely fundamental. Within the power transfer, the possibility of exchanging active power between an EV and the power grid is considered as a promising operation mode, especially considering the possibility of selling demand response services for the electrical power grid. Contemplating the vehicle electrification context, in addition to the latent possibility of interaction between EVs and the power grid for active power exchange, other possibilities of interaction can also be considered, providing advantageous services for the power grid. Thus, this article approaches the V2X concept for off-board systems in the power transfer perspective for vehicle electrification, aggregating new contributions related with the interaction between an EV and any external electrical system (operating as source or load), and both from on-grid or off-grid point of view. Contributions are meticulously presented, recognizing their advantages and disadvantages in a real-scenario of operation. A comparison in terms of cost of implementation and in terms of efficiency is presented considering the various solutions of the vehicle electrification in a smart grid perspective.

INTRODUCTION

Modern societies are adopting new paradigms of mobility for mitigating greenhouse gases emissions and problems of environmental air pollution (Alam, Khusro, and Naeem 2018; Hernandez, Kreikebaum, and Divan 2010) targeting smart grids and smart cities (Bose 2010; Bozchalui, Canizares, and Bhattacharya 2015) In this context, the vehicle electrification will be crucial for such objective, both in terms of communication and power transfer with external systems. Therefore, as demonstrated in the overviews presented in (Gungor et al. 2012) and (Hashmi, Hänninen, and Mäki 2011), advanced functionalities can be associated with vehicle electrification, mainly considering electric vehicles (EVs). The new paradigm of mobility, sustained by the vehicle electrification, is even more motivated by the technological advances in the areas of power electronics and communications, where such perspectives are offered in (Yu et al. 2011), (Vitor Monteiro et al. 2017), and (Ferreira, Monteiro, and Afonso 2014). Therefore, the concept of a bidirectional power transfer will be a reality also for vehicle electrification, where, in addition to the possibility of exchanging active power with the electrical power grid, it will be possible to implement other interactions with external electrical systems, including sources or loads (as renewable energy sources, RES, or energy storage systems, ESS). For instance, smart charging methodologies for EVs maximizing the power utilization from RES is presented in (Peças Lopes et al. 2009), and concerted collaborations also with ESS are introduced in (Su et al. 2012), (Vítor Monteiro et al. 2017), and (Martinez et al. 2017). Scheduling plans for the EV charging under the RES uncertainties are proposed in (Saber and Venayagamoorthy 2012) and (Zhang et al. 2014), and a contextualization with the energy management of smart homes is offered in (Pedrasa, Spooner, and MacGill 2010), (Tsui and Chan 2012), and (Monteiro et al. 2014). Considering the aforementioned points, a comprehensive summary concerning the vehicle electrification is introduced in (Boulanger et al. 2011). However, for the vehicle electrification it is also essential to take into account the requirements of the power grid or the system where the EV is plugged-in. In (Dyke, Schofield, and Barnes 2010), it is investigated the impact that the vehicle electrification can cause in the present power grid, prospecting an effective economic dispatch and avoiding depth changes on its structure, even considering sudden variations to respond the requirements of the charging process. Contextualizing all aspects related to the vehicle electrification, this paper approaches the vehicle-to-anything (V2X) concept focusing on the power transfer perspective in off-board systems (charging systems installed outside the EV), where the main contributions are: (1) Aggregation of all operation modes related to the interaction between an EV and any external electrical system operating as a source or as a load (RES or ESS), connected or not to the power grid (on-grid or off-grid); and (2) Economical and efficiency comparison of the various solutions that can be adopted for the vehicle electrification in the context of smart grids.

VEHICLE ELECTRIFICATION: PRESENT STATUS

The vehicle electrification is an attractive solution for the transportation sector, providing appealing benefits and research developments in different scientific areas toward a smart grid. Aiming to deal with this new reality, charging infrastructures of power electronics, dedicated communication platforms of interface and protocols are being implemented along the last decades for this specific purpose (Turitsyn et al. 2010). However, on the other hand, the vehicle electrification can also accommodate disadvantages when its large diffusion into the grid is uncontrolled, i.e., without considering the constraints of the power grid in terms of active and reactive power, voltage, and frequency control (Markel, Kuss, and Simpson 2010) As the power grids were designed without considering the new dynamic and unpredictable load that the vehicle electrification represents, new challenges are being induced in terms of controllability for the power grids (also prospecting the connected electrical appliances through the internet-of-things concept). Besides the perspective of the power grid toward a global smart grid, the resultant advantages and disadvantages of the vehicle electrification adoption are also framed in smart homes scenarios, identified as one of the main steps toward smart grids, and in smart building scenarios (Liu et al. 2013).

Analyzing from the power grid point of view, the vehicle electrification represents a new load for the power grid, imposing some requisites in terms of the available power to perform the battery charging process, whose power can be provided by the traditional non-renewable sources or by the large-scale integration of RES in on- or off-grid perspectives. Assuming the plug-in full-battery EV as the main representative and influent element for supporting the vehicle electrification introduction and off-board systems for interfacing the EV and the grid, since the moment that the EV is plugged-in to the power grid (G2V, grid-to-vehicle charging mode), the EV battery charging power can be controlled in accordance with two main points: (i) The requisites and benefits of the EV user (in terms of schedules, energy prices, and battery state-of-charge); and (ii) The requisites and benefits of the power grid. In these circumstances, the EV battery charging can be controlled by the power grid, accomplishing with the set-points of the user, but in a perspective of the grid benefits, for instance, increasing the power during high periods of energy production from RES and decreasing the power otherwise. In a smart home perspective, this controllability can be executed by the home management, establishing a harmony cooperation between the EV charging and the operating power of the turned-on electrical appliances. Besides the aforementioned approaches for controlling the G2V operation, it is also predictable that the EV will also be able to discharge the battery through the injection of energy into the grid, an operation denominated as vehicle-to-grid (V2G) discharging. Assuming an EV with this bidirectional functionality, for instance, it can charge the batteries with energy from the power grid and, posteriorly, deliver the stored energy back to the grid. From this analysis, two points are highlighted: (i) The EV can be used as moving energy buffer to store energy produced from RES when it is not required from the power grid for other purposes; and (ii) The EV can be charged and discharged at different points of the power grid, representing an attractive dynamic solution when well controlled by the power grid. In this scenario, the requirements of the EV user are preserved, and he has the opportunity to benefit of charging the EV batteries at low-price and selling energy to power grid at higher prices (Kempton and Tomić 2005) In (Nguyen and Le 2014) is presented an optimization between the EV and the smart home energy scheduling toward the user comfort, and in (Pang et al. 2010) is introduced the EV as dispersed energy storage in a building perspective into smart grid.

The G2V (and V2G) is a classical approach and, from the EV point of view, it does not present any inconvenient, since the batteries are charged or discharged in harmony with the user necessities in terms of schedule and place where the EV is plugged-in. However, in the grid perspective, it represents a disadvantage precisely because of these two aspects, since, nowadays, it is not possible to predict the schedule when the EV will be charged, during how much time, and where it will be plugged-in. Although the grid is prepared to deal with some uncertainties in terms of the connected electrical appliances, considering a massive spread of plugged-in EVs in this circumstances, it can be chaotic for the grid power management. Therefore, one of the required new operations for the EVs will be the controlled G2V or V2G. In a smart grid perspective, concerning the necessities of the power management by the transmission system operator (TSO) and distribution system operator (DSO), the EV will be controlled receiving set-points of operation. DSOs are responsible for maintaining the operability of the grid at the distribution level (in terms of medium and low voltages), where the public EV charging systems will be installed. In this perspective, it is imperative to establish a bidirectional data transfer, informing the DSOs about the schedules and operating power of the EV charging stations. Based on such information, it will be possible to define control strategies for the EV G2V or V2G modes considering the DSOs planning control. Basically, at this public level of EV charging, the perspectives are only related with control strategies based on turn-on or turn-off the EV charging along the charging process, i.e., it is guaranteed that the EV batteries will be charged according to the defined schedule by the user, but during the EV charging, the process can be interrupted to comply with the DSO necessities. On the other hand, from a smart home point of view, the controlled G2V and V2G is related with charging or discharging the batteries according with the additional electrical appliances, permitting to prevent overloads in the installation. This operation mode is denominated home-to-vehicle (H2V). Besides the aforementioned on-grid operations, the same EV bidirectional system can be used for supplying loads in a smart home during power outages or in isolated or islanding grids (off-grid scenarios). This operation is denominated vehicle-to-home (V2H). Besides, by employing a bidirectional charging system (for the G2V and V2G modes), the EV can also be controlled for preventing power quality problems, establishing compensating currents even when the EV is not plugged-in (i.e., the EV is indispensable for this mode). This operation mode is denominated vehicle-for-grid (V4G). Summarizing, in terms of exchanging power, all of these EV bidirectional activities can be uniformed under the same designation as vehicle-to-anything (V2X). The present status regarding the above-mentioned operation modes for an off-board system are demonstrated in Figure 1.

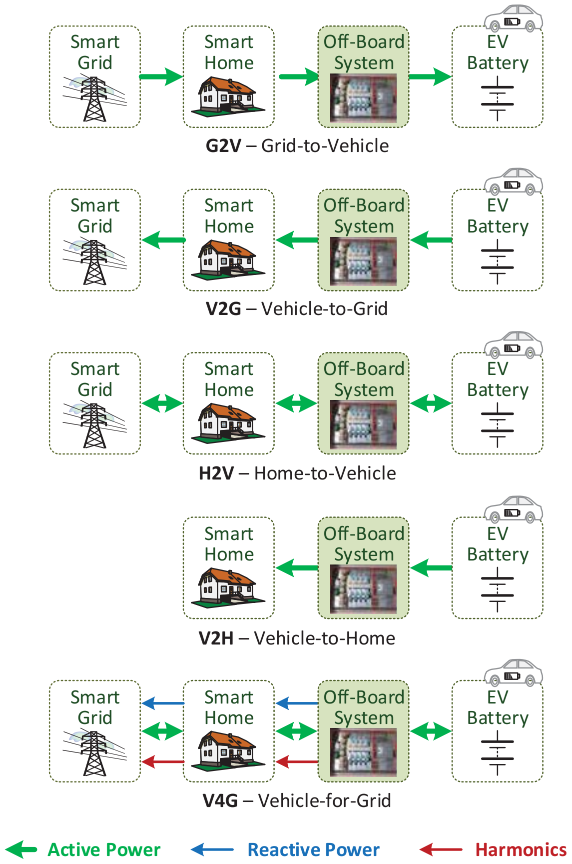


Figure 1: Present status regarding the operation modes for EV off-board systems.

VEHICLE ELECTRIFICATION: OPPORTUNITIES IN THE CONTEXT OF SMART GRIDS

Contextualizing with smart grids, new opportunities are appearing for the vehicle electrification and there are few publications about this point. Taking into account as main objective to obtain a near zero CO2 emissions concerning the vehicle electrification, it is imperative to charge the batteries with energy from RES. This is even more convenient knowing that the costs are falling along the last decades and the integration into the grid can be realized at different distribution levels. Therefore, mainly supported by solar photovoltaic (PV) panels, industries, office buildings and smart homes are good candidates for installing PV panels at the rooftops. This scenario is important, but toward optimizing the charging process, it is important to install the RES near the charging points (off-board systems). Therefore, parking charging stations are the most indicated candidates for installing RES. Consequently, besides the advantage of reducing the CO2 emissions, the main advantages are identified as: (i) Optimized energy transfer from RES to the EV; (ii) The EV can be employed for operating as an ESS; and (iii) Reducing the energy necessities from the grid. However, as the EV can be seen as a random electrical appliance, if no EV is plugged-in, the produced energy from RES is directly injected into the power grid. On the other hand, if the number of EVs plugged-in for the charging process exceeds the maximum power produced from RES, it is necessary to require power from the grid. Nowadays, this cooperation of RES and EVs is performed in terms of a collaborative and predictive control, however, for a better utilization and collaboration of both, the integration of ESS is vital. Consequently, it is possible to optimize the energy transactions between the EV charging, as well as the RES and ESS integration also for supporting the grid controllability. Since these three technologies (EV, RES and ESS) are designed with power converters, specially dedicated for controlling the consumed or injected current, by analyzing them in terms of topologies, it is possible to identify that the same converter topology, consisting of a full-bridge bidirectional converter, is always employed. Thus, in terms of power electronics, it is possible to use only one converter (ac-dc) to control the current consumed or injected on the grid-side, maintaining the same structure of the converters (dc-dc) used for the EV, RES and ESS interface. In this sense, instead of employing three equal converters to the grid-side, only one converter is used. It is further emphasized that this converter (ac-dc) does not need to have an operating power three times higher, since it will never be doing the three operations at the same time. This unification for just one ac-dc converter will be a key point for smart grids. Using Figure 1 as a starting point, Figure 2 identifies a new opportunity for vehicle electrification also framed with RES and ESS. In this figure are identified the additional operating modes that an off-board system can perform, being necessary to highlight that all of the operating modes identified in Figure 1 can also be performed.

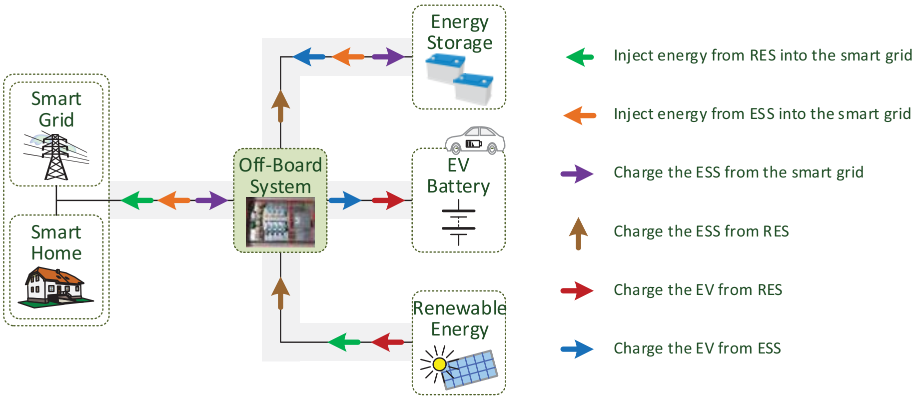
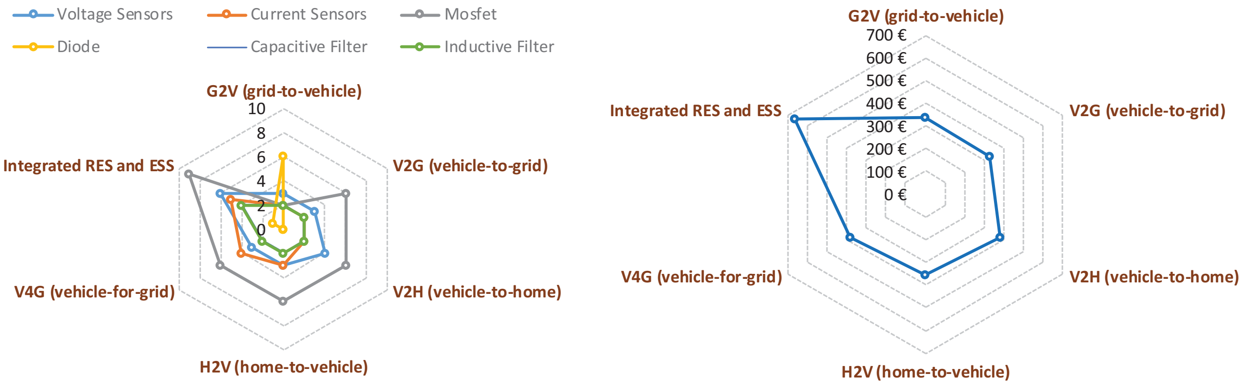


Figure 2: New opportunity for the vehicle electrification concerning a unified off-board system also for interfacing RES (e.g., PV panels) and ESS (e.g., batteries).

VEHICLE ELECTRIFICATION: ECONOMIC AND EFFICIENCY STUDY

Assuming the different operation modes identified in Figure 1 and Figure 2, this section presents an analysis of the cost of implementing an off-board system with each solution. Thus, starting from the traditional solution for a charging process (G2V) only with unidirectional operation, a comparison is presented for all the operating modes in terms of the necessary system components and, finally, a comparison in terms of the total cost for implementing each solution. In order to obtain a realistic comparison in terms of implementation, the following conditions were considered for each operation mode: In G2V mode it is considered a classic power factor correction converter (only allowing the unidirectional mode); In V2G mode it is considered a full-bridge bidirectional converter, which simply allows the V2G with the user or grid control; In H2V mode it is also considered a bidirectional converter, but it is possible to control the batteries charging or discharging in accordance with the requirements of the installation where the EV is plugged-in, being necessary to equip the off-board system with an additional current sensor; In V2H mode it is considered a converter similar to the previous one, but it requires an additional voltage sensor in order to recognize when there are power outages in the installation, i.e., the system needs two sensors on the grid-side; In V4G mode it is also considered a bidirectional converter similar to the previous one, but that requires two additional current sensors, one to measure the grid current and another for the electrical appliances current. In the unified structure (Figure 2) with RES and ESS, a full-bridge bidirectional converter was considered. In addition to the grid-side interfacing converter, it is also important to mention that unidirectional and bidirectional dc-dc converters for the dc interface with the EV batteries or with the RES and ESS systems were considered. As a unidirectional dc-dc converter, the buck-converter was considered, and as a bidirectional dc-dc converter it was considered the half-bridge buck-boost converter. Figure 3(a) shows a comparison in terms of the number of components required for implementing an off-board system with each operating mode and an unified off-board with RES and ESS interface. Figure 3(b) is presented a comparison in terms of total implementation costs for each solution, being for that purpose considered market prices of each component, allowing to obtain reliable results. It is noteworthy that, although the unified solution presents a higher cost, in part, this cost is associated with the dc-dc converters for RES and ESS (which do not exist with the other modes of operation). Although they cost more, the efficiency gains are higher. Figure 4 shows a comparison in terms of estimated efficiency between an off-board system with the operating modes identified in Figure 2 and an unified off-board system with RES and ESS. In this figure, three main scenarios were considered, namely: (i) During the G2V traditional mode with a unidirectional off-board system; (ii) During the G2V indirectly from RES; (iii) During the G2V direct from RES (through the dc-dc interfaces). As it can be seen, it is much more efficient when the G2V is performed directly from RES (through the dc-dc interfaces) than when performed using the grid as intermediary.



(a) (b)

Figure 3: Comparison of off-board systems with different operating mode and an unified off-board system with RES and ESS interface: (a) Number of components required for the hardware implementation; (b) Total cost for the implementation of each solution.

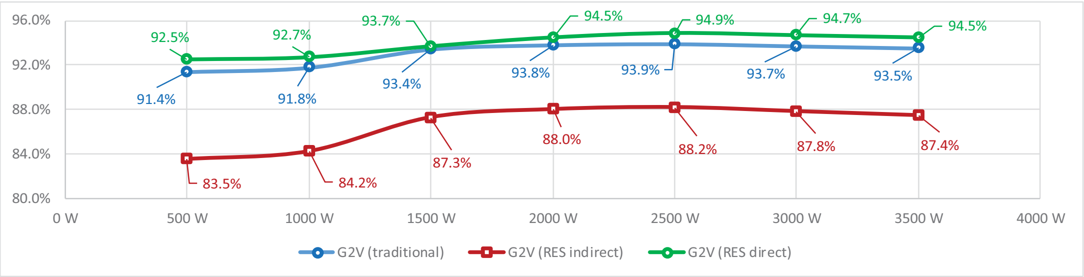


Figure 4: Comparison in terms of estimated efficiency between an off-board system with the operating modes identified in Figure 2 and an unified off-board system with RES and ESS: (i) During the G2V traditional mode; (ii) During the G2V indirectly from RES mode (using the grid as intermediary); (iii) During the G2V directly from RES mode.

CONCLUSIONS

The paper introduced the vehicle-to-anything (V2X) concept regarding the power transfer perspective for electric vehicle (EV) off-board systems. The different operating modes that can be addressed for the future vision of the vehicle electrification in smart grids are presented considering an economic point of view about the implementation of different solutions. Along the paper are described the presented and future perspectives about operation modes for the EV incorporation in smart grids and smart homes considering off-board systems, also framed with the integration of renewable energy sources (RES) and energy storage systems (ESS). The comparison was established considering the traditional solutions in terms of power electronics converters, and also using commercial prices to define the cost of each solution. The obtained results show that unified structures are more expensive, but provide more attractive functionalities for interfacing RES and ESS, and also present better results in terms of energy efficiency, allowing to conclude that unified structures present advantageous features, and thus are a relevant solution for the vehicle electrification in smart grids prospecting V2X scenarios.

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