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Comparison of Charging Systems for Electric Vehicles and Their Impact on Electrical Grid

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***Abstract* — This paper presents a comparison of four types of on-board batteries charging systems for Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs), and their impact on the power quality of the electrical power grid. In the comparison are analyzed the features, the characteristics and the operation of each charging system, aiming their controllability and their impact on the electrical grid, mainly considering the Total Harmonic Distortion (THD) of the consumed current and the power factor. Besides the normal mode of operation to charge the batteries, denominated Grid-to-Vehicle (G2V), in this paper is also discussed the possibility of operation as Vehicle-to-Grid (V2G), in which the batteries of the Electric Vehicle return part of the stored energy back to the electrical grid. The operation of the batteries charging systems for EVs is shown through simulations and experimental results.**

Keywords - Batteries Chargers; EV Charging System; Electric Vehicles; Power Quality; Sinusoidal Current; Unitary Power Factor; Bidirectional Converters.

I. INTRODUCTION

The recent and massive bet in electric mobility around the world, mainly in Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs) represents a new paradigm in transports sector, alternatively to the vehicles with Internal Combustion Engines (ICE), and a strong independence of the oil cost, allowing an effective fight against the climate change. These alternatives are becoming increasingly popular, as demonstrated with the various vehicles available in the market, as the EV Nissan Leaf and the PHEV Toyota Prius. Thereby, for the electrical power grid these vehicles are extra loads that will consume energy to charge the batteries, and in many cases at the same time and in the same charging point.

Taking into account the global scenario of electric mobility is extremely necessary charge the EVs and PHEVs batteries in accordance with the electrical power grid capabilities and with benefits in terms of power quality through a sinusoidal current consumption with unitary power factor [1]. At the same time, is also extremely important, charge the batteries through proper charging algorithms aiming preserve their lifespan. These requirements should be taken into account to the on-board and off-board chargers, because many of these vehicles are designed to be charged with both types of chargers, from a standard outlet (e.g., at home), or on a car parking lot (where there are external chargers) [2].

Nowadays, the batteries charging process is performed without any type of coordination between the vehicles and the electrical power grid. When a vehicle is plugged into the electrical power grid, theoretically it is possible to have a bidirectional flux of energy. This interactivity between the EVs and PHEVs, with the electrical grid is expected to be one of the key technologies in the future of the Smart Grids concept [3]. From the moment that the vehicle is plugged into the electrical power grid the charging can starts immediately or after a fixed time delay (controlled by the user). Typically, the charging process occurs overnight, bringing problems to the electrical grid due to uncontrolled demand [4]. Nevertheless, in future, the charging process will be performed in coordinated mode according to the real time capabilities and requirements of the electrical power grid, and according to the needs of the drivers of the EVs (mainly focusing the energy price and the batteries State-of-Charge). In [5] are described technical solutions to integrate EVs in the electrical power grid, and in [6] is proposed a coordinated charging of multiple PHEVs in residential distribution grids, in order to minimize the power losses and maximize the efficiency of the electrical grid. As described in [7], to the Portuguese case, to prevent a large demand from the electrical power grid, it will be necessary a coordinated charging strategy for the Electric Vehicles.

In [8] is presented a study that encompasses the impact of EVs on the electrical power grid in isolated systems. For this type of electrical power grid, these vehicles can operate as Energy Storage Systems (ESS), and if they are equipped with bidirectional chargers, in accordance with the Vehicle-to-Grid (V2G) concept, they can be used to stabilize the production and consumption of electrical energy, controlling the demand peak periods.

Focusing the integration of EVs and PHEVs in the electrical power grid, in this paper is analyzed and compared four batteries chargers, taking into account that the main requirement to preserve the power quality is the sinusoidal current consumption with unitary power factor. On other hand, to preserve the batteries lifespan is extremely important respect their nominal values as voltages, currents and temperatures. The batteries chargers are power electronics converters, which consist in AC-DC and DC-DC converters. In [9] are compared the basic topologies for power factor correction (PFC), highlighting DC-DC converters operating in discontinuous conduction mode. In [10] is presented a comprehensive review of various techniques to PFC with their control systems and advantages and disadvantages. The simplest AC-DC power electronics converter to charge the batteries use only non-controlled components, as illustrated in Fig. 1. This type of converter is easy to implement, is inexpensive, and is less susceptible to damage. However, the output voltage and the consumed current are not controlled. Consequently, in this type of converter the waveform of the consumed current is distorted, contributing to the degradation of the power quality of the electrical grid.

On the other hand, using controlled power electronic semiconductors it is possible control the waveform of the AC consumed current, as well as the DC voltage and the DC current in the batteries side. Comparing with the chargers which use only non-controlled semiconductors, the power circuit and the control system (which can be digital or analog) is more complex, and the cost of implementation and maintenance is increased. However, the improvement of power quality, through a sinusoidal current consumption, and unitary power factor, are the main features. Fig. 2 illustrates these types of converters as interface between the electrical power grid and the batteries. In a report published by the California Energy Commission [11] is presented a study about the impact of the residential electric vehicles charging systems. As example, for the GM EV1, the Total Harmonic Distortion (THD) of the current has a variation from 3% (at beginning of charging) to 28.11% (at end of charging). For this vehicle, and to these two periods, the power factor has a variation from 1 to 0.96. In this report are also presented other results about other EVs. A similar study is presented in [12].

In the comparison presented in this paper are analyzed the main characteristics and the operation of four charging systems. One of them uses uncontrolled semiconductors and passive components, and the others chargers use controlled semiconductors and passive components. The comparison is based on the controllability, the impact on the electrical power grid, mainly the current Total Harmonic Distortion (THD) and the power factor, and the possibility of operation as Vehicle - to - Grid (V2G). As defined by Mid-Atlantic Grid Interactive Cars Consortium (MAGICC) [13], V2G technology utilizes the stored energy in the EV batteries to contribute with electricity back to the grid when the grid operators request it. This technology makes an interaction between vehicles and grid, in order to control the needs of both.

II. BATTERY CHARGER ESPECIFICATIONS

EVs and PHEVs are becoming a part of the electrical power grid day by day, and consequently, the chargers for these vehicles have the ability to make this interaction better for the consumer and for the electrical power grid. Thus, in these vehicles, the batteries charging process can be performed on-board or off-board, and through the conductive or inductive method. An on-board charging system is referred to a charger that is implemented inside the vehicle. The user only accesses the input of the charger, to plug the vehicle into the electrical power grid. This charger is used to charge the batteries slowly, denominated slow charge (AC voltage). On the other hand, an off-board charger system is implemented out of the vehicle, and accesses directly the batteries (DC voltage). Contrarily of the on-board charger, this is used to charge the batteries as fast as possible, denominated fast charge. The conductive charge presupposes a physical contact between the electrical power grid and the chargers, instead, with the inductive charger there are not a physical contact between both. Independently of the charger type, the interaction between the EVs and PHEVs with the electrical power grid should comply with the norms. The main norms presented by the International Electrotechnical Commission (IEC) are IEC 62196 and IEC 61851.

III. POWER CONVERTERS AND CONTROL SYSTEM

In this section is compared the hardware of the power electronics converters and their control system. In terms of hardware, basically, the presented converters differ in the number of components used and in the control methodology. In Fig. 3 are shown the four converters under comparison with respective control algorithm. The detail of the implementation of each control algorithm is not approached in this paper.

During the EV or PHEV charging process, typically, the energy flows from the electrical power grid to the batteries (Grid-to-Vehicle G2V), through the power converters, without any concern about power quality, resulting in distorted currents with high harmonic content. However, using active converters, it is possible control the waveform of the consumed current and the power factor. To obtain good performances with the batteries is necessary implement the algorithms indicated by the manufacturers and use Battery Management Systems (BMS), as presented in [14][15]. The BMS and the details of the algorithms to charge the batteries are not discussed in this paper. However, in these tests were considered four lead-acid batteries (48 V – 44 Ah), and was considered the charging algorithm that consists in apply to the batteries constant current (first stage of the charging) followed by constant voltage (second stage of the charging).

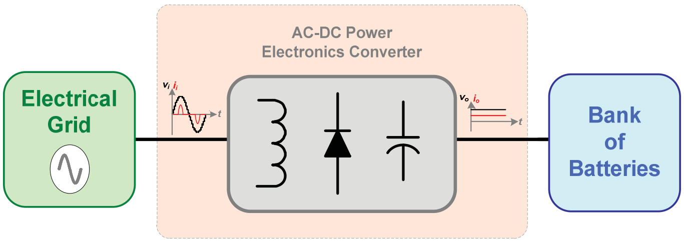

Figure 1. Structure of an AC-DC power electronics converter using only non-controlled semiconductors.

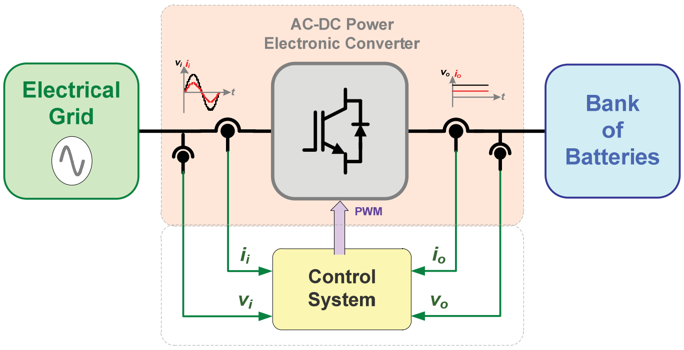

Figure 2. Structure of the AC-DC power electronic converters using controlled semiconductors.

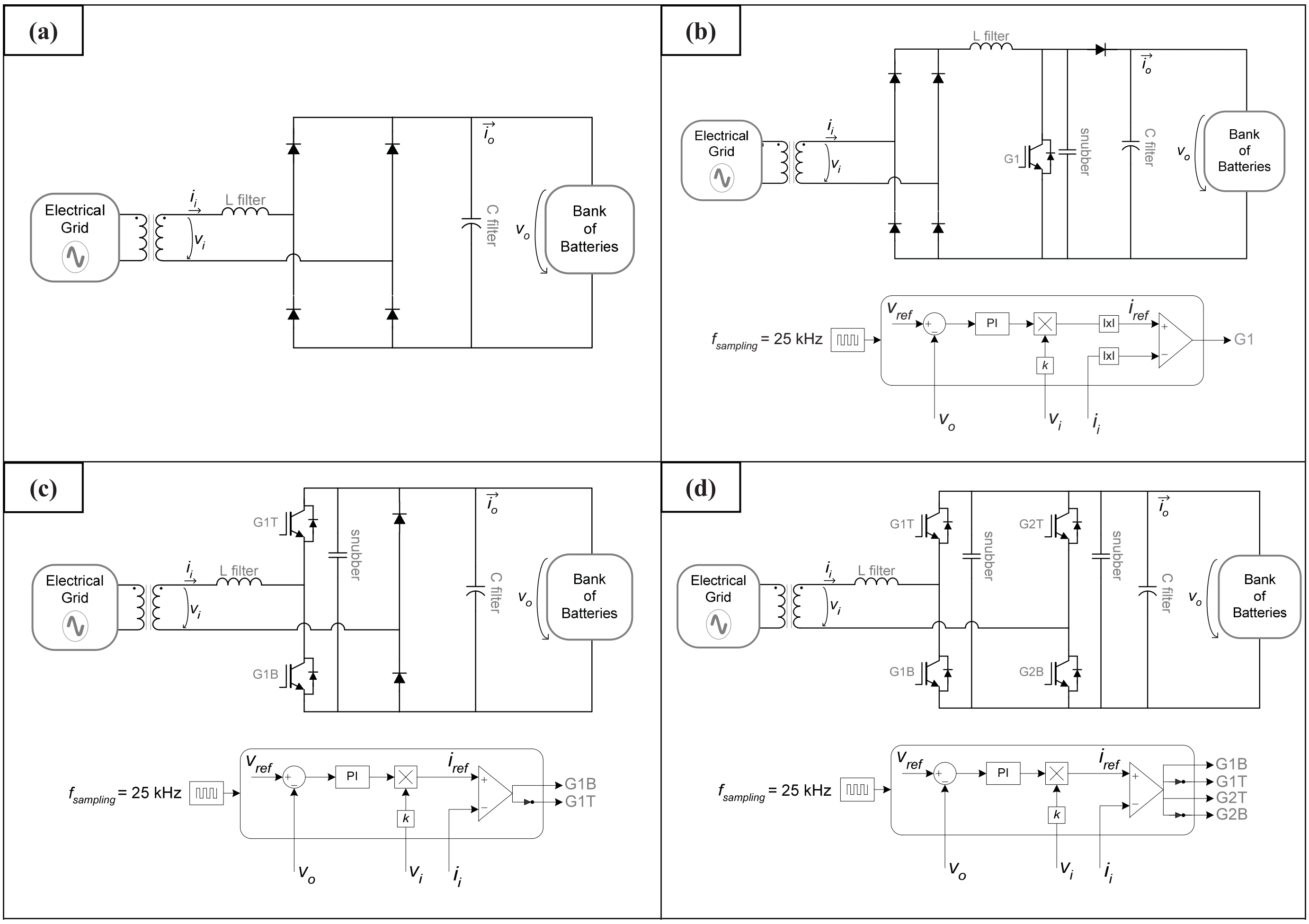

Figure 3. Four converters under comparison with respective control algorithm:
(a) Full-bridge diodes AC-DC converter with input current filter;
(b) Full-bridge diodes AC-DC converter and a boost converter as Power Factor Corrector (PFC);
(c) Full-bridge AC-DC converter half-controlled with input current filter;
(d) Full-bridge AC-DC converter full-controlled with input current filter.

The converter shown in Fig. 3 (a) is composed by four power diodes and by the capacitor filter in output, and only allows charge the batteries with constant voltage imposed by the maximum of the input voltage, and without any type of control of voltage. Despite the input current filter, the consumed current is distorted, with high value of THD, contributing to damaging the power quality. Consequently, this converter isn't the most indicated to charge the EVs and PHEVs batteries.

In Fig. 3 (b) is shown a converter more complex than the previous, and consequently with more advantages. The first stage of this converter is equal to the previous (four power diodes connect in bridge) followed by a dc-dc boost converter, functioning as Power Factor Corrector (PFC). Thereby, the consumed current is sinusoidal with unitary power factor. This converter allows control the output voltage and current, contributing to preserve the batteries lifespan.

In Fig. 3 (c) is shown a converter similar to the previous in terms of characteristics, i.e., the consumed current is sinusoidal with unitary power factor and allows control the output voltage or current. However, are used two controlled semiconductors and consequently the hardware is more complex.

In Fig. 3 (d) is shown a converter with the characteristics of the previous (sinusoidal current consumption with unitary power factor, with output voltage and current control). Besides the operation as Grid-to-Vehicle (G2V), the great advantage is the operation as Vehicle-to-Grid (V2G) (bidirectional mode of operation), allowing deliver back to the electrical power grid, a small amount of the stored energy in the batteries. With these performances, the batteries nominal values are respected, and is mitigated the power quality degradation. In this converter are used four controlled semiconductors, increasing the complexity of the hardware and the control system.

IV. SIMULATION RESULTS

In this section are presented the simulations results obtained with the simulation tool PSIM 9.1. In the simulations was used an electrical model of the batteries (48 V – 44 Ah), a microcontroller model (programmed in C language), and the respective converters.

In Fig 4 are shown the results obtained of the consumed current and the electrical power grid voltage during the charging process. In Fig 5 is shown the results obtained to the power electronic converter presented in Fig. 3 (d) during their operation as V2G, i.e., when is delivered to the electrical power grid a small amount of the stored energy in the batteries.

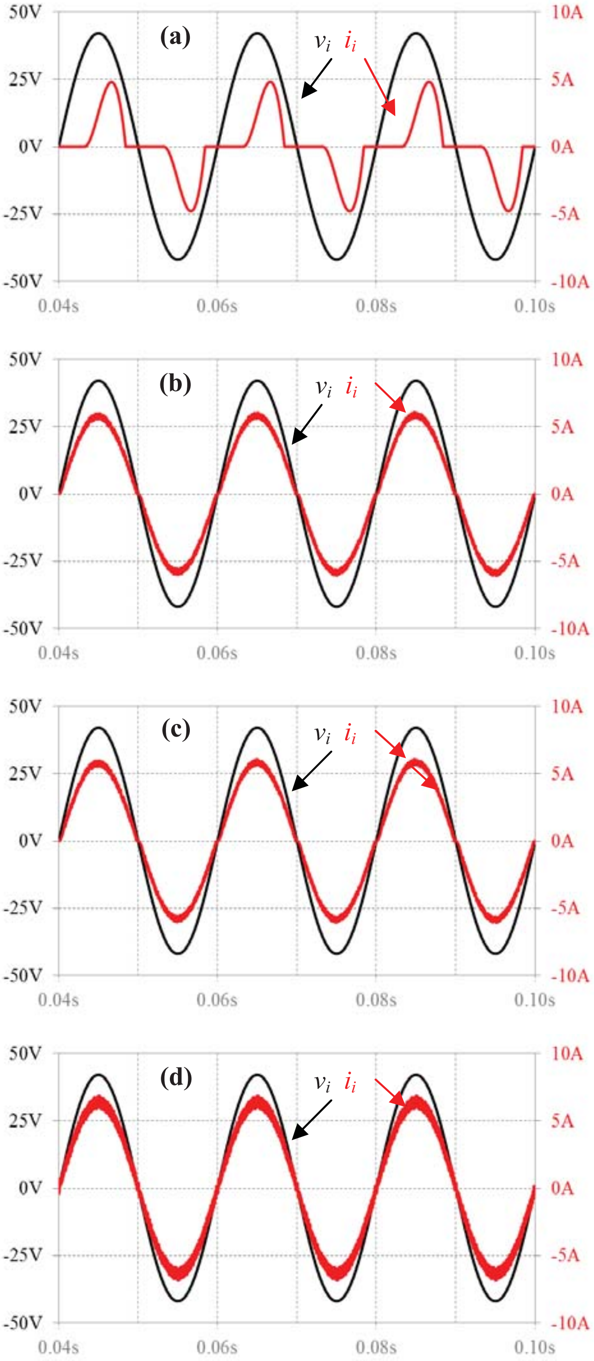

Figure 4. Simulation results of the consumed current and electrical power grid voltage: (a) Full-bridge diodes AC-DC converter; (b) Full-bridge diodes AC-DC converter and a boost PFC; (c) Full-bridge AC-DC converter half-controlled; (d) Full-bridge AC-DC converter full-controlled.

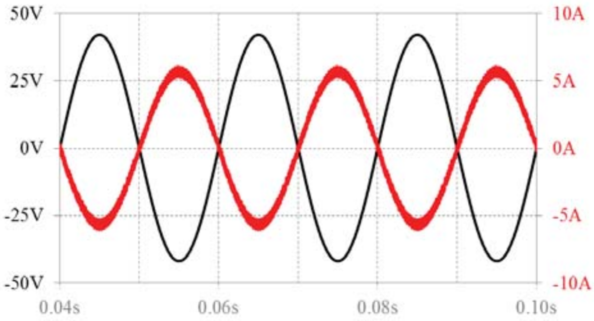

Figure 5. Simulation results of the current and electrical power grid voltage during the operation of the converter of Fig. 3 (d) as Vehicle-to-Grid.

V. EXPERIMENTAL RESULTS

In this section are presented the experimental results obtained for all the presented converters. Then, is described the developed hardware of the power electronic converters and the developed control system.

A. Power Converters

In Tab. 1 is shown a comparative analysis of the presented converters, taking into account the number of semiconductors (controlled or not), the converters controllability (drivers, microcontroller, and voltage and current sensors), and the average cost associated with each converter. In Fig. 6 is shown the hardware of the power converters (implemented in a test bench), and in Fig. 7 are shown the four lead acid batteries (48 V – 44 Ah) used.

The power converter consists of the converters (composed by IGBTs FGA25N120ANTD 50 A – 1200 V and fast diodes), snubber capacitors (1 uF – 400 V), inductance (5 mH – 10 A), the circuit to pre-charge the output capacitor, and the four lead-acid batteries connected in series.

TABLE I. COMPARATIVE ANALYSIS OF THE PRESENTED CONVERTERS

Type	**(a)**	**(b)**	**(c)**	**(d)**
Non-Controlled Semiconductor (30 A–600 V)	4 x 3.2 €	5 x 3.2 €	2 x 3.2 €	-
Controlled Semiconductor (50 A–1200 V)	-	1 x 4.7 €	2 x 4.7 €	4x 4.7 €
Drivers Semiconductor	-	1 x 56 €	1 x 56 €	2 x 56 €
Microcontroller (microchip)	-	1 x 77 €	1 x 77 €	1 x 77 €
Voltage Sensors (500 V)	-	2 x 48 €	2 x 48 €	2 x 48 €
Current Sensors (20 A)	-	1 x 12 €	1 x 12 €	1 x 12 €
Total Price	**12.8 €**	**261.7 €**	**208.8 €**	**315.8 €**

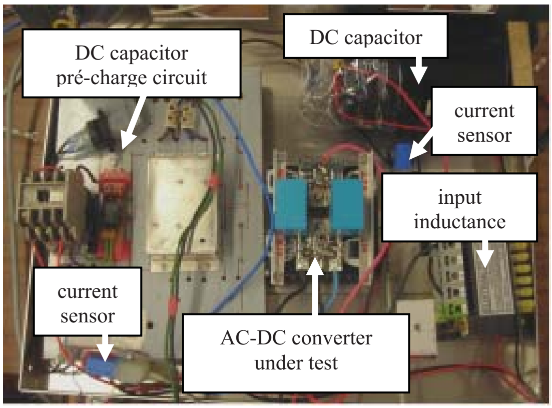

Figure 6. Hardware of the power converters (implemented in a test bench).

Figure 7. Used lead-acid batteries (48 V – 44 Ah).

B. *Control System*

Despite the control system can be implemented in analog form, nowadays, the use of digital control through a microcontroller is more common, because it is configurable, easy to implement, and the associated costs are not high. The developed control system, presented in Fig. 8, is composed by the Microcontroller PIC32MX360F512L, the Digital Analog Converter DAC - DAC712P, Voltage and Current Sensors LEM - Hall Effect Sensors, a Signal Conditioning Circuit, a Circuit to Detect Errors, a Command Circuit, and a Drivers Circuit.

In Fig. 9 are shown the results obtained for the electrical power grid voltage and for the consumed current during the charging process (G2V). On the other side, in Fig. 10 are shown the results obtained to the converter presented in Fig. 3 (d) during the operation as V2G.

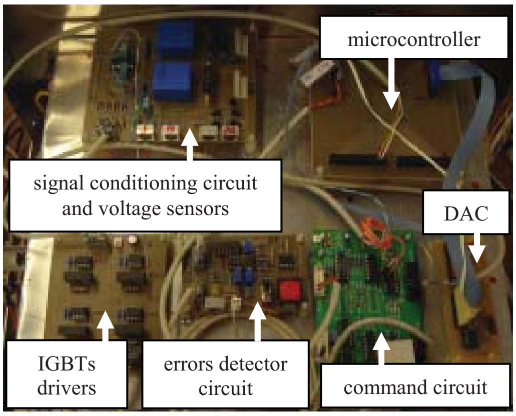

Figure 8. Developed control system.

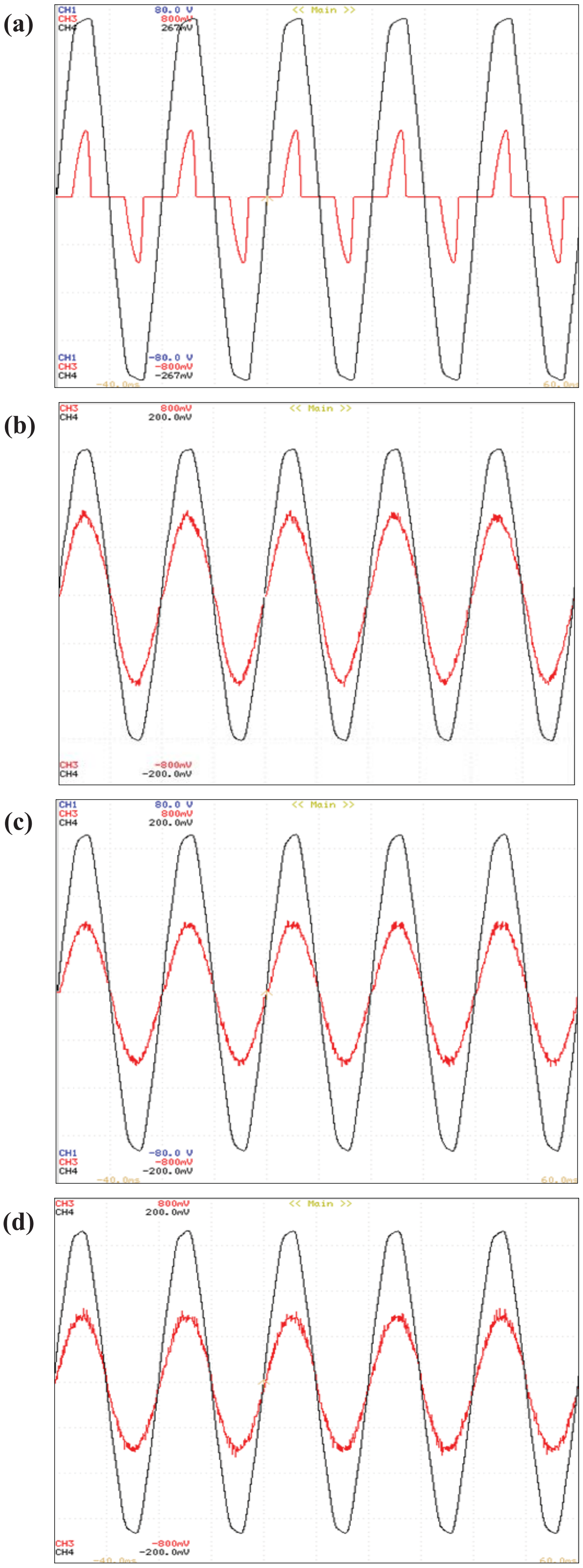

Figure 9. Experimental results for the electrical grid voltage and for the consumed current during the charging process (G2V):
(a) Full-bridge diodes AC-DC converter;
(b) Full-bridge diodes AC-DC converter and a boost PFC;
(c) Full-bridge AC-DC converter half-controlled;
(d) Full-bridge AC-DC converter full-controlled.

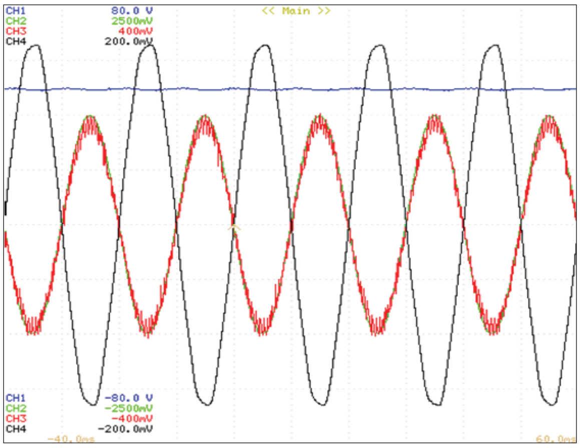

Figure 10. Experimental results of the current and electrical power grid voltage during the operation of the converter presented in Fig. 3 (d) as Vehicle-to-Grid.

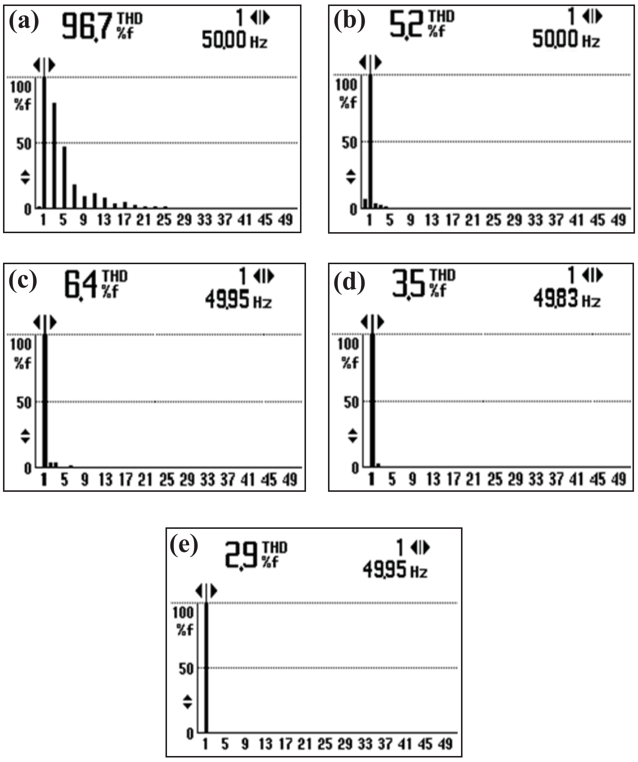

Figure 11. Experimental results obtained of the consumed current THD:
(a) Full-bridge diodes AC-DC converter;
(b) Full-bridge diodes AC-DC converter and a boost PFC;
(c) Full-bridge AC-DC converter half-controlled;
(d) Full-bridge AC-DC converter full-controlled as G2V;
(e) Full-bridge AC-DC converter full-controlled as V2G.

In Fig. 11 are shown the results obtained for the consumed current THD for the experimental results shown in Fig 9 and Fig 10.

VI. CONCLUSION

In this paper were compared four different batteries chargers that can be implemented on-board in Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs). The operation of the four chargers is shown through simulation and experimental results, and it is assessed their impact on the electrical power grid, mainly in what concerns to the current Total Harmonic Distortion (THD) and the power factor. As shown, some of the chargers allow controlling the charge of the batteries in order to preserve their lifespan, without deteriorating the power quality of the electrical grid. Besides the charging process as Grid-to-Vehicle (G2V), were also presented results of the operation as Vehicle-to-Grid (V2G) for the full-bridge AC-DC converter full-controlled.

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