New Opportunities and Perspectives for the Electric Vehicle Operation in Smart Grids and Smart Homes Scenarios

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Abstract: New perspectives for the electric vehicle (EV) operation in smart grids and smart homes context are presented. Nowadays, plugged-in EVs are equipped with on-board battery chargers just to perform the charging process from the electrical power grid (G2V – grid-to-vehicle mode). Although this is the main goal of such battery chargers, maintaining the main hardware structure and changing the digital control algorithm, the on-board battery chargers can also be used to perform additional operation modes. Such operation modes are related with returning energy from the batteries to the power grid (V2G- vehicle-to-grid mode), constraints of the electrical installation where the EV is plugged-in (iG2V – improved grid-to-vehicle mode), interface of renewables, and contributions to improve the power quality in the electrical installation. Besides the contributions of the EV to reduce oil consumption and greenhouse gas emissions associated to the transportation sector, through these additional operation modes, the EV also represents an important contribution for the smart grids and smart homes paradigms. Experimental results introducing the EV through the aforementioned interfaces and operation modes are presented. An on-board EV battery charger prototype was used connected to the power grid for a maximum power of 3.6 kW.

1 INTRODUCTION

Each time more, the electric mobility is presented in our society as a new paradigm that contributes for a more efficient and sustainable mobility (Rajashekara, 2013), (Raghavan, 2012), as well as an important benefit to reduce the oil costs and the greenhouse gas emissions (Milberg, 2011). In this context, electric vehicles (EVs) are the main boosters to support the electric mobility (Chan, 2010), (Chan, 2007), however, a full electric mobility adoption is also dependent of major technological issues (Khaligh, 2010), (Inoa, 2011), (Ferreira, 2013). Nowadays, in order to perform the EV batteries charging process, on-board or off-board chargers are used (Gautam, 2012), (Monteiro, 2014), with contact or contactless (wireless power transfer) technologies (Ibrahim, 2015). Besides these approaches, integrated EV chargers with the motor drive or reconfigured chargers to support the auxiliary battery are also used (Haghbin, 2013), (Pinto, 2014). Independently of the EV charger, for all the aforementioned solutions the EV is plugged-in to the power grid to receive energy. Nevertheless, with the EV adoption around the world (for instance Canada (Hajimiragha, 2010) and China (Song, 2010)), the power grids are facing a new problem, once they were not projected to support this new type of uncontrolled load, which can cause power quality issues (Monteiro, 2011), (Lopes, 2011), (Wirasingha, 2011). At the same time, new opportunities for electricity markets and for the integration of EVs with renewables are emerging (Saber, 2011), (Zhao, 2012), (Ferreira, 2013). A scheme to manage the EV charging process considering their uncertain arrival (as well as the battery state-of-charge) and the energy prices is presented in (Zhang, 2014), and an integrated scheme to incorporate EVs with renewables is presented in (Gao, 2014). Taking into account the EV capacity to store energy and its dynamic connection in the power grid, through bidirectional chargers (Monteiro, 2016), it can operate as a dynamic energy storage system, capable to consume or deliver energy to the power grid in the place where it is plugged-in (Kramer, 2008). When the EV receives energy from the grid to charge the batteries, the process is known as grid-to-vehicle (G2V), and

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when the EV delivers energy to the grid, the process is known as vehicle-to-grid (V2G) (Kempton, 2005)(Yilmaz, 2013). An aggregator to manage such operation modes is proposed in (Escudero-Garzás, 2012). A detailed study about the V2G mode as support to stabilize the power grid and renewables integration is analysed in (Kempton, 2015), and a cost function considering the charging and discharging process is presented in (Zhou, 2011). The aforementioned scenarios are related with the EV operation neglecting, for instance, the operation of the other electrical appliances plugged-in in the same electrical installation. In order to overcome this drawback, a dynamic operation in G2V and V2G modes according to the operation of the other electrical appliances is presented. Hereafter, this modes are identified as improved G2V (iG2V) and improved V2G (iV2G). This dynamic operation consists in adjust the consumed current to charge the batteries according to the consumed current of the electrical appliances, maintaining constant the total current consumed by the electrical installation. Therefore, overloads and overcurrent trips in the main circuit breaker are prevent. This is more relevant considering the future smart homes scenarios. Besides exchange energy in bidirectional mode with the power grid, the EV can also operate as power quality compensator. This mode can be divided in three cases: (1) The EV produces a current without fundamental component to compensate the current harmonic distortion of the electrical installation caused by the nonlinear electrical appliances, where it does not use any energy from the batteries, preventing their aging; (2) The EV produces a current to compensate the power factor of the electrical installation caused by the reactive power consumption of the electrical appliances, where the EV does not use energy from the batteries; (3) The EV operates as an off-line uninterruptible power supply (UPS) during power outages in short periods of time once is used energy from the batteries (Monteiro, 2016).

Figure 1 shows the integration of an EV into a home considering the different energy flows. All of the aforementioned operation modes will contribute to the interactivity between the EVs and the smart grids, as well as to the development of smart homes (Gungor, 2012). In such context, global energy management solutions are presented in (Liu, 2013) and (Jin, 2013). Therefore, the EV can operate as an adaptable active element, with skills for consuming, storing, and providing energy. Associated with these operation modes, the EV should establish a bidirectional interactivity with the power grid, where

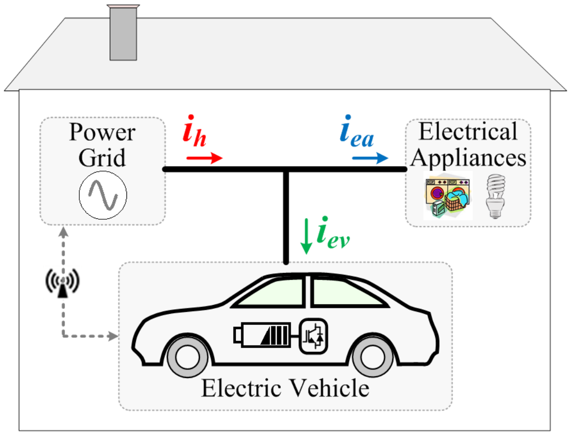

Figure 1: Integration of an EV into the electrical installation of a home.

information and communication technologies are presented (Güngör, 2011). A mobile information system used to inform the EV user about recommendations to manage the autonomy, the electricity market and charging stations is proposed in (Ferreira, 2014).

This paper aims to demonstrate an overview about the EV operation through an experimental validation of the aforementioned operation modes and its contribution as enabler for the future paradigms of smart grids and smart homes. For such purpose, a 3.6 kW on-board EV battery charger was used to validate all the operation modes. The rest of this paper is organized as follows. Section II introduces the on-board EV charger used to validate the operation modes. Section II presents the experimental results and a detailed and independent analysis of each operation mode. A discussion is presented in section IV, and, finally, the main conclusions are in section IV.

2 ON-BOARD EV BATTERY CHARGER

This section describes the developed 3.6 kW on-board EV battery charger, which is composed by an ac-dc-dc converter, i.e., an ac side to interface the power grid, a shared dc-link between the two converters, and a dc side to interface the EV batteries. IGBTs model IXXR110N65B4H1 and gate drivers model SKHI61R are used. This EV charger has a total power density of 0.43 kW/liter and presents 94% of efficiency for the maximum power of 3.6 kW. Figure 2 shows the laboratorial setup used to obtain the experimental results, where is presented the developed on-board EV charger, and table I presents its main characteristics.

3 EXPERIMENTAL RESULTS

This section presents a detailed explanation about the main experimental results of the EV introduction into the power grids in smart grids and smart homes context. Such experimental results were obtained in laboratory environment with the aforementioned on-board EV charger and with a set of lead-acid batteries, electrical appliances, and a system emulating a set of PV panels. The operation in the different operation modes was selected by the user. A digital oscilloscope Yokogawa DL708E was used to catch the experimental results. It is important to note that the battery state-of-charge was not analyzed in this paper due to space restrictions.

3.1 Improved Grid-to-Vehicle

The actual EVs are equipped with on-board battery chargers to perform the charging process from the power grid without consider constraints of the electric installation. This operation mode is identified in the literature as grid-to-vehicle (G2V). Figure 3 shows the power grid voltage (v_g), the total home current (i_h), the electrical appliances current (i_{ea}) and the EV current (i_{ev}) during the charging process (G2V). In this operation mode, the charging power is defined by the battery management system, which establishes two distinct charging stages in the dc side (i.e., in the batteries): (1) initially with constant current and variable voltage; (2) and after the first stage with constant voltage and variable current. In this experimental result, a power of 3 kW, a total harmonic distortion (THD) of 3% in the voltage, a THD of 2% in the current, and a power factor of 0.99 were measured. It is important to note that the EV current is sinusoidal due to the current control strategy. Therefore, the EV does not contributes to aggravate the power quality in the electrical installation.

The main disadvantage of this operation mode is related with the operation of the other electrical appliances that are also plugged-in in the same electrical installation and working at the same time. Turning on several appliances at the same time in the electrical installation, the main circuit breaker acts to prevent damages for the installation. This situation will interrupt the charging process and, inherently, will increase the time required to perform the charging process. In order to mitigate this drawback, the EV charging process can be performed with a smart control strategy, where the EV charging power is adjusted according to the operation of the other electrical appliances.

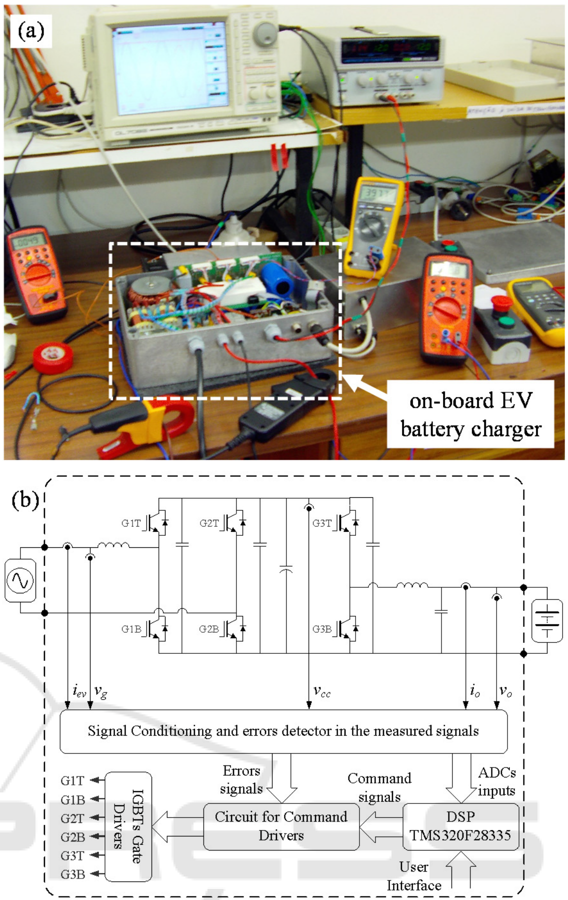

Figure 2: Laboratorial setup used to obtain the experimental results (a) and structure of the on-board EV charger (b).

Table 1: Main characteristics of the on-board EV battery charger.

Parameter	Value
Grid Voltage	230 V
Grid Frequency	50 Hz
Maximum Power	3.6 kW
Maximum dc Current	10 A
Output Voltage	250 V to 400 V
Switching Sampling	40 kHz
Switching Frequency	20 kHz
Input Inductance	5 mH
Output Inductance	2 mH
Output Capacitor	0.68 mF
Dc-link Capacitor	3 mF

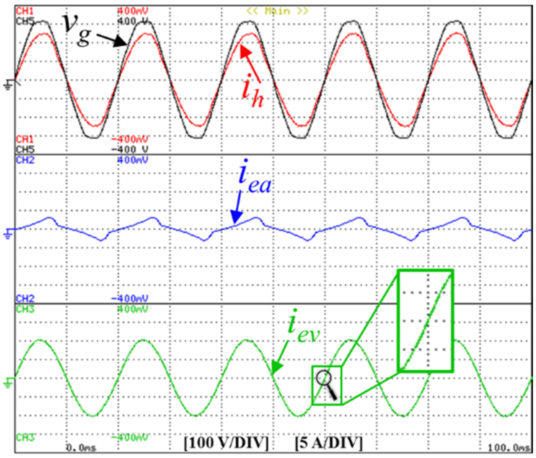

Figure 3: Experimental results during the EV battery charging: Power grid voltage (v_g); Total home current (i_h); Electrical appliances current (i_{ea}); EV current (i_{ev}).

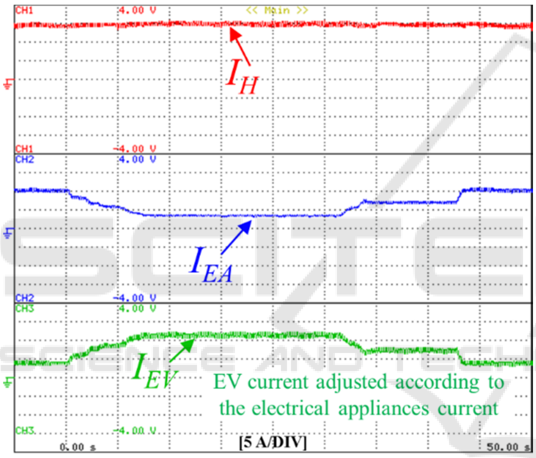

Figure 4: Experimental results during the controlled EV battery charging as iG2V: Total home current (I_H); Electrical appliances current (I_{EA}); EV current (I_{EV}).

Figure 4 shows the root mean square (rms) values of the home current (I_H), the current consumed by the electrical appliances (I_{EA}) and the EV current (I_{EV}). As expected, the EV charging current is adjusted according to the current consumed by the electrical appliances in order to prevent the main circuit breaker actuation, i.e., the home current is maintained with the same amplitude.

Figure 5 shows the instantaneous values of the same variables (as presented in the previous figure) in order to highlight the adjustment of the EV current. It is important to note that this adjustment is performed without sudden variations in the EV current and without jeopardize the hardware of on-board EV battery charger or the normal operation of the electrical appliances. For such purpose,

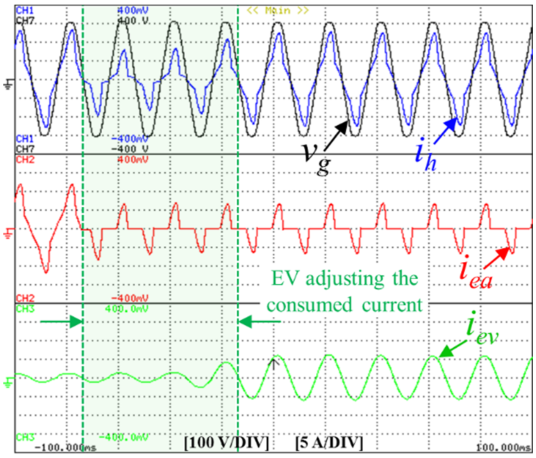

Figure 5: Experimental results during the controlled EV battery charging as iG2V: Power grid voltage (v_g); Total home current (i_h); Electrical appliances current (i_{ea}); EV current (i_{ev}).

advanced digital current control techniques are used to control the EV current.

3.2 Improved Vehicle-to-Grid

Typically, the EV is introduced in the power grid to perform the battery charging process, however, it can also be used in bidirectional mode. Therefore, instead of receiving energy, the EV is used to deliver energy back to the power grid, i.e., part of the stored energy in the batteries is returned to the power grid. From the power grid point of view, this operation mode, identified as vehicle-to-grid (V2G), is important to contribute to stabilize the power grid and, in a smart grid scenario, is performed with the power grid agreement and the convenience of the EV driver in terms of the energy stored in the batteries. For such purpose, the EV should receive a set point of energy and a time interval to operate in V2G mode. Figure 6 shows the power grid voltage (v_g), the total home current (i_h), the electrical appliances current (i_{ea}) and the EV current (i_{ev}) during the V2G mode, i.e., when is delivered energy to the power grid from the EV batteries. It is important to note that the EV current (i_{ev}) is in phase opposition with the power grid voltage (v_g), meaning that the power grid receives energy.

Considering a smart home scenario, besides the simple discharging process to the power grid, the EV can be used to deliver energy to the home when the required current exceeds the nominal current of the electrical installation. Figure 7 shows this scenario, where in an initial phase the EV is just plugged-in (without operating in G2V nor V2G) and when the

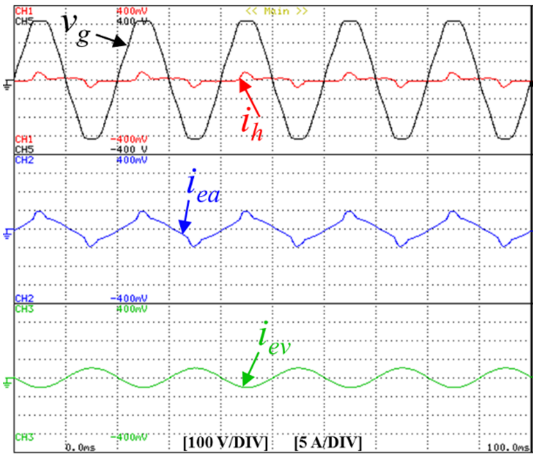

Figure 6: Experimental results during the EV battery discharging: Power grid voltage (v_g); Total home current (i_h); Electrical appliances current (i_{ea}); EV current (i_{ev}).

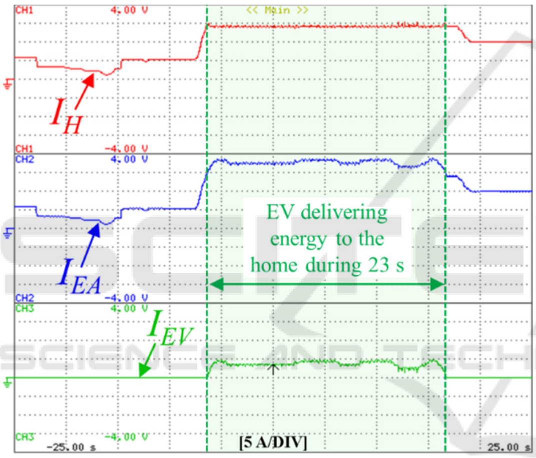

Figure 7: Experimental results during the controlled EV battery discharging as iV2G: Total home current (I_H); Electrical appliances current (I_{EA}); EV current (I_{EV}).

total current exceeds the nominal current the EV starts its operation as V2G, i.e., the EV delivers the difference of current. This kind of operation is proposed as improved vehicle-to-grid (iV2G) and is directly associated with the EV operation in smart homes.

3.3 Interface with Renewables

As described in the previous items, the EV can be introduced into the power grid to perform the charging (iG2V) or discharging (iV2G) process. Such operation modes can be framed with the smart grids or smart homes scenarios, where is also predictable the introduction of renewables, mainly PV panels. Therefore, besides the power grid, the

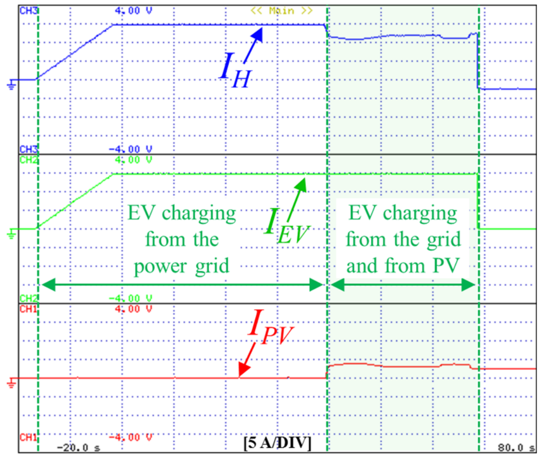

Figure 8: Experimental results during the EV battery charging from the power grid and from renewables: Total home current (I_H); EV current (I_{EV}); PV panels current (I_{PV}).

EV can also perform the charging process with energy from renewables. Figure 8 shows the rms values of the total home current (I_H), the EV current (I_{EV}) and the PV panels current (I_{PV}) for a case, where, in an initially phase the EV batteries are charged only with energy from the power grid and in a second phase with energy from the power grid and from renewables. This experimental result was obtained in laboratory environment with an emulated installation of PV panels. Taking into account the predictable smart homes with the integration of renewables (mainly PV panels), this scenario will be frequently due to the variable energy production from renewables.

3.4 Integration as a Power Quality Compensator

As presented in the previous items, the EV can be used to dynamically exchange energy with the power grid in bidirectional mode considering the power grid constrains and the requirements of the EV user. Nevertheless, the EV can also be integrated into the power grid as a power quality compensator. This operation mode is directly associated with the future smart homes, and is proposed in this paper considering three distinct cases: (1) the EV is used to compensate current harmonics in the electrical installation caused by the nonlinear electrical appliances; (2) the EV is used to compensate the power factor of the electrical installation caused by the reactive power consumption of some electrical appliances; (3) the EV is used as energy backup system, i.e., operating as an off-line uninterruptible power supply (UPS). The experimental results presented in this item were obtained in laboratory environment with real nonlinear electrical appliances. Figure 9 shows the power grid voltage (v_g), the total home current in the electrical installation (i_h), the current consumed only by the electrical appliances (i_{ea}), and the current produced by the EV (i_{ev}) during the EV operation compensating current harmonics. Taking into account that the EV produces a current with high harmonic distortion, the total home current is sinusoidal and in phase with the power grid voltage, i.e., it is the sum of the i_{ea} current with the i_{ev} current. The EV current is determined according to the harmonic distortion of the current consumed by the electrical appliances, i.e., the EV current does not have fundamental component once the objective is compensate the harmonic distortion of the electrical installation. It is important to note that during this operation mode is not used any energy from the EV batteries, i.e., the current circulates in the phase and neutral wires only through the ac-dc front-end converter. Besides the aforementioned case, Figure 10 shows the power grid voltage (v_g) and the EV current (i_{ev}) when the EV is used to compensate the power factor of the electrical installation where it is plugged-in. For such purpose, the EV produces a current (that can be leading or lagging with the power grid) in order to obtain a unitary power factor in the point of common coupling. The phase angle between the EV current and the power grid voltage is determined according to the reactive power consumed by the electrical appliances connected in the same electrical installation. Also in this case is not used any energy from the EV batteries, representing an important advantage. In the previous operation modes, the EV is used to compensate power quality problems associated with the total current in the home. However, the EV can also be useful to operate as an off-line UPS during short periods of power outages. Figure 11 shows the voltage applied to the electrical appliances (v_{ea}), the current consumed by the electrical appliances (i_{ea}), and the EV current (i_{ev}). As shown, this experimental result was obtained when a power outage occurs. In this case, initially, the EV is just plugged-in and, when the power outage occurs, the EV starts its operation as UPS, i.e., producing a voltage to feed the electrical appliances. Taking into account that the transition was performed in a short period of time (much smaller than the grid frequency), from the point of view of the electrical appliances was not identified any disturbance in its operation. This operation mode represents an important contribution for the future smart homes, where can be preferable to use a small part of the stored energy from the EV batteries, instead of stay without energy during a power outage.

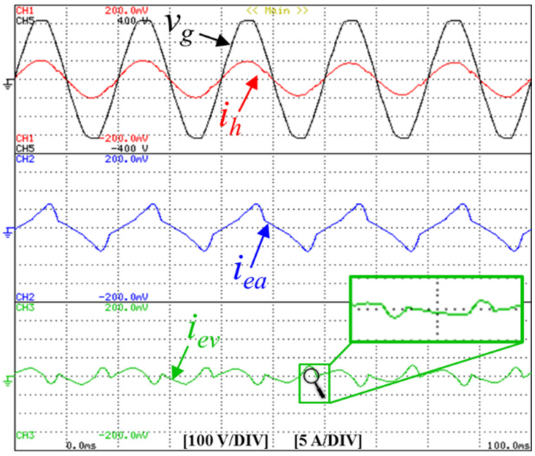

Figure 9: Experimental results during the EV operation compensating current harmonics: Power grid voltage (v_g); Total home current (i_h); Electrical appliances current (i_{ea}); EV current (i_{ev}).

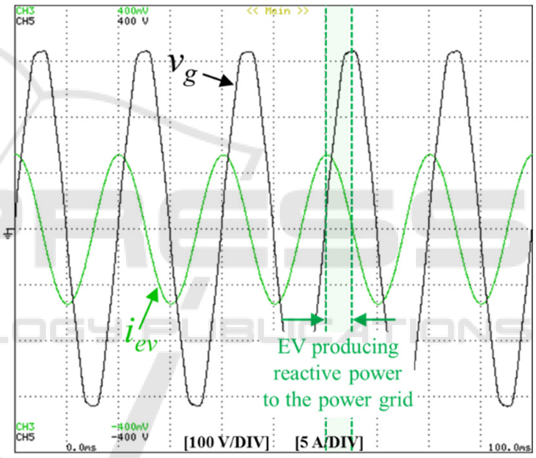

Figure 10: Experimental results during the EV operation producing reactive power: Power grid voltage (v_g); EV current (i_{ev}).

4 DISCUSSION

Nowadays, the EV is considered the main alternative for replacing the traditional polluting vehicles with internal combustion engines. This is an important contribution, however, the EV can also emerge in the future smart grids and smart homes with a set of new valences. Besides the operation modes grid-to-

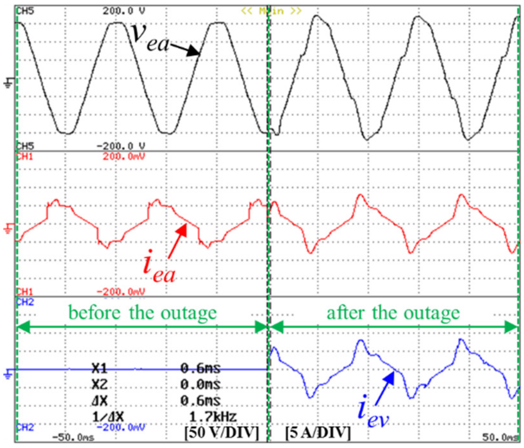

Figure 11: Experimental results during the EV operation as an UPS: Power grid voltage (v_g); Total home current (i_h); Electrical appliances current (i_{ea}); EV current (i_{ev}).

vehicle (G2V), improved grid-to-vehicle (iG2V) and vehicle-to-grid (V2G), validated in the experimental results, the EV can also contribute with other innovative modes. For instance, the EV can combine the operation in G2V, V2G, or iG2V with the operation as power quality conditioner. Moreover, besides the operation in smart homes scenario, the presented operation modes can be extended to smart grids, i.e., the EV can operate in such modes in any place where it is plugged-in.

5 CONCLUSIONS

This paper presents new opportunities and perspectives for the electric vehicle (EV) operation in smart grids context. For such purpose a 3.6 kW on-board EV battery charger was developed and used in the experimental validation. Along the paper several experimental results are presented, including the EV charging and discharging processes from and to the power grid, the charging process from renewables, and the operation according to the other electrical appliances connected in the electrical installation, mainly, to prevent power quality problems. As shown in the paper, these operation modes represent an added value to the EV introduction into power grids, and an important contribution for the smart grids and smart homes paradigms.

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