Operation Modes of Battery Chargers
for Electric Vehicles in the Future Smart Grids

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Abstract. This paper presents an on-board bidirectional battery charger for Electric Vehicles (EVs), which operates in three different modes: Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), and Vehicle-to-Home (V2H). Through these three operation modes, using bidirectional communications based on Information and Communication Technologies (ICT), it will be possible to exchange data between the EV driver and the future smart grids. This collaboration with the smart grids will strengthen the collective awareness systems, contributing to solve and organize issues related with energy resources and power grids. This paper presents the preliminary studies that results from a PhD work related with bidirectional battery chargers for EVs. Thus, in this paper is described the topology of the on-board bidirectional battery charger and the control algorithms for the three operation modes. To validate the topology it was developed a laboratory prototype, and were obtained experimental results for the three operation modes.

Keywords: Battery Charger, Grid to Vehicle (G2V), Vehicle to Grid (V2G), Vehicle to Home (V2H), Electric Vehicles, Smart Grids.

1   Introduction

Nowadays, the electric mobility is the main alternative to the traditional transportation system in order to reduce the greenhouse gases emission and to help to address environmental and energy issues [1]. It is also important to reduce the oil consumption in this sector [2], where it is predictable that 55% of the total oil consumption in the world will be allotted by this sector in 2030 [3]. This new paradigm has been supported by the several alternatives that are already available, mainly Electric Vehicles (EVs), as the Nissan Leaf. Nevertheless, the impact of the electric mobility cannot be neglected [4], [5], [6]. The uncontrolled EVs proliferation, which represents extra loads to the power grids, can worsen some power quality problems, as power losses and high values of Total Harmonic Distortion (THD) in the currents and voltages [7]. These problems are caused by the EV battery chargers that are implemented with static power converters. Considering this scenario, it is extremely necessary equip the EVs with battery chargers with sinusoidal current consumption and controlled power factor, aiming to preserve the power quality [8], [9].

Currently, the energy required to the battery charging process follows from the power grid to the EVs. This operation mode is identified in the literature as Grid-to-Vehicle (G2V) [10]. Nevertheless, considering that the energy can follow in opposite sense, arises the operation mode Vehicle-to-Grid (V2G) [11]. Taking into account the future smart grids, where the EVs will be connected to a collaborative broker [12], the aforementioned operation modes can be used to help the power grid, especially for load-shedding and compensation of renewable production intermittency (providing both backup and storage). Besides the G2V and V2G operation modes, the energy stored in the batteries can also be used to feed other loads, typical at home. This operation mode is denominated as Vehicle-to-Home (V2H) [13]. The selection of each one of the G2V, V2G and V2H operation modes, will be optimized taking into account the EV driver profile and benefits, and the power grid capabilities. These operation modes are further described in detail. Fig. 1 illustrates the operation modes of the EVs in the future smart grids. As shown in this figure, the G2V and V2G operation modes can be performed at private (homes) or public places, and the V2H is performed at private (homes) places.

This paper results from a preliminary studies conducted in the first year of a PhD work, and intents contribute to the technological innovation of the electric mobility in smart grids. It is presented an on-board bidirectional battery charger with respective control algorithms, which enables the G2V, V2G and V2H operation modes. In order to evaluate these operation modes are presented some experimental results.
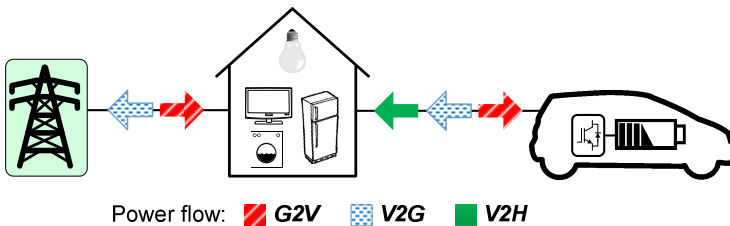

Power flow: G2V   V2G   V2H

Fig. 1. Representation of Electric Vehicle with G2V, V2G and V2H operation modes

2   Relationship to Collective Awareness Systems

The future smart grids will bring a set of advantages to the end-user. This is more relevant taking into account that it involves the introduction of several technologies aiming to establish a bidirectional communication between the power grid collaborative broker and the users. Knowing that the electric mobility is a topic of highest importance in smart grids, the end-user will have the opportunity to participate actively in the energy market. Thereby, to the smart grids will be possible predict the energy demand and control the energy production [14], [15]. This interactivity, including supervision, control and communication applications, will be the final topic that will be addressed in the PhD work. For such purpose it will be developed an Information and Communication Technologies (ICT) application.

The main goal of the G2V, V2G and V2H operation modes that are described in this paper is establish a bidirectional flux of energy and information between the EVs and the power grids. This collaboration will strengthen the collective awareness systems, contributing to solve and organize issues related with the energy resources and power grids.

3   System Architecture and Operation Modes

The on-board bidirectional battery charger that is presented in this paper is composed by two power converters, one ac-dc and other dc-dc. The ac-dc converter is a full-bridge bidirectional converter that works in three distinct ways according to the operation mode. The dc-dc converter is a buck-boost bidirectional converter. Fig. 2 shows the electric diagram of the on-board bidirectional battery charger.
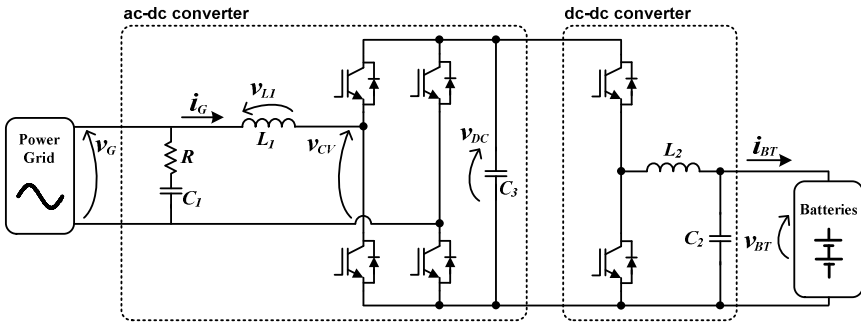

Fig. 2. On-board bidirectional battery charger composed by two power converters: ac-dc full-bridge bidirectional converter and dc-dc buck-boost bidirectional converter

3.1   Grid-to-Vehicle (G2V) Operation Mode

During the G2V operation mode the energy flows from the power grid to the batteries. In this operation mode the ac-dc full-bridge bidirectional converter works as active rectifier with sinusoidal current consumption and unitary power factor. The dc-dc buck-boost bidirectional converter works as buck converter aiming to charge the batteries with different stages of current and voltages. In this operation mode, the current reference ($i_G{}^*$) is obtained through:

$$i_G{}^* = \frac{P_{DC}{}^* + i_{TB} v_{TB}}{V_G{}^2} \, v_G \ , \tag{1}$$

where, V_G is the RMS value of the power grid voltage, v_G the instantaneous value of the power grid voltage, i_{TB} and v_{TB} the current and voltage in the batteries, and $P_{DC}{}^*$ is the power reference obtained through the dc-link voltage. The dc-link voltage is controlled by a Proportional-Integral (PI) control:

$$P_{DC}{}^* = k_p(v_{DC}{}^* - \overline{v_{DC}}) + \ k_i \int (v_{DC}{}^* - \overline{v_{DC}}) dt \ , \tag{2}$$

where, $v_{DC}{}^*$ is the dc-link voltage reference and $\overline{v_{DC}}$ the average value of the dc-link voltage during one cycle. In this controller is used the $\overline{v_{DC}}$ instead of v_{DC} because it avoid introduce the dc-link voltage oscillation into the control. For such purpose, $\overline{v_{DC}}$ in discrete samples is obtained by:

$$\overline{v_{DC}[n]} = \frac{1}{T} \sum_{n=1}^{T} v_{DC}[n] \ ,$$ (3)

where, T corresponds to one cycle of the power grid voltage (50 Hz), and taking into account that the sampling frequency is 40 kHz in digital control corresponds to 800 samples. Analyzing the circuit presented in Fig. 2 it can be established:

$$v_G(t) = v_{L_1}(t) + v_{CV}(t) \ ,$$ (4)

where, $v_G(t)$, $v_{L_1}(t)$ and $v_{CV}(t)$ are, respectively, the instantaneous values of the power grid voltage, inductance voltage, and voltage produce by the ac-dc converter. With the instantaneous values of the current $i_G(t)$, and the current reference $(i_G{}^*)$ can be determined the current error by:

$$i_{Gerror}(t) = i_G{}^*(t) - i_G(t) \ .$$ (5)

Combining (4) and (5), and substituting the inductance voltage can be established that:

$$v_{CV}(t) = v_G(t) - L_1 \frac{i_G{}^*(t)}{dt} + L_1 \frac{i_{Gerror}(t)}{dt} \ .$$ (6)

Rewriting (6) in terms of discrete samples, where k is the actual sample and $k-1$ the previous sample, it is obtained:

$$v_{CV}[k] = v_G[k] - \frac{L_1}{T} \left(2i_G{}^*[k] - i_G{}^*[k-1] - i_G[k] - i_{Gerror}[k-1]\right) \ .$$ (7)

With this voltage (v_{CV}) is implemented a predictive current control. With the help of a unipolar sinusoidal Pulse Width Modulation (PWM) strategy with a 20 kHz are calculated the gate pulse patterns. In order to avoid the effects of the deadtime in the produced current, the voltage reference $(v_{pwm}{}^*[k])$ that is compared with the triangular carrier is given, at each k sample, by:

$$v_{pwm}{}^*[k] = v_{CV}[k] + u\Delta v \ ,$$ (8)

where, Δv is the voltage that is added to the voltage $v_{CV}[k]$, and u assumes the value 1 when the reference current $(i_G{}^*)$ is greater than zero, and -1 when is lesser than zero. To the dc-dc bidirectional converter, which works as buck converter during this operation mode, the voltage reference that the converter must produce during the constant current $(v_{pwm\_CI}{}^*)$ and constant voltage $(v_{pwm\_CV}{}^*)$ stages is given by PI controllers and are, respectively:

$$v_{pwm\_CI}{}^* = k_p(i_{BT}{}^* - i_{BT}) + k_i \int (i_{BT}{}^* - i_{BT})dt$$ (9)

$$v_{pwm\_CV}{}^* = k_p(v_{BT}{}^* - v_{BT}) + k_i \int (v_{BT}{}^* - v_{BT})dt$$ (10)

3.2   Vehicle-to-Grid (V2G) Operation Mode

During the V2G operation mode the energy flows from the batteries to the power grid. In this operation mode the ac-dc full-bridge bidirectional converter works also as an inverter, however, with sinusoidal current injection. The dc-dc buck-boost bidirectional converter works as boost converter aiming to discharge the batteries with constant power (as presented in this paper, however, can also be constant current). In this operation mode, the ac-dc converter control is similar to the one used in the G2V operation mode. To synthesize the reference current it was also used the predictive current control. The main difference is the dc-dc operation, which, in this case, operates as boost converter. The power to be delivered to the power grid is established as external input parameter. In the context of this paper, the value of the power is received through a serial port, however, it is predictable that it will be received through a wireless communication aiming to enable the collaborative integration of the EV in the future smart grids. With the reference power ($P_{BT}{}^*$) and the batteries voltage (v_{BT}) is determined the current reference ($i_{BT}{}^*$):

$$i_{BT}{}^* = \frac{P_{BT}{}^*}{v_{BT}} \, , \tag{11}$$

and the voltage reference ($v_{pwm\_CP}{}^*$) that the converter must produce is obtained by:

$$v_{pwm\_CP}{}^* = k_p(i_{BT}{}^* - i_{BT}) + k_i \int (i_{BT}{}^* - i_{BT})dt \ . \tag{12}$$

3.3   Vehicle-to-Home (V2H) Operation Mode

During the V2H operation mode the energy flows from the batteries to feed home loads during power outages. It also can be used to feed loads in places without connection to the power grid. In this operation mode the ac-dc full-bridge bidirectional converter works as inverter aiming to produce a true sine wave voltage output to feed the home loads. The dc-dc buck-boost bidirectional converter also works as boost converter aiming to increase the batteries voltage to an appropriated value to the operation of the ac-dc converter. In this operation mode the ac-dc converter works as voltage source inverter. Thus, analyzing the circuit presented in Fig. 2 it can be established:

$$v_{CV}(t) = v_G{}^*(t) - v_{L_1}(t) \, , \tag{13}$$

where, $v_{CV}(t)$, $v_G{}^*(t)$, and $v_{L_1}(t)$ are, respectively, the instantaneous values of the voltage produce by the ac-dc converter, the reference voltage, and the inductance voltage. Substituting $v_{L_1}(t)$ it can established:

$$v_{CV}(t) = v_G{}^*(t) - L_1 \frac{di_{L_1}(t)}{dt}, \tag{14}$$

Also in this control was used the strategy presented to the G2V operation mode in order to avoid the effects of the deadtime.

In this operation mode the dc-dc converter operates as boost converter in order to maintain the dc-link voltage regulated to the proper functioning of the ac-dc converter. For such purpose, the dc-link voltage is controlled through a PI and the voltage reference ($v_{pwm\_DC}{}^*$) that the converter must produce is given by:

$$v_{pwm\_DC}{}^* = k_p(v_{DC}{}^* - v_{DC}) + k_i \int (v_{DC}{}^* - v_{DC})dt \tag{15}$$

4   Experimental Results

In order to evaluate the on-board bidirectional battery charger working in the G2V, V2G and V2H operation modes it was developed a laboratory prototype. Fig. 3 shows part of the developed prototype.
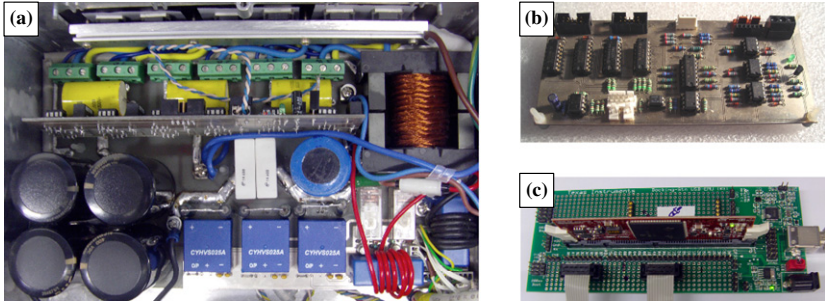

Fig. 3. Parts of the developed prototype of the on-board bidirectional battery charger: (a) Power converters; (b) Signal conditioning circuit; (c) Digital control platform
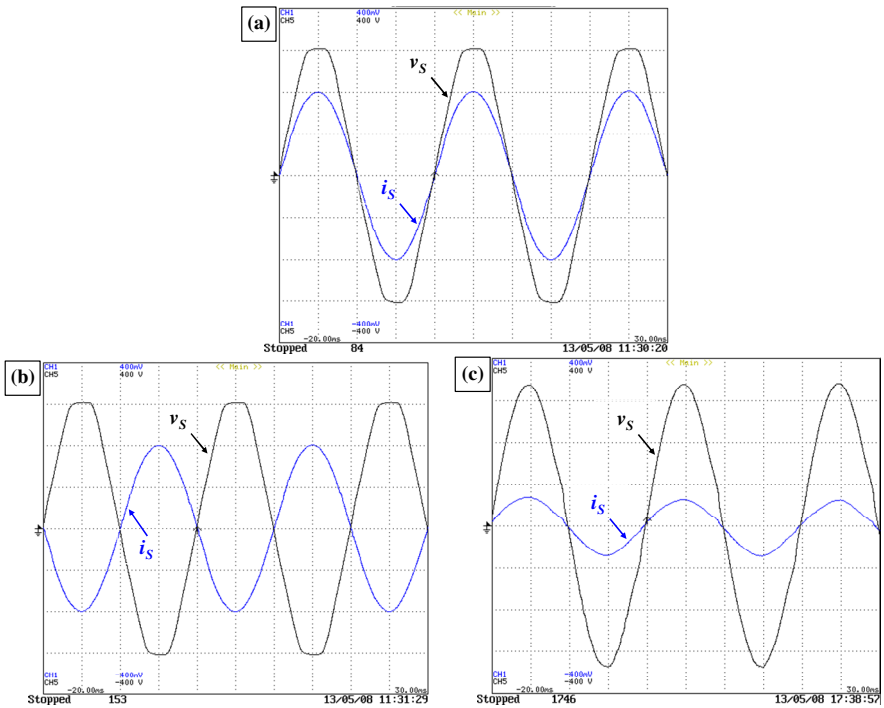

Fig. 4. Experimental results of the power grid voltage (v_G – 100 V/div) and current (i_G – 10 A/div): (a) G2V operation mode; (b) V2G operation mode; (c) V2H operation mode

The experimental results were obtained with the on-board bidirectional battery charger and with a set of 24 sealed 12 V 33 Ah Absorbed Glass Mat (AGM) batteries. Fig. 4 shows the obtained results. More specifically: Fig. 4 (a) shows the power grid voltage (v_G) and the current (i_G) during the G2V operation mode; Fig. 4 (b) presents the power grid voltage (v_G) and the current (i_G) during the V2G operation mode; and Fig. 4 (c) shows the output voltage (v_G) and the load current (i_G), during the V2H operation mode.

5   Conclusions and Further Work

This paper presents the development of an on-board bidirectional battery charger for Electric Vehicles (EVs), which can work in Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), and Vehicle-to-Home (V2H) operation modes, targeting the future smart grids scenario. Taking into account that the introduction of EVs in smart grids will be an important subject, the bidirectional communication between EV drivers and the collaborative brokers of smart grids will strengthen the collective awareness systems. Therefore, it will contribute to solve and organize issues related with energy resources and power grids. The developed laboratory prototype, functioning in the three operation modes, was validated through experimental results.

Currently, the selection of the operation modes (G2V, V2G and V2H) is performed manually by the driver, through the user interface of the EV. Nevertheless, until the final of the PhD work where this paper is encompassed, this selection will be wireless controlled. Besides, it will be developed an Information and Communication Technologies (ICT) application aiming to allow the communication with a collaborative broker of the smart grids.

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