A New Bi-Directional Charger for Vehicle-to-Grid Integration

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***Abstract*—Bidirectional and efficient on-board charger systems for electric vehicles is a challenge nowadays. This paper describes a novel power converter system that implements bidirectional flow between the grid and an electric vehicle battery, where a dual active bridge is advantageous. With a bidirectional topology and proper control all the major grid constraints, such as power quality, harmonic rejection, active and reactive power control, and others, can be easily satisfied. A hardware prototype of the power converter is built.**

Experimental results from this hardware prototype verify the preliminary operation and claims of the V2G power interface.

I. Introduction

Electric Vehicles (EV) are expected to become commonly used all around the world in a near term and offering this way a high potential for long term reduction of CO_2 - emissions, leading to green transport roads, [1]. The current development efforts doing by the auto makers are mainly focused on weight reduction on the electric power train, energy storage systems and cost. However, for the massive introduction of the fully electric vehicles into the European and global markets to happen in the forthcoming years implies that the development of energy efficient and bidirectional chargers system has to be taken into account, [2]. The Internal Combustion Engine (or ICE) vehicle can be refuelled very quickly and without great losses, contrariwise in a fully electric vehicle, the charger has a significant impact on the total energy consumption of the vehicle and the charging process is much more complex and with negative impact on the electric power grid, [3]. First, several on-board electronic control units have to operate with power grid energy. Second, the high storage capacity of the batteries in the vehicles creates a new kind of electric load to the electric power grid.

Because of the special nature of these active loads a new interface paradigm arises with widespread EV integration, which is leading to develop more efficient and reliable means of interface with the power grid, [4]. Charging methods can be classified into two main types: Dumb chargers and Smart chargers. Although many authors in the specialized literature point out that the dumb charging method does not allow a desirable widespread EV integration, [5]. The results of such charging method are branch congestion and unacceptable voltage drops in some branches due to an uncontrolled peak of consumption that coincides with simultaneous vehicle charge. The dumb charging does not allow large scale integration with the existing power grid, motivating the appearance of increased intelligence systems such as smart charging or vehicle-to-grid (V2G) power interface, [6].

The bidirectional smart charger concept is an effective solution to interact with the grid. Several power electronics solutions have been presented in the literature, [7]–[10].

These more advanced charging systems claims for new solutions in power conversion systems with functionalities to exchange data and commands with a centralized smart grid controller, [11], [12]. With this system, users can set the desired time in which the car should be charged and the controller will choose the adequate period and possibly the charging ratio, sending accordingly the command for the charger. These functionalities should be available in a smart charger system. Systems should be able to operate in inverter mode feeding power back to the grid. Proper control scheme will adjust charging/discharging ratio with respect not only to battery requirements but also grid constraints, [12].

The V2G concept can be seen as the future of charging systems, [13]. It is applied to on-board chargers or charging stations. Such systems can become profitable to the owner and very helpful to the grid, [14]. The identified benefits from the electric power system point of view are: maximization of intermittent sources integration, reactive power compensation, branch congestion avoidance, auxiliary frequency regulation and assistance in failure recovery. From the vehicle owner side some interesting opportunities have yet been identified such as residential uninterrupted power supplies or potential revenue from electricity market, [12].

This paper proposes a novel bidirectional charger with a unity power factor operation capability and a Dual Active Bridge (DAB), which is composed of two full-bridge converters. A medium frequency transformer is found between the two AC sides of the full-bridges. The power flow modes, control and some aspects of the transformer design are given. Some required experiments are carried out on a laboratory setup to demonstrate the effectiveness of the architecture and the control strategies.

II. Charging Topology

The primary aspect when choosing a converter for an EV is to choose between an on-board or an off-board charger. Although the off-board chargers can have better characteristics and the advantage of no-size limitations, the on-board charger can be incorporated in any EV and give them the possibility

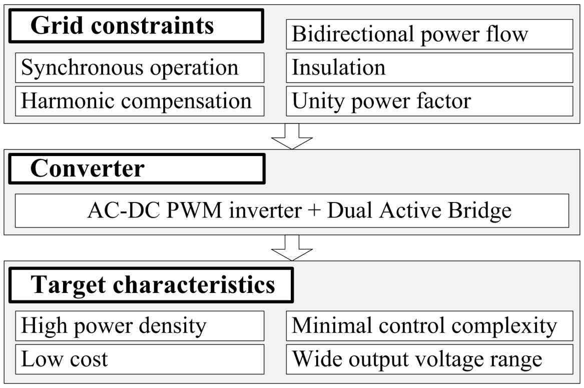


Fig. 1. Converter Characteristics.

to be charged at any available outlet, [15]. For this reason and because the on-board chargers are more challenging in terms of safety and protection constraints this work is focused on those converters.

Bi-directional charger topology have been considered one of the best approaches to develop smart chargers for electric vehicles, [13].

Figure 1 shows the relevancy of each characteristic and the main features of the proposed converter, the PWM rectifier associated with a dual active bridge.

The converter under study has a high switch utilization ratio, but on the other hand this topology allows high performance control structures while maintaining reasonable power density and wide output voltage range. In addition, all the major grid constraints are respected.

A. Settings definition

The actual legislation on electric vehicle chargers stand that the protection is ensured with earth grounding and galvanic isolation, [16].

Four modes are defined on the IEC standard. Each mode sets specific electric boundaries mainly regarding voltage and current limits. For the proposed converter has been chosen the mode number 3. This mode predicts the pilot control cable. With this signal is possible to control the energization and de-energization of the system while detecting if the vehicle is properly connected. A couple of optional functions in this mode render it very appropriate for V2G, like the selection of charging rate, control of bi-directional power flow, detection and adjustment of the real time available load current of the supply equipment.

In the end, a consideration about the control complexity should be made. Since a V2G application predicts interaction between the charger and management systems, [12], [13], the control structure has to be simple and easily configurable. Because of this assumption the control chose, is based on individual stage control. This means that there is different and independent loops controlling the AC side and the DC side, like explained in the following section.

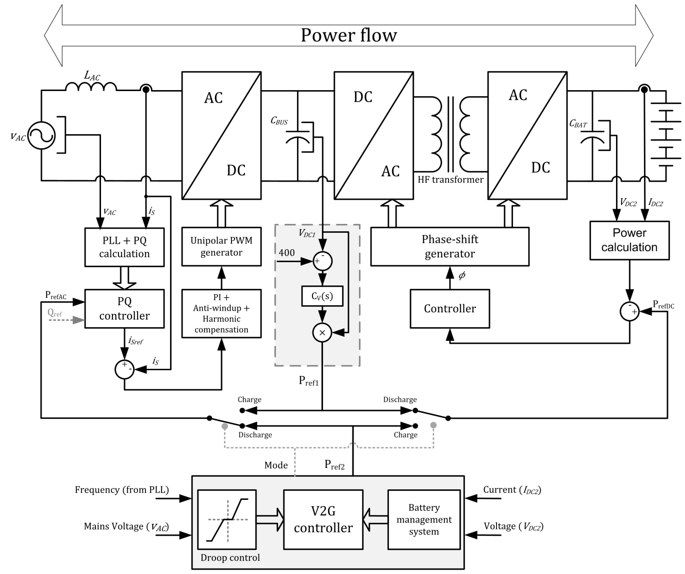


Fig. 2. Converter structure.

III. Converter architecture

To comply with all the characteristics stated in the previous section the converter architecture features a multiple stage topology. This topology is represented in Figure 2 as well as the converter control scheme. As can be seen, this converter, has three important stages, the grid interface, the isolation transformer together with the DC stage. All three stages will be discussed in the following subsections.

A. Power structure

The power converter hardware can be split into two stages, each with different purposes. An AC-DC converter where the AC terminals are connected to mains through a single inductive filter and DC terminals connected to a DC bus. The second stage of the converter consists of two full bridges connected by means of a high frequency transformer, implementing the so called Dual Active Bridge (DAB). One side of the converter is connected to the DC bus and the other to the battery pack. Concerning passive elements, L_{AC} is used to filter the high frequency components produced by the AC-DC converter, allowing to shape a sinusoidal waveform for the i_S grid current. Regarding the C_{BUS} a large capacitor is placed in order to achieve a continuous and stable power transfer between the two conversion stages. The battery side capacitor, C_{BAT}, aims to reduce the ripple during the battery charging or discharging process.

B. Control Scheme

The control of the power converter described in previous section is implemented on a commercial board DS1103 produced by Dspace.

The control scheme measures the mains voltage and grid current variables (v_{AC} and i_S) as well as the DC bus voltage V_{DC1}. In a first step, using grid voltage and current, a PLL algorithm estimates the frequency and phase of the grid voltage, allowing the design of a real time synchronous current control scheme.

These variables are used to estimate active and reactive power that will be used to implement a PQ control based on indirect voltage oriented technique. The error compensation is performed by a proportional-integrative controller with anti-windup and harmonic compensation features. Thus the power circuit is switched to adjust the power according to a given reference (P, Q). This reference can be set by an external high level control. For the DC-DC stage, the measured variables are the battery voltage and current (V_{DC2} and I_{DC2}), and the DC bus voltage V_{DC1}. This converter is controlled in terms of active power flow to the battery pack. Using the battery variables the battery power flow is computed and an error related to a given reference is determined. Once compensated by a controller this error is used as a control variable. In this particular case, the manipulated variable is the phase shift between the pulses used to control the two bridges. The expression that shows this control action is:

$$P_o = \frac{2V_{DC1}^2}{\omega L_\sigma} M\phi(1 - \frac{|\phi|}{\pi}), \tag{1}$$

Considering a V2G interface, a coordinator block is needed to set the reference power transfer and also to determine the power flow direction. So far it was determined that this block should integrate information from grid variables and from battery management system. In that specific case the battery management system (BMS) is integrated on this block. Using battery voltage, current and possibly other variables, the BMS should set the reference power according to current battery requirements. The grid integration is performed combining frequency and voltage values, which can estimate the local grid condition and implement limitations to the reference power and also can change the power flow direction if the battery is able to handle the situation. Combining the decisions from both blocks the converter is operated in order to satisfy the needs from both sides.

C. Power flow modes

As mentioned earlier, the converter has two power flow modes/directions and a charging throttle which is implemented by the reference power. In charge mode, the AC-DC converter is controlled as a voltage regulated power supply, feeding energy to the DC-DC stage with a constant voltage on the DC bus. This method is implemented by a voltage regulation block, which generates a power reference to the previously described control system. The DC-DC stage receives the reference power from the coordinator block and regulates the power supplied to the battery pack in order to respect the given reference. For control purposes the power on the battery side and the power on the grid side are considered to be equal. In discharge mode the DC-DC stage is controlled to regulate the DC bus voltage and feed the AC-DC inverter at constant voltage. To achieve such regulation the control block used is the same from the charge mode. This turn, the AC-DC stage has the aim control in the power injected on the grid, according to a reference given by the coordinator block (V2G controller).

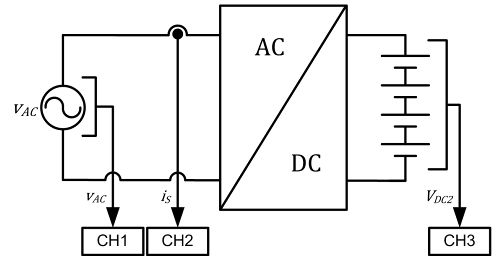


Fig. 3. Experimental setup diagram.

TABLE I
EXPERIMENTAL SETUP.

Parameter	Value
Grid voltage and frequency	230 V_{RMS} 50Hz
Power rating	3.68 kW
Battery voltage	384 V
Stored energy	2.76 kWh

IV. Experimental results

To validate the converter two experiments were performed. The first one, is aimed to demonstrate the grid interface. In this experiment is possible to analyse the phase relationship between the grid current and voltage, in both directions, and the correct behaviour of the power controller. The second experiment, shows an harmonic histogram, used to infer about the action of the harmonic compensator implemented. The experimental setup is represented in Figure 3 and the electrical parameters are in Table I.

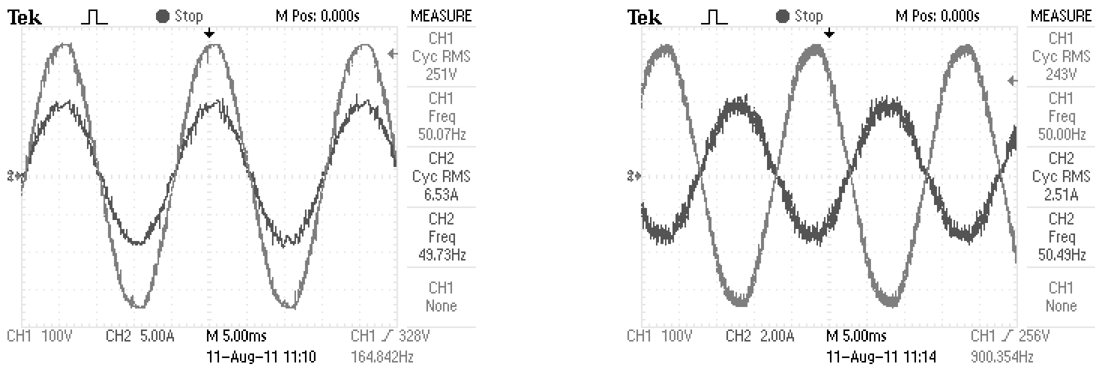
A. Grid Interface

In Figure 4 are represented the voltage and current waveforms in the grid interface. In Figure 4a the energy flows from the batteries to the grid, with an average active power of 1.5kW. In this experiment is possible to see the correct operation of the power circuit, the measuring system as well as the control algorithm implemented. Besides the hardware and software validation, in Figure 4b is also possible to verify the reverse energy flow, where the current and voltage have an oppose phase relation.

In addiction were performed tests to evaluate the controller performance, applying abrupt changes in the operation point. This validation was accomplished by acquiring the voltage and current waveforms in the grid interface and the battery voltage drop. Firstly, a step on the power reference from 500W to 1.5kW is represented in Figure 5a. Secondly, a step from -500W to 1.5kW, which also represents a variation in the energy flow direction. These results are illustrated in Figure 5b.

B. Harmonic Compensation

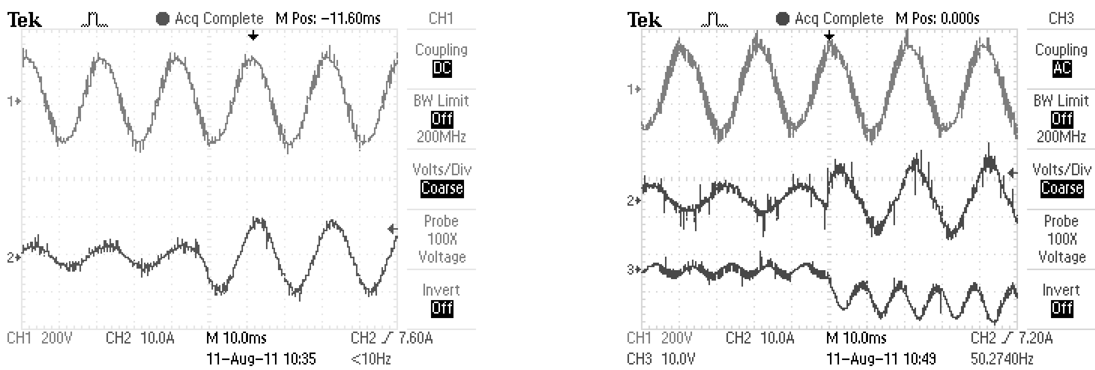
A key factor when connecting to the grid is ensure proper power quality. In this field, harmonic distortion plays an important role so, measuring the effects of the converter connection



(a) VI in phase.

(b) VI opposing phase.

Fig. 4. Voltage and current in the grid interface.



(a) Power Step - (500W to 1500W).

(b) Power Step - (-500W to 1500W).

Fig. 5. Power variation simulation results.

into the grid with and without harmonic compensation is of great value to evaluate the adequacy of the system built within a real household application. Thus, the results submitted in this subsection are all about it. Note that, in Figure 6a is possible to see the harmonic distortion generated in the grid interface when the compensator algorithm is turned off. When activating the harmonic compensator algorithm the enhancements are easily noted, as are shown in by Figure 6b.

V. Discussion of results

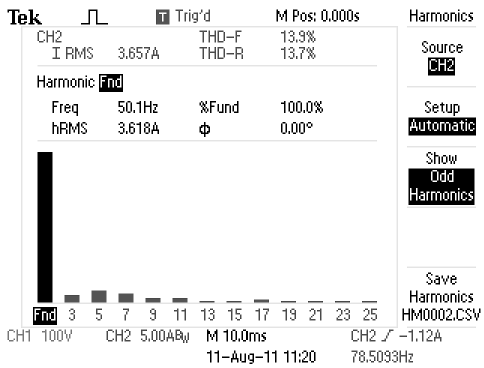
Analysing the experiments conducted in the previous section, is possible to conclude about the good behaviour of the control structure as well as the proper tuning performed in the controllers.

The first experiment, grid interface, as already pointed out, shows the converter capability of use energy from the grid as well as fed it back. Such characteristic is enough to verify the bi-directional ability. Nevertheless, some considerations are to be made. Looking to the power factor between the grid voltage and current one can see that its value is near one. This means that the synchronization techniques are properly implemented, but the major conclusion is about the reactive power. Having a unitary power factor indicates that the control implemented is able to compensate the converter capacitance, a desirable feature in V2G applications. Regarding the step variations on the power, this experiment shows the ability of properly following different references. The converter control was developed to interact with management systems, which will analyse, in real time, the grid conditions, sending accordingly the operation point for each of the converters. For this to happen, following fast and accurately variations in the reference is essential in every control algorithm.

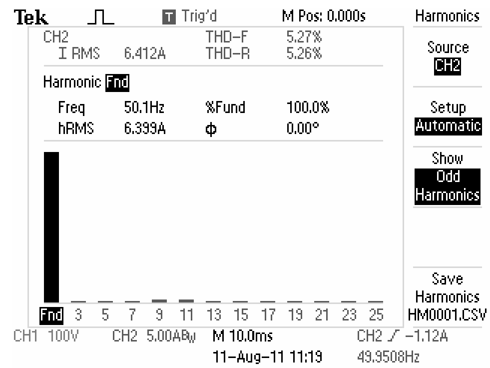
Looking at the harmonic spectrum obtained in the second set of experiments, a total harmonic distortion reduction of 8% is clearly visible. The controller has great impact in the 3^{rd}, 5^{th}, and 7^{th} harmonics, corresponding to the frequencies provided in the compensator.

VI. Conclusion

A bidirectional and isolated power structure suitable to be used in full featured V2G interface has been presented. The proposed converter architecture has been defined based on some requirements and considering the most feasible topologies, and its advantages have been pointed out. Power and control blocks were extensively described as well as the power flow modes. Through the development of an experimental prototype, the required functionalities for the two power flows modes have been verified and step variations are applied to the power set point resulting in a stable and fast response. The PQ



(a) Harmonic histogram without compensation.



(b) Harmonic histogram with compensation.

Fig. 6. Compensation of harmonics.

control strategy and proper operating modes are able to track the requests generated by the high level V2G controller.

Future developments should include the evaluation and improvement of the conversion system efficiency and optimize the design of passive components. To verify the practicality of the proposed converter an on board testing prototype need to be implemented in a real vehicle, integrated in the car energy management system.

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