

Smart Charging System of the Electric Vehicle CEPIUM

Vítor Monteiro¹, Delfim Pedrosa¹, Bruno Exposto¹, João C. Ferreira², João L. Afonso¹

1 – Centro Algoritmi – University of Minho – Guimarães, Portugal

2 – Centro Algoritmi – ADEETC – ISEL – Lisbon, Portugal

vmonteiro@dei.uminho.pt, dpedrosa@dei.uminho.pt, bexposto@dei.uminho.pt,
jferreira@deetc.isel.ipl.pt, jla@dei.uminho.pt

Abstract — In this paper is presented the development of a smart batteries charging system for the Electric Vehicle (EV) CEPIUM, aiming the integration of EVs in the future Smart Grids. The main features of the developed charging system are the mitigation of the power quality degradation and the bidirectional operation, as Grid-to-Vehicle (G2V) and as Vehicle-to-Grid (V2G). The batteries charging process is controlled by an appropriate control algorithm, aiming to preserve the batteries lifespan. During the charging process (G2V), the consumed current is sinusoidal and the power factor is unitary. Along the discharging process (V2G), when the equipment allows delivering back to the electrical power grid part of the energy stored in the batteries, the current is also sinusoidal.

Keywords – Batteries Charging System; Electric Vehicles; Electric Mobility; Power Quality; Bidirectional Converter.

I. INTRODUCTION

The recent increase in the utilization of Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs), which use batteries, as primary or secondary source of energy, represents a gain for independence of the cost of the oil, and an effective fight against the climatic changes. These vehicles give a good contribute to the new transports paradigm, however, they are limited in terms of the stored energy in the batteries [1][2]. Nevertheless, there also are EVs and PHEVs that use other sources of energy as ultracapacitors and fuel cells [3][4] and different studies about the performances [5] and possible configurations [6][7][8] can be found. However, the batteries still are the key of the success since they are the most used technology, and can be used in conjunction with ultracapacitors to store energy, during transient moments, as during regenerative braking. Actually, the ultracapacitors are used in this way to receive a significant amount of energy in a short time, and to provide this energy to the next acceleration, or to be used to charge the batteries. In [9] is proposed a new energy storage system, including both batteries and ultracapacitors in Hybrid Electric Vehicle (HEV) and EVs applications.

In EVs, the autonomy is extremely dependent of the amount of energy stored (batteries capacity in kWh), however, others features as the driver behavior has extremely importance, because the users always want large autonomy and short recharging times. Analyzing the batteries charging process many considerations must to be taken into account.

Different charging conditions are applicable according to the constructive technology of the battery (physical and chemical technology), charging cycle time, nominal voltage, nominal capacity and range of temperatures. A generic charging system needs to know what type of battery is in use to adapt the charging algorithm in order to optimize the charging time and to preserve the batteries lifespan [10]. Different battery charging techniques are presented in [11] including constant current, constant voltage and pulse charging. Another aspect that is very important during the batteries charging and discharging processes is the equalization in terms of capacity and voltage [12]. The batteries equalization can be implemented through Battery Management Systems (BMS) [13][14]. An optimal BMS not only implements the equalization of the batteries voltage but also monitors the key operational parameters during the charging and discharging processes, such as voltages and currents in the batteries and the temperatures. The BMS is not described in this paper.

Traditionally, the batteries chargers are implemented with static power converters; however, almost all consume distorted currents and do not allow the implementation of different charging algorithms in order to be adapted to the different batteries technologies. With the proliferation of the EVs and PHEVs the current distortion introduced by these vehicles will bring problems to the electrical power grid as power losses, and harmonics and unbalances in the voltages and currents [15]. Taking into account these problems, it is absolutely necessary to use efficient battery charging methods, not only to preserve the lifespan of the batteries [16][17] but also to preserve the power quality in the electrical grid [18].

With the mass proliferation of EVs and PHEVs a considerable amount of energy is stored in the batteries of these vehicles. Thus, besides the charging process (Grid-to-Vehicle – G2V), is the possibility of the energy flow in opposite sense (Vehicle-to-Grid – V2G) [19], in accordance with the electrical power grid capabilities, the price of energy to sell or to buy, and the batteries State-of-Charge (SoC). Taking into account this context of Smart Grids, there are many benefits to profitable the grid management, especially for ancillary services, emergency power supply, compensation of the renewable energy sources intermittency (providing both backup and storage) and electric power support [20][21][22][23]. Thereby, the Smart Grids are presented as a promising solution to manage the electrical grid, avoiding

power limitations and to control the consumption in simultaneously, mainly during the EVs and PHEVs charging process [24][25].

Thus, in this paper is described the development and implementation of the Smart Charging System of the Electric Vehicle CEPIUM. The main features of the equipment are the controlled charging algorithm, the mitigation of the power quality degradation and the bidirectional operation, as G2V and as V2G. During the charging process (G2V), the consumed current is sinusoidal and the power factor is unitary. Along the discharging process (V2G), when the equipment allows delivering back to the electrical power grid a small amount of the energy stored in the batteries, the current is also sinusoidal with unitary power factor. In order to validate both modes of operation are shown the obtained computer simulations and the experimental results.

II. CEPIUM ENERGY STORAGE SYSTEM

The CEPIUM energy storage system is only composed by Absorbed Glass Matt (AGM) batteries. The used AGM batteries technology was special developed to reduce weight, increase power handling and improve reliability. Typically, AGM batteries has very low internal resistance, are capable to deliver high currents on demand and offers a relatively long lifespan, even with large Depth-of-Discharge (DoD). AGM batteries are maintenance free, providing good electrical reliability, are lighter than the flooded lead-acid batteries, and have a low self-discharge. As with all gelled and sealed units, AGM batteries are sensitive to overcharging.

In the CEPIUM project were used the WCG-U1 AGM batteries from the POWER MOBILITY series, each one with the characteristics shown in Tab. 1. In Fig. 1 is presented the relation of the capacity (Ah), the current (A) and the time (hours), during the discharging process. As shown, with the increase of the discharging current, the capacity decreases. Consequently, the maximum capacity is obtained with the minimal current discharging. On the other hand, in Fig. 2 is shown the relation of the battery lifespan, in number of cycles, in function of the Depth-of-Discharge (DoD %). The maximum number of cycles, maintaining the main features of the batteries is obtained with a small range of discharging.

TABLE I. CHARACTERISTICS OF EACH AGM (WCG-U1) BATTERY

Characteristic	Nominal Value
Voltage	12 V
Capacity	33 Ah
Maximum current charging	6.5 A
Maximum voltage charging	14.2 V
Maximum discharging current (1 min)	245 A
Internal impedance	7.33 mΩ
Range of charging temperature	-50°C to 70°C
Range of discharging temperature	-40°C to 60°C
Mass	12.11 kg
Dimensions in mm	19.58 x 13.16 x 18.26

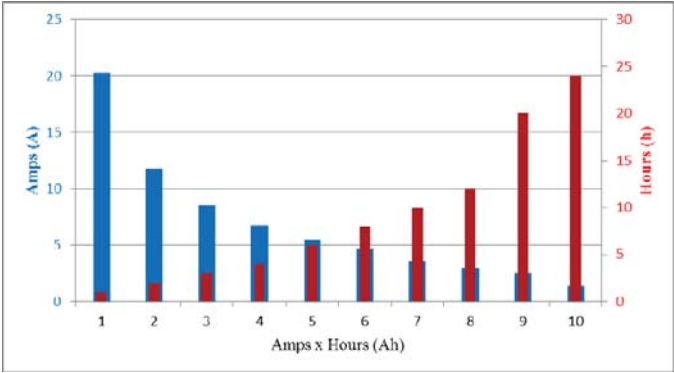


Figure 1. Relation of the capacity (Ah), the current (A) and the time (hours), during the discharging process of a WCG-U1 AGM battery.

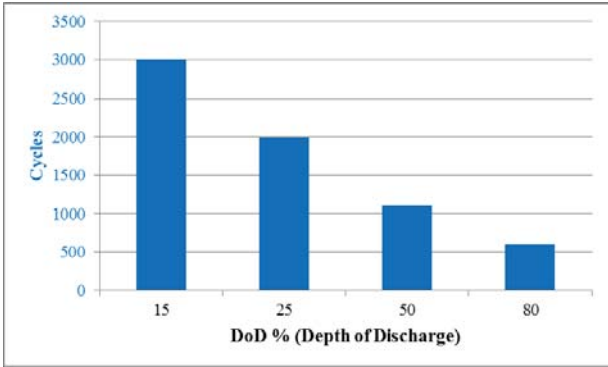


Figure 2. Relation of the battery lifespan, in number of cycles, in function of the Depth-of-Discharge (DoD) for a WCG-U1 AGM battery.

In order to obtain 6.7 kWh of stored energy were used 17 batteries connected in series. In Fig. 3 are shown the batteries used in the Electric Vehicle CEPIUM. These batteries, were specifically designed for mobility with high reliability, combine the best features of AGM and GEL into one battery. They are highly resistant to vibrations and rough handling, allowing a large range of temperatures during the charge and discharge processes, and they can be used in any position, except upside down.

III. CONTROL ALGORITHMS

The algorithm to optimize the batteries charging process should be defined taking into account their nominal values and their chemical technology. These algorithms, which consist in different stages of voltage or current, are implemented by the digital control system.

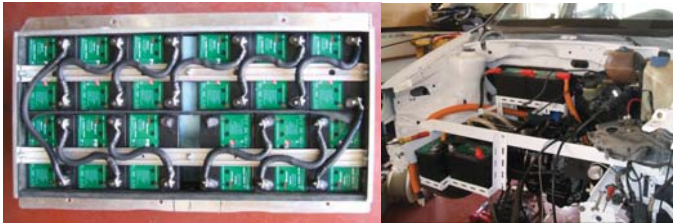


Figure 3. Batteries used in the Electric Vehicle CEPIUM: 12 batteries at the vehicle bottom, and 5 at the front of the vehicle (near of the motor).

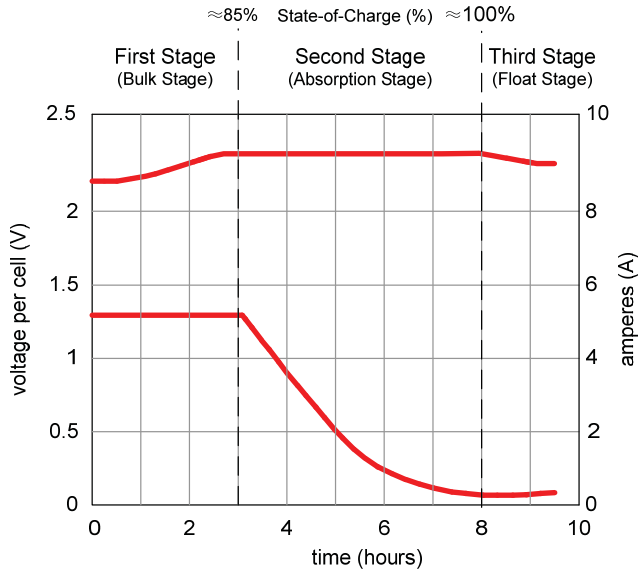


Figure 4. Three stages of the AGM cells charging algorithm.

The developed control system is able to implement several charging algorithms, however, as were used AGM batteries (each battery with 6 cells), is described in detail the charging algorithm shown in detail in Fig. 4. This algorithm is controlled by the developed control system, and it consists in three stages. Then are described these charging stages, however, the presented values are for these AGM batteries. For each specific AGM batteries these values should be adjusted according with the manufacturer information.

In Fig. 5 is shown the block diagram of the control system, which implements the voltage and current stages. The regulation of the voltages and currents to the required references is obtained through PI controllers.

A. Bulk Stage

Typically the Bulk Stage consist in charge the batteries with constant current, however, also can be constant power, pulsed current or taper charger. In this stage, the optimal current charge should be limited to less than or equal to 20 amps per 100 ampere hour (20 hour rate) of battery capacity or 0.2C. The end of this charging stage occurs when the cell voltage is between 2.35 V and 2.4 V per cell at 25°C. This stage represents approximately 60% of the total charging time, and the battery is charged near 80% - 90% of their capacity.

B. Absorption Stage

The second stage, the Absorption Stage, consist in impose constant voltage to the batteries. Typically, in this stage, the charging voltage is maintained at 2.4 V per cell at 25°C (with variable temperature). The charging current is maintained until the current accepted by the battery falls below than 0.1 A over a 1 hour period (other possibility to determine the end of this stage is determined when the current falls below than 3% of the nominal current referred to 1 hour). At the end of this charging stage, the battery should be charged near of 100% of their capacity.

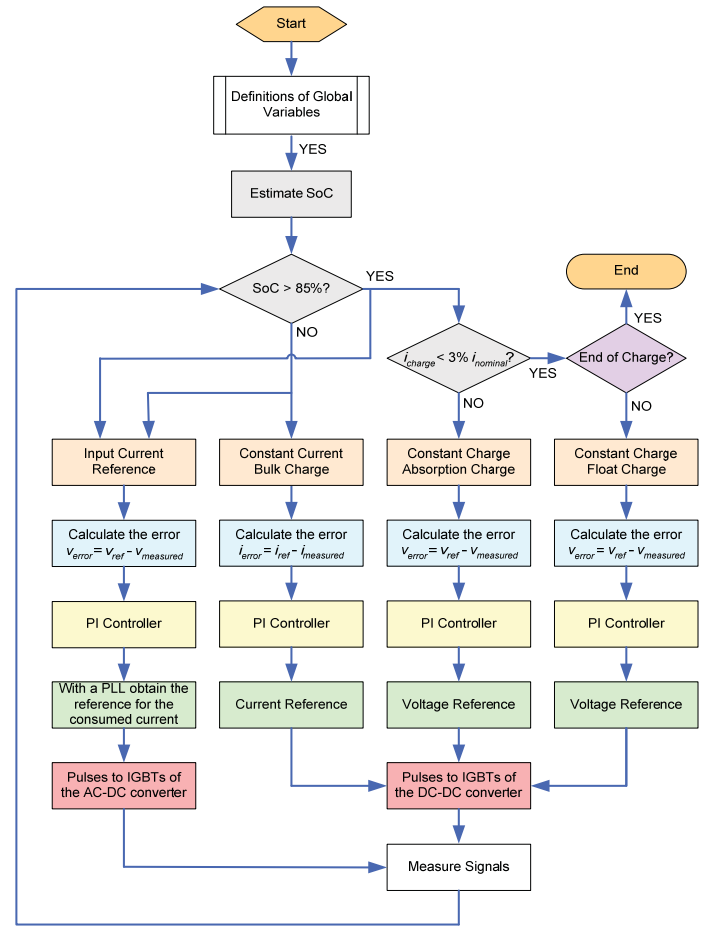


Figure 5. Block diagram of the control system, which implements the voltage and current stages of the AGM batteries charging algorithm.

C. Float Stage

The third stage, the Float Stage, is also denominated as the maintenance and monitor stage. The float charge stage compensates for the loss caused by self-discharge. The float voltage should be maintained at 2.25 V – 2.30 V per cell.

IV. DEVELOPED CHARGING SYSTEM

The conceptual diagram of the bidirectional charging system, which consists in the Digital Control System and in the Bidirectional Power Converter, is presented in Fig. 6.

A. Digital Control System

The digital control system, which implements the algorithms during the operation as G2V and V2G, is composed by several electronic circuits with analogue and digital signals. The developed digital control system is shown in Fig. 7.

The algorithms of the charging and discharging processes are implemented in the DSP microcontroller TMS320F28335. This DSP receives the voltages and the currents signals, and in conjunction with the user interface, generates the control signals to the command circuit.

The voltage signals of the power electronic converter are obtained through LEM sensors LV-25P and the currents

through LEM sensors LA-55P. The signal conditioning circuit receives these signals as inputs, and then adjusts these signals taking into account the voltage range of the DSP Analog to Digital Converters (ADCs). In this circuit are controlled the signals limits and are detected errors of overvoltages (in the input and in the DC bus) and overcurrents (in the input and output current). In case of error, is generated an output signal (correspondent to the error) to the command circuit in order to stop the operation of the charging or discharging processes.

The command circuit receives the control signals from the DSP microcontroller, receives the errors signals provided by the signal conditioning circuit, receives the errors from the drivers circuit, and in accordance with the user interface are generated the control signals to the IGBTs drivers circuit. The user can reset the errors, and define the start and stop of the charging or discharging process.

The IGBTs drivers circuit has as function make the interface between the signals received from the command circuit and the IGBTs. To this interface were used the Semikron drivers SKHI 21A. The received signals are adapted to the proper IGBTs pulses, and in this process the dead-time between the IGBTs of the same leg are controlled. In case of error in any driver is generated an error to the command circuit.

B. Bidirectional Power Converter

The bidirectional power converter is composed by an AC-DC bidirectional converter and a DC-DC bidirectional converter. This power converter is shown in Fig. 8. The bidirectional AC-DC converter is a full-bridge full controlled topology composed by two IGBTs modules SKM50GB063D (each one with two IGBTs). In parallel with each module is used a snubber capacitor (1 μ F – 1000 V). To interface with the electrical power grid is used an inductance (3 mH – 30 A), and in the DC bus is used a capacitor (4.7 mF – 450 V). To the bidirectional DC-DC converter is used one module of IGBTs, an inductance (220 μ H – 15 A) and an output capacitor (470 μ F – 400V). The bidirectional flux of energy is obtained through an adequate control of the IGBTs.

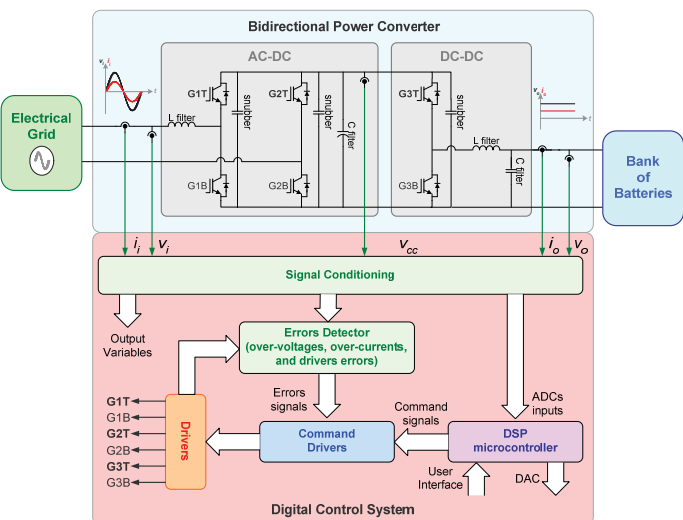


Figure 6. Conceptual diagram of the Smart Charging System of the Electric Vehicle CEPIUM.

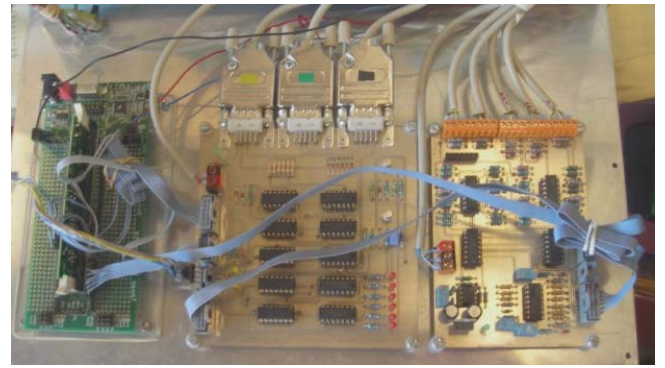


Figure 7. Digital Control System of the developed Smart Charging System of the Electric Vehicle CEPIUM.

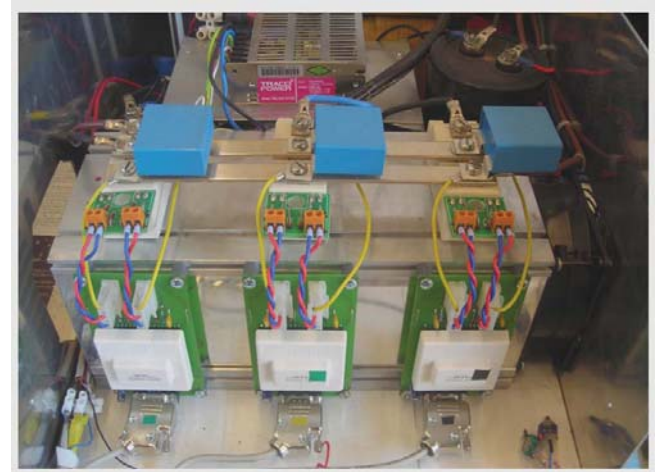


Figure 8. Bidirectional Power Converter of the developed Smart Charging System of the Electric Vehicle CEPIUM.

V. SIMULATION AND EXPERIMENTAL RESULTS

In a early stage, in order to analyse the operation of the converters in both modes of operation was developed a simulation model using the simulation tool PSIM 9.1, and were realized different computer simulations. Taking into account this presupposition are presented results of both modes of operation: during the batteries charging and discharging processes. In the simulations was used an electric model of the AGM batteries with nominal voltage 204 V, nominal capacity 33 Ah, and with 6.7 kWh.

The obtained simulations results of the consumed current and the electrical power grid voltage during the charging process (G2V) are shown in Fig. 9. In order to preserve the power quality, during this process the consumed current is sinusoidal with unitary power factor. During the discharging process (V2G), when is delivered back to the electrical power grid a small amount of the e/nergy stored in the batteries, the simulations results obtained are shown in Fig. 10. As during the charging process, the current is sinusoidal with unitary power factor.

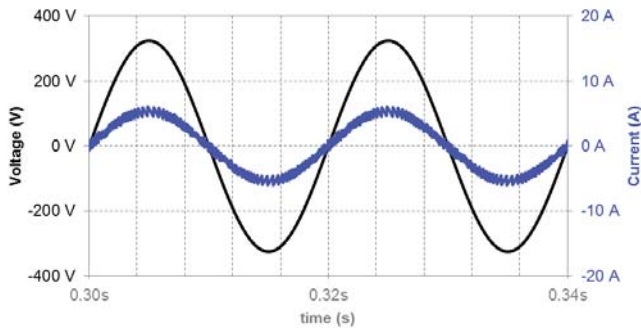


Figure 9. Electrical power grid voltage and consumed current during the charging process (G2V).

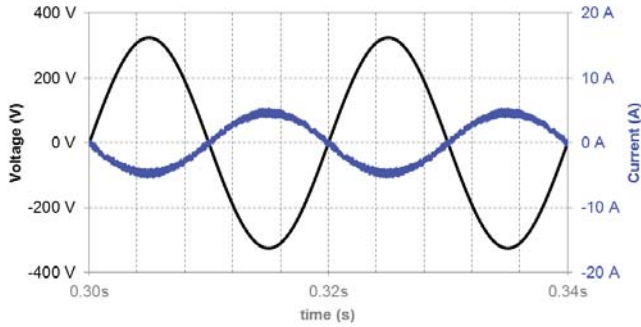


Figure 10. Electrical power grid voltage and current when is delivered part of the stored energy in the batteries back to the electrical power grid (V2G).

The developed laboratory prototype is shown in Fig. 11 and Fig. 12. The experimental results obtained with the developed prototype during the charging process (G2V) are shown in Fig. 11. In this figure is shown the consumed current and the electrical power grid voltage. As the results obtained in the simulations, the consumed current is sinusoidal with unitary power factor, contributing to preserve the electrical grid power quality. On the other hand, during the discharging process (V2G), when is delivered part of the stored energy in the batteries back to the electrical power grid, in Fig. 14 are shown the experimental results obtained. As shown the current is sinusoidal with unitary power factor. The batteries discharging process is controlled, respecting the batteries SoC, in order to avoid damages and to preserve their lifespan.

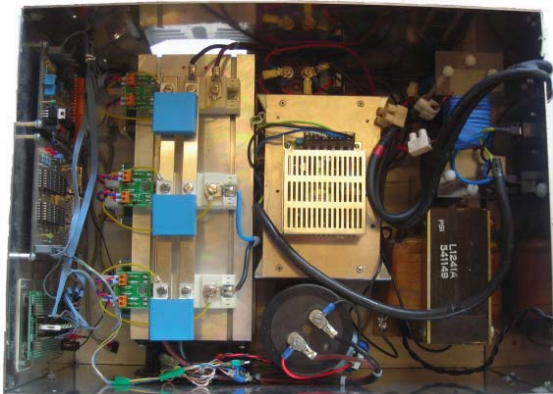


Figure 11. Internal view of the developed laboratory prototype of the Smart Batteries Charging System of the Electric Vehicle CEPIUM.



Figure 12. External view of the developed laboratory prototype of the Smart Batteries Charging System of the Electric Vehicle CEPIUM.

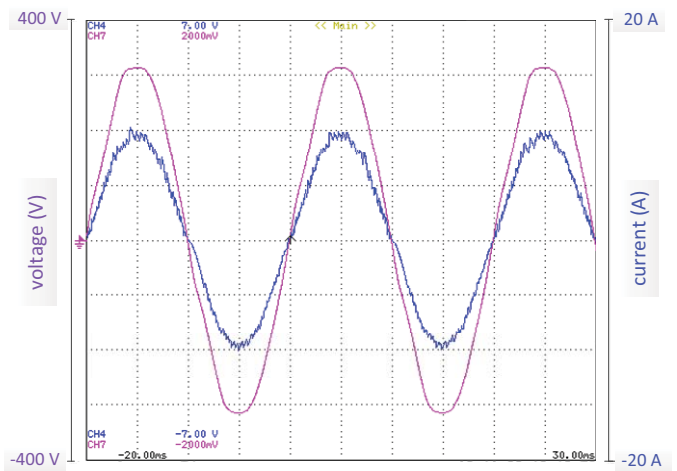


Figure 13. Experimental results of the electrical power grid voltage and consumed current during the charging process (G2V) of the AGM batteries.

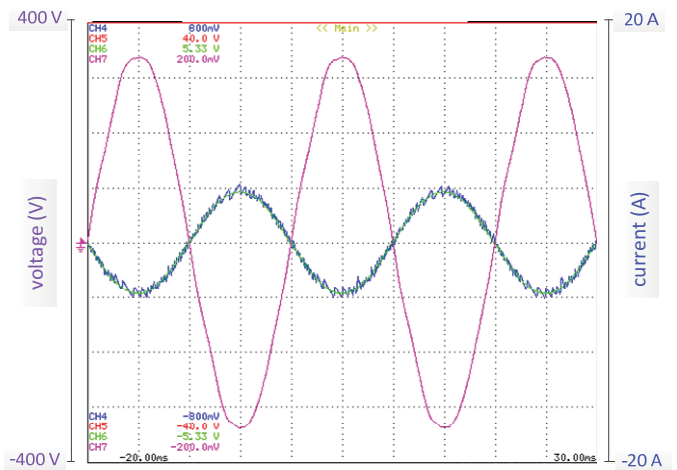


Figure 14. Experimental results of the electrical power grid voltage and current when is delivered part of the stored energy in the batteries back to the electrical power grid (V2G).

VI. CONCLUSION

In this paper was presented the development of a smart batteries charger for the Electric Vehicle (EV) CEPIUM. Aiming the integration of the EV CEPIUM in the future Smart Grids, one of the main features of the developed equipment is the bidirectional operation, allowing the charge of the batteries from the electrical power grid (Grid-to-Vehicle - G2V operation), and also permitting the delivery of a small amount of the energy stored in the batteries back to the electrical power grid (Vehicle-to-Grid - V2G). In both of these modes of operation, the equipment is designed to mitigate the power quality degradation, by working with a sinusoidal current at the side of the electrical power grid. Besides, when operating in G2V mode, it also works with unitary power factor.

The energy storage system of the EV CEPIUM is composed by 17 WCG-U1 AGM batteries connected in series, with nominal voltage of 204 V, nominal capacity of 33 Ah, and with 6.7 kWh of stored energy. In this paper were presented the charging algorithm and the block diagram of the charger digital control system used to charge the batteries of the EV CEPIUM. This charging algorithm consists in three stages of voltages and currents: Bulk Stage, Absorption Stage, and Float Stage.

In order to analyze the behavior of the presented smart batteries charger for the EV CEPIUM were presented results obtained through computer simulations, using the simulation tool PSIM, and were also presented experimental results.

ACKNOWLEDGMENTS

This work is financed by FEDER Funds, through the Operational Programme for Competitiveness Factors – COMPETE, and by National Funds through FCT – Foundation for Science and Technology of Portugal, under the project PTDC/EEA-EEL/104569/2008 and the project MIT-PT/EDAM-SMS/0030/2008.

REFERENCES

- [1] M. Andrew and C. Weinlein, "The lead-acid battery—Demonstrating the systems design approach to a practical electric vehicle power source," *IEEE Transactions on Vehicular Technology*, Vol. 32, pp. 21-25. Year 1983.
- [2] Y. Gao and M. Ehsani, Investigation of battery technologies for the army's hybrid vehicle application, *IEEE 56th Vehicular Technology Conference Proceedings*. Year 2002.
- [3] A. Khaligh and Z. Li, "Battery, Ultracapacitor, Fuel Cell and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State-of-the-Art," *IEEE Transactions on Vehicular Technology*, pp. 1-1. Year 2010.
- [4] I. Weinstock and V. Matricardi, "Summary of electric vehicle energy source technologies," *IEEE Transactions on Vehicular Technology*, Vol. 32, pp. 15-20. Year 1983.
- [5] S. Williamson and A. Emadi, "Comparative Assessment of Hybrid Electric and Fuel Cell Vehicles Based on Comprehensive Well-to-Wheels Efficiency Analysis," *IEEE Transactions on Vehicular Technology*, vol. 54, pp. 856-862. Year 2005.
- [6] A.I. Antoniou, J. Komyathy, J. Bench, and A. Emadi, "Modeling and Simulation of Various Hybrid-Electric Configurations of the High-Mobility Multipurpose Wheeled Vehicle (HMMWV)," *IEEE Transactions on Vehicular Technology*, vol. 56, pp. 459-465. Year 2010.
- [7] C.C. Chan, A. Bouscayrol, and K. Chen, "Electric, Hybrid, and Fuel-Cell Vehicles: Architectures and Modeling," *IEEE Transactions on Vehicular Technology*, vol. 59, pp. 589-598. Year 2010.
- [8] S. Onoda, S. Lukic, A. Nasiri, and A. Emadi, A PSIM-based modeling tool for conventional, electric, and hybrid electric vehicles studies, *IEEE 56th Vehicular Technology Conference Proceedings*. Year 2002.
- [9] Shuai Lu, Corzine K.A., Ferdowsi, M., "A New Battery Ultracapacitor Energy Storage System Design and its Motor Drive Integration for Hybrid Electric Vehicles", *IEEE Transactions on Vehicular Technology*. Volume: 56, Issue: 4, Part: 1, pp. 1516-1523. Year 2007.
- [10] E. Tara, S. Shahidinejad, S. Filizadeh, and E. Bibeau, "Battery Storage Sizing in a Retrofitted Plug-in Hybrid Electric Vehicle," *IEEE Transactions on Vehicular Technology*, pp. 1-1. Year 2010.
- [11] H. Chih-Chiang and L. Meng-Yu, "A study of charging control of lead-acid battery for electric vehicles," *ISIE'2000 - IEEE International Symposium on Industrial Electronics*, IEEE, pp. 135-140. Year 2000.
- [12] P.A. Cassani and S.S. Williamson, "Feasibility Analysis of a Novel Cell Equalizer Topology for Plug-In Hybrid Electric Vehicle Energy-Storage Systems," *IEEE Transactions on Vehicular Technology*, vol. 58, pp. 3938-3946. Year 2009.
- [13] A. Szumanowski and Y. Chang, "Battery Management System Based on Battery Nonlinear Dynamics Modeling," *IEEE Transactions on Vehicular Technology*, vol. 57, pp. 1425-1432. Year 2008.
- [14] M. Maskey, M. Parten, D. Vines, and T. Maxwell, An intelligent battery management system for electric and hybrid electric vehicles, *IEEE 49th Vehicular Technology Conference*. Year 1999.
- [15] M. Basu, K. Gaughan, and E. Coyle, "Harmonic distortion caused by EV battery chargers in the distribution systems network and its remedy," *UPEC 2004 - 39th International Universities Power Engineering Conference*, 2004, pp. 869-873. Year 2004.
- [16] J. McDowall, "Conventional battery technologies-present and future," *IEEE Power Engineering Society Summer Meeting*, IEEE, 2000, pp. 1538-1540. Year 2000.
- [17] I. Buchmann, "Understanding your batteries in a portable world. Article on battery choice and how to maximize service life," *Fourteenth Annual Battery Conference on Applications and Advances*, IEEE, pp. 369-373. Year 1999.
- [18] V.Monteiro, H.Goncalves, J.L.Afonso, "Impact of Electric Vehicles on power quality in a Smart Grid context," *IEEE EPQU 11th International Conference on Electrical Power Quality and Utilisation*, pp.1-6, 2011.
- [19] V.Monteiro, J.C.ferreira, J.G.Pinto, D.Pedrosa, J.L.Afonso, "iV2G Charging Platform," *13th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, pp.409-414, 2010.
- [20] B. Kramer, S. Chakraborty, and B. Kroposki, "A review of plug-in vehicles and vehicle-to-grid capability," *IECON 2008 - 34th Annual Conference of IEEE Industrial Electronics*, pp. 2278-2283, Year 2008.
- [21] W. Kempton, V. Udo, K. Huber, K. Komara, S. Letendre, S. Baker, D. Brunner, and N. Pearre, "A test of vehicle-to-grid (V2G) for energy storage and frequency regulation in the PJM system," *University of Delaware*. Year 2008.
- [22] W. Kempton and J. Tomic, "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," *Journal of Power Sources*, vol. 144, pp. 268-279. Year 2005.
- [23] J. Tomic and W. Kempton, "Using fleets of electric-drive vehicles for grid support," *Journal of Power Sources*. Vol. 168, pp. 459-468. Year 2007.
- [24] V.Monteiro, J.L.Afonso, J.C.Ferreira, "An Agent Model for the Simulation of Electrical Vehicle Charging Management," *IEEE CISTI 6th Iberian Conference on Information Systems and Technologies*, pp.1-4, June 2011.
- [25] J.C.Ferreira, V.Monteiro, J.L.Afonso, "V2G smart system: An intelligent system to the electric vehicle charging problem," *IEEE CISTI 6th Iberian Conference on Information Systems and Technologies*, pp.1-4, June 2011.