Vítor Monteiro, Pedro Alves, Andrés A. Nogueiras Meléndez, Carlos Couto, João L. Afonso

"A Novel Modular Voltage Balancing Topology for Active Battery Management System"

IEEE ISIE International Symposium on Industrial Electronics, Santa Clara CA USA, June 2016.

http://ieeexplore.ieee.org/document/7744991/

ISBN: 978-1-5090-0872-8

ISSN: 2163-5145

DOI 10.1109/ISIE.2016.7744991

Vítor Monteiro, Pedro Alves, Andrés A. Nogueiras Meléndez, Carlos Couto, João L. Afonso, "*A Novel Modular Voltage Balancing Topology for Active Battery Management System*", IEEE ISIE International Symposium on Industrial Electronics, Santa Clara CA USA, pp.793-798, June 2016. DOI: 10.1109/ISIE.2016.7744991 ISSN: 2163-5145 ISBN: 978-1-5090-0872-8

A Novel Modular Voltage Balancing Topology for Active Battery Management System

Vítor Monteiro[1], Pedro Alves[1], Andrés A. Nogueiras Meléndez[2], Carlos Couto[1], João L. Afonso[1]
[1]ALGORITMI Research Centre – University of Minho, Guimarães – Portugal
[2]Departamento de Tecnología Electrónica – University of Vigo, Vigo – Spain
[1]{vitor.monteiro | pedro.alves | carlos.couto | joao.l.afonso}@algoritmi.uminho.pt [2]aaugusto@uvigo.es

***Abstract*—This paper proposes a novel modular voltage balancing topology for an active battery management system (BMS). The proposed topology consists of two power stages. The first stage is composed by a switch network, which is responsible for selecting the battery that will provide energy and the battery that will receive energy. In the switch network, for each battery, are used two cells, which allow the operation with bidirectional current flow and bipolar voltage. The second stage is composed by a capacitor used as energy storage element, which consists in the component used to link both batteries. The switch network control and its interaction with the energy storage element is performed by a digital controller. The paper presents the main computer simulations, as well as the main experimental results obtained to validate the proposed voltage balancing topology for an active BMS.**

Keywords—Active Battery Management System; Modular Topology; Voltage Balancing.

I. Introduction

Nowadays, energy storage systems (ESS) have gained notoriety mainly due to the renewables introduction and electric mobility applications [1][2][3]. Although exist other technologies for energy storage, the most common are based in batteries or in hybrid systems composed by ultracapacitors and batteries [4][5][6]. Using batteries as ESS, it is also required use smart battery chargers to perform the charging process with the most adequate algorithm and according to the different features of the electrical installation [7][8][9], as well as a system capable to perform their energy management and also monitor the key parameters of the batteries (e.g., current, voltage, remaining capacity and temperature). These systems are connected directly to the batteries and are defined as battery management systems (BMS) [10][11][12].

The main task of a BMS consist in guarantee that the batteries are always operating within its nominal values, offering protection against to its natural changes in characteristics and also against misapplication [13][14]. Therefore, it is possible to obtain the maximum efficiency during the batteries charging or discharging process contributing to preserve its lifetime [15][16]. As aforementioned, the BMS has the capability to measure voltages, currents and temperatures, and based on these variables, estimate, in each moment, the state-of-charge (SoC) and the state-of-health (SoH) [17][18][19]. Nevertheless, the main functionality that should be performed by a BMS is the voltage balancing of the batteries [20][13]. Neglecting this functionality, the different individual battery voltages will drift apart over time, and the global batteries capacity will decreased fast contributing to an aging more than expected.

There are several circuit topologies to implement the batteries voltage balancing. These topologies are divided in passive and active. A comparison between passive and active battery balancing based on MATLAB simulations is presented in [21]. The first method consist in remove energy from the batteries with higher voltage through a passive element (resistor). The second method consist in remove energy from the batteries with higher voltage to the batteries with lower voltage [22]. In this method is required an intermediary energy storage element (capacitor or inductor). The main topologies that use the capacitor as energy storage element are: switched capacitor; double-tiered switched capacitor; single switched capacitor; and modularized switched capacitor [21]. On the other hand, the main topologies that use the inductor as energy storage element are: single/multi inductor; single windings transformer; and multi/multiple windings transformer [21]. The complexity of a BMS is dependent of the batteries technology and is divided in two main architectures: centralized and distributed [23]. In a centralized architecture the different functions are incorporated in a single system that is responsible for the BMS. In a distributed architecture the battery bank is divided in modules identified as slaves, where there are a master module that is responsible for the management of all the slaves [23].

In this context, this paper proposes a novel modular voltage balancing topology for BMSs. Fig. 1 shows the architecture of the proposed modular topology for active BMS. As it can be seen, it is composed by the bidirectional (current) bipolar

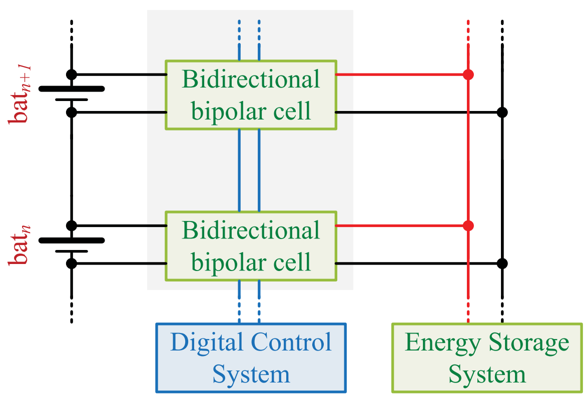

Fig. 1. Architecture of the proposed modular topology for an active battery management system (BMS).

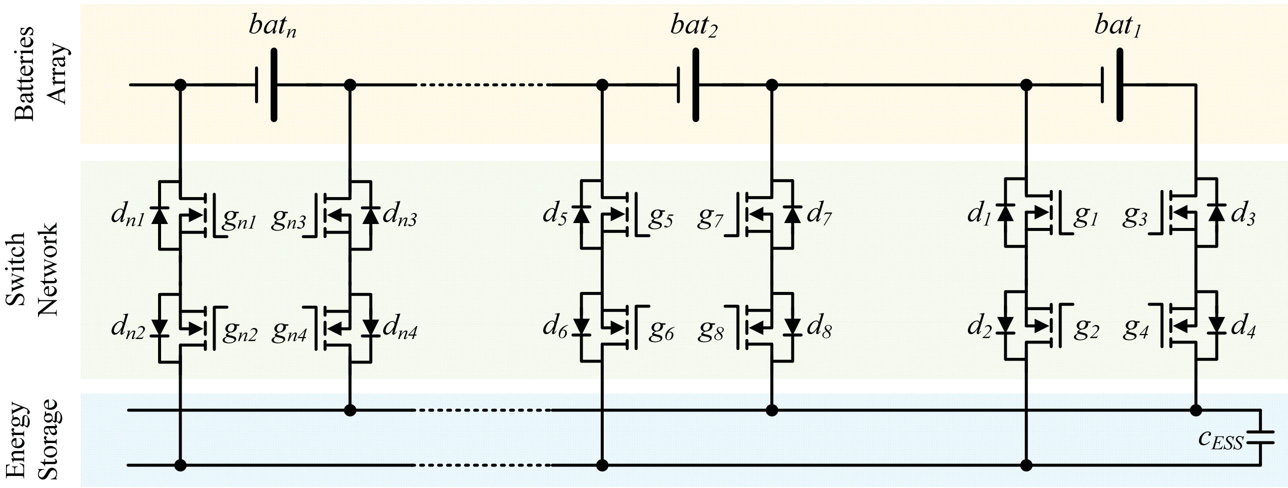

Fig. 2. Proposed modular topology for active battery management system (BMS).

(voltage) cells that are part of the switch network, by the energy storage system, and by the digital control system. Comparing with the traditional solutions, the main advantages of the proposed topology are: possibility to balance the voltage of two batteries independently of their position in the batteries array; modular architecture, which allows add/remove batteries to/from the batteries array.

In section II is described in detail the principle of operation of the proposed voltage balancing topology for BMSs, i.e., it is described the power stage and the digital control system and are presented the main simulation results. In section III is presented and described the developed laboratorial prototype. Section IV presents the main experimental results obtained to validate the proposed voltage balancing topology for BMSs. Finally, section V presents the main conclusions.

II. Proposed Topology: Principle of Operation

This item presents in detail the principle of operation of the proposed modular topology for an active BMS.

A. *Power Stage*

Fig. 2 shows the proposed modular topology for active BMS. The main purpose of the proposed system is balance the voltage across batteries array. Therefore, the balancing process is performed in three main stages. In a first stage, it is measured the voltage of each battery in order to identify the batteries with lower and higher voltages. After that, in a second stage, the battery with higher voltage is connected to the energy storage system through the switch network. Finally, in a third stage, the battery with lower voltage is connected to the energy storage system also through the switch network. The second and third stages are repeated until the balance the voltage across both batteries.

B. *Digital Control System*

As aforementioned, the process to balance the voltage across the batteries is determined by the switch network, which is controlled by the digital control system. The simpler process to control the MOSFETs of the switch network consists in use a pulse-width modulator (PWM) with fixed or variable duty-cycle. Using a fixed duty-cycle it is established the same time for the capacitor charging and discharging. On the other hand, using a variable duty-cycle it is established different times for the capacitor charging and discharging. The selection of each method should be done according to the capacitor behavior. Moreover, also the PWM frequency should be selected according to the capacitor behavior, otherwise the balancing process is not optimized. The influence of this parameters in the balancing process is demonstrated through simulation results.

C. *Simulation Results*

This section presents the main simulation results that illustrate the principle of operation of the proposed modular topology for BMSs. The simulation results were obtained with the software PSIM v9.0.

Analyzing Fig. 2, and assuming that the voltage across the battery 1 (bat_1) is greater than the voltage across the battery 2 (bat_2), it will be removed energy from bat_1 to be delivered to bat_2. Therefore, when the MOSFETs g_3 and g_2 are *on* and the MOSFETs g_1 and g_4 are *off*, the current follows through the MOSFETs g_3 and g_2 and through the reverse diodes of the MOSFETs g_1 and g_4. In this situation, the bat_1 will be connected to the capacitor (C_{ESS}), and the capacitor will be charged with the same voltage of bat_1. The current path for this situation is shown in Fig. 5(a).

On the other hand, analyzing Fig. 2, when the MOSFETs g_1 and g_4 are *on* and the MOSFETs g_2 and g_3 are *off*, the current follows through the MOSFETs g_1 and g_4 and through the reverse diodes of the MOSFETs g_3 and g_2. In this situation, the bat_2 will be connected to the capacitor (c_{ESS}), and bat_2 will be charged with the voltage of the capacitor c_{ESS}. It is also important to note that this process of charge (from bat_1) and discharge (to bat_2) the capacitor c_{ESS} will be repeated until both batteries reach the same voltage. The current path for this situation is shown in Fig. 5(b).

The current to charge the capacitor is established according to the difference of voltage between batteries, i.e., increasing this difference increases the current. Therefore, the balancing process should be performed with a lower difference of voltage in order to reduce the current and optimize the balancing time.

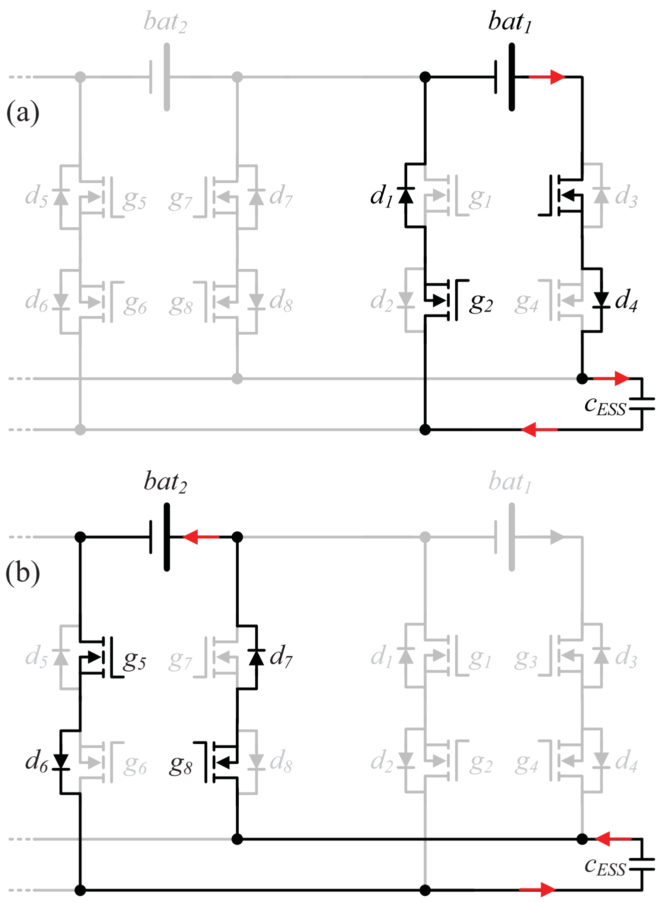

Fig. 5. Principle of operation of the proposed modular topology for active BMS: (a) The capacitor c_{ESS} is charged from the baterry bat_1; (b) The energy stored in the capacitor c_{ESS} is delivered to the battery bat_2.

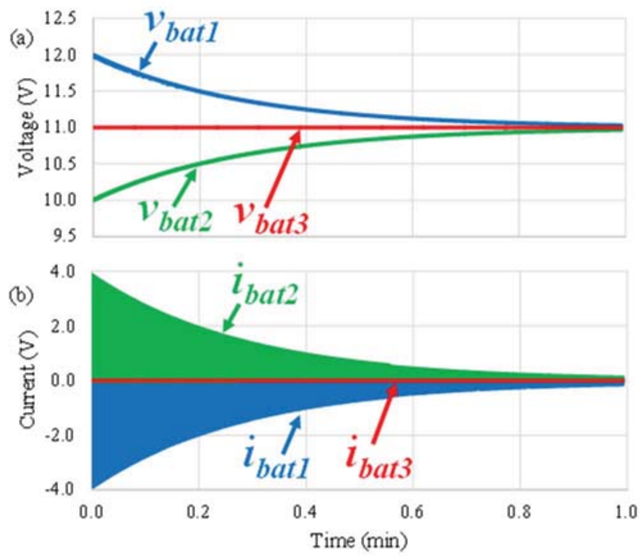

Fig. 3. Principle of operation of the proposed modular topology for active BMS during the voltage balancing process: (a) Volatge in each battery (v_{bat1}, v_{bat2}, v_{bat3}); (b) Current in each battery (i_{bat1}, i_{bat2}, i_{bat3}).

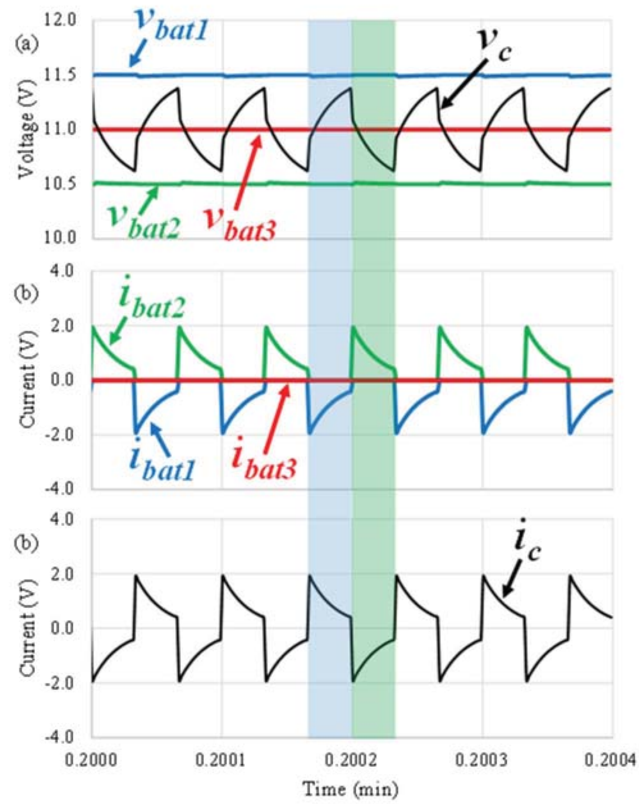

Fig. 4. Principle of operation of the proposed modular topology for active BMS during the balancing process: (a) Voltage in each battery (v_{bat1}, v_{bat2}, v_{bat3}) and in the capacitor; (b) Current in each battery (i_{bat1}, i_{bat2}, i_{bat3}); (c) Current in the capacitor (i_c).

In order to illustrate that the proposed topology is suitable to balance the voltage across the batteries, it was considered a scenario with three batteries with three different initial voltages (v_{bat1} = 12 V, v_{bat2} = 10 V, v_{bat3} = 11 V). After the voltage balancing, it is predictable that three batteries will have the same voltage, i.e., the mean value of the three voltages (11 V).

Fig. 3 shows the principle of operation of the proposed modular topology for active BMS during the voltage balancing process. Fig. 3(a) shows the voltages of the batteries (v_{bat1}, v_{bat2}, v_{bat3}). As it can be seen, initially, the three voltages are unbalanced and after the balancing process, the three voltages are balanced. In this case, the voltage of the battery bat_2 remains the same, and is transferred energy from the battery bat_1 to the battery bat_3. Fig. 3(b) shows the current in each battery. Once that is only transferred energy from the battery bat_1 to the battery bat_3, the measured current in the battery bat_1 is positive and the current in the battery bat_2 is negative.

Fig. 4 shows in detail the voltages and currents in the batteries (bat_1, bat_2, bat_3) and in the capacitor (c_{ESS}). Fig. 4(a) shows the voltages in the batteries (v_{bat1}, v_{bat2}, v_{bat3}) and the voltage in the capacitor (v_c). On the other hand, Fig. 4(b) shows the currents in the batteries (i_{bat1}, i_{bat2}, i_{bat3}) and Fig. 4(c) shows the current in the capacitor (i_c). As it can be seen, the voltage balancing between the batteries bat_1 and bat_2 is manly divided in two main stages. In a first stage, the capacitor is charged from the battery bat_1. Therefore, there are only current (i_{bat1}) in the battery bat_1 and in the capacitor (i_c). In a second stage, the battery bat_2 is charged with the energy stored in the capacitor. Therefore, there are only current (i_{bat2}) in the battery bat_2 and in the capacitor (i_c).

III. DEVELOPED PROTOTYPE

The developed prototype is divided in two main parts, the switches network of the power circuit and the digital control system.

The switches network is constituted by three parts: the MOSFETs of the bidirectional bipolar cells, the MOSFETs drivers, and the capacitors of the energy storage system. For the MOSFETs it is used the model IXFQ50N50P3 from the manufacturer IXYS. The MOSFETs drivers is mainly composed by the driver ADUM5230 from the manufacturer Analog Devices. This driver has two channels, therefore, it is used one driver in each bidirectional bipolar cell. The main advantage of this driver is related with the internal isolated dc-dc converter. This driver also guaranties that the output signals are isolated from the input signals, i.e., it is used to isolate the control circuit from the power circuit. The energy storage system is composed by an array of five capacitors (connected in parallel) in order to obtain a capacitance of 50 µF. Taking into account that this is a laboratory prototype were selected capacitors with nominal voltage of 100 V (although using a batteries with nominal voltage of 12 V).

The digital control system is mainly based in the DSP TMS320F28027 from the manufacturer Texas Instruments. This DSP is programmed in C language using the software code composer studio from Texas Instruments. Fig. 6 shows the flowchart of control algorithm of the proposed modular active BMS. As it can be seen, the control algorithm is divided in three main stages. In a first stage are measured the voltages of the batteries using the internal ADCs of the DSP. In a second stage, the acquired voltages are filtered with a digital filter and is used an algorithm to identify the batteries with higher and lower voltages. In the third stage is applied the PWM signal to the bidirectional bipolar cells of the batteries with higher and lower voltages. The balancing process is interrupted when the voltages are similar.

IV. EXPERIMENTAL RESULTS

This item presents the main experimental results obtained with the developed prototype (cf. item III) of the proposed modular voltage balancing topology for active BMS. The experimental results were obtained with the digital oscilloscope Tektronix model TPS 2024.

Fig. 7 shows the developed printed circuit board for each bidirectional and bipolar cell of each battery. Specifically, Fig. 7(a) shows the top view where it is possible identify the connections (PWM, MOSFETs, and battery) and Fig. 7(b) shows the bottom view where it is possible identify the MOSFETs driver (this driver is used to separate the control circuit from the power circuit).

Fig. 8 shows the laboratorial setup used to test the proposed modular active BMS. Taking into account the final application of the proposed topology for active BMS (c.f. section I), the experimental results were obtained with lead acid batteries, each one with nominal voltage of 12 V and nominal capacity of 33 Ah.

Fig. 9 shows the first experimental results obtained to balance two batteries. These experimental results were

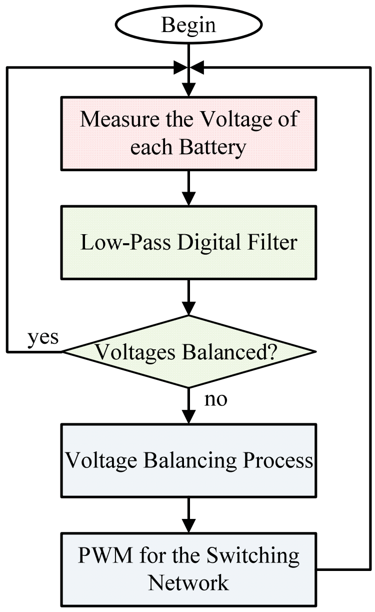

Fig. 6. Flowchart of the control algorithm for the proposed modular active BMS.

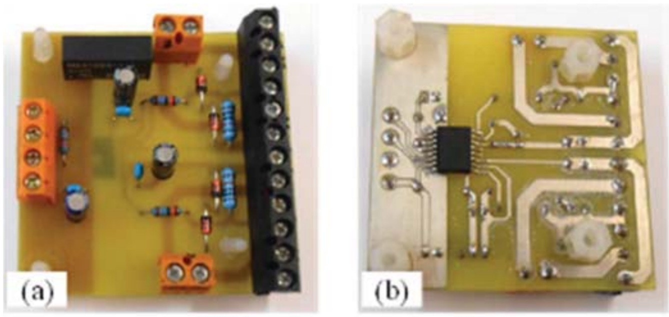

Fig. 7. Developed printed circuit board for each bidirectional and bipolar cell: (a) Top view; (b) Bottom view.

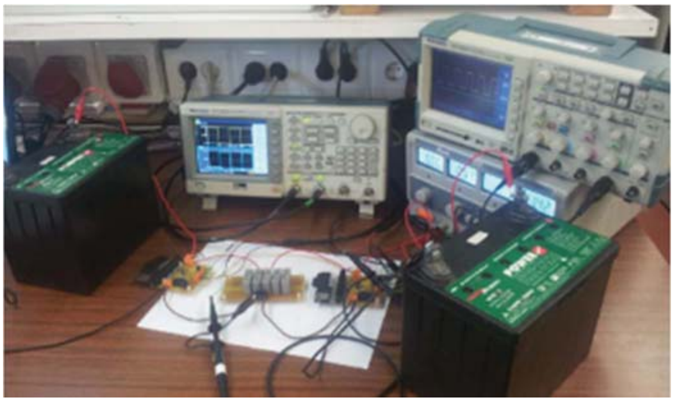

Fig. 8. Laboratorial setup used to test the proposed modular voltage balancing topology for active BMS.

obtained in order to illustrate the influence of the switching frequency of the MOSFETs in the voltage balancing process. Initially, the battery bat_1 has a voltage of 12 V and the battery bat_2 has a voltage of 8.5 V, representing an initial Δv of 3.5 V. This figure shows the voltage (v_c) in the capacitor c_{ESS}, the current in the battery bat_1 and the current in the battery bat_2. Specifically, Fig. 9(a) shows the experimental results for a

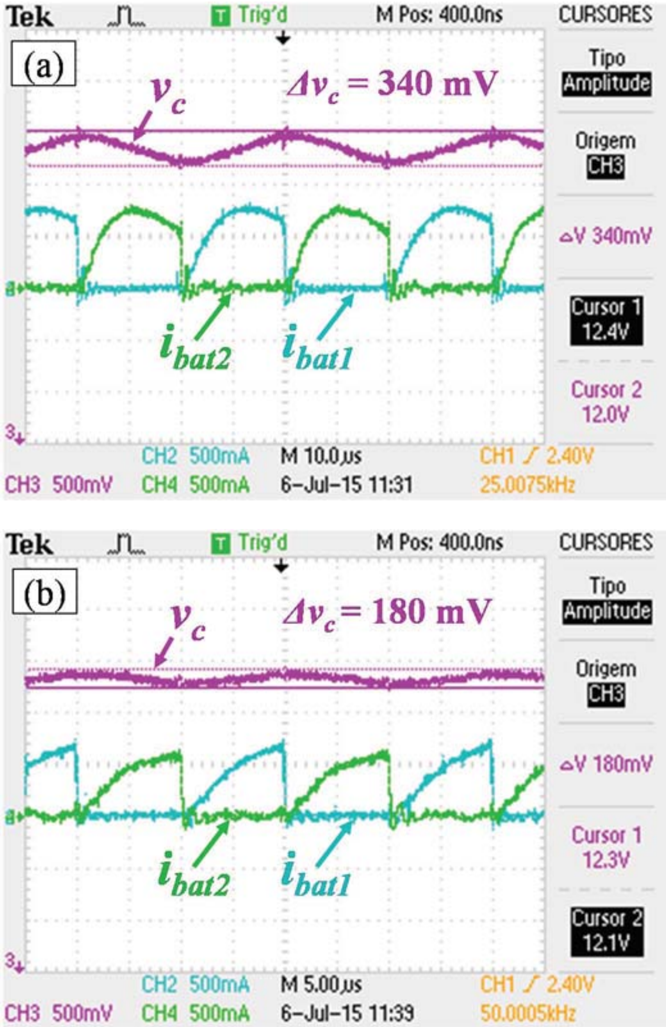

Fig. 9. Experimental results of the voltage in the capacitor (v_c), current in the battery bat_1 (i_{bat1}), and current in the battery bat_2 (i_{bat2}): (a) For a switching frequency of 25 kHz; (b) For a switching frequency of 50 kHz.

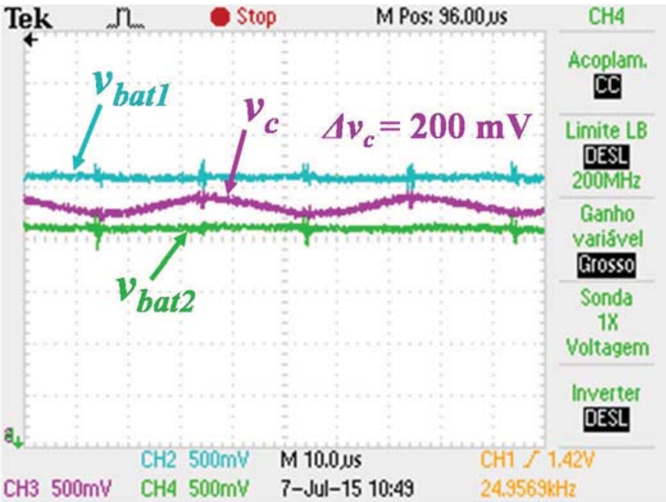

Fig. 10. Experimental results of the voltage in the capacitor (v_c), and the voltage in the batteries bat_1 (v_{bat1}) and bat_2 (v_{bat2}) for a switching frequency of 50 kHz.

switching frequency of 25 kHz, and Fig. 9(b) for a switching frequency of 50 kHz. As it can be seen, in both cases, the

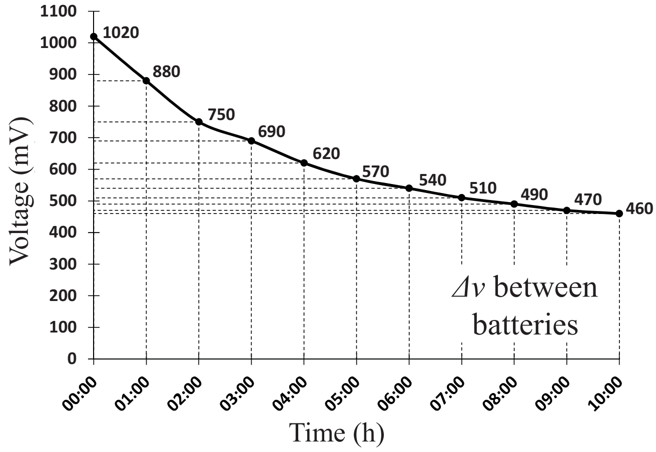

Fig. 11. Experimental results of the voltage balancing of two batteries with a switching frequency of 50 kHz, and with an initial Δv of 1020 mV and a final Δv of 460 mV.

capacitor is charged from the battery bat_1 and discharged to the battery bat_2. The maximum current in each battery is influenced by the switching frequency. As expected, it is greater with lower switching frequency. This current is also influenced due to the initial difference of voltage between the two batteries (Δv = 3.5 V), i.e., increasing the Δv will increase the current in each battery. Fig. 10 shows the experimental results of the voltage in the capacitor (v_c), and the voltage in the batteries bat_1 (v_{bat1}) and bat_2 (v_{bat2}) for a switching frequency of 50 kHz.

Fig. 11 shows the experimental results of the voltage balancing of two batteries. Initially, the measured voltage difference (Δv) between the batteries bat_1 and bat_2 was 1020 mV and the final voltage difference (Δv) was 460 mV, i.e., a reduction of about 45%. As it can be seen, to balance 560 mV were required 10 hours. From this experimental result it can be conclude that the voltage balancing is faster in the first hour and lower in the last hour. It can also be concluded that this initial voltage unbalance (1020 mV) should be avoid in order to optimize the time required to perform the voltage balancing. Therefore, the control algorithm should detect a minimum initial voltage unbalance between the batteries in order to optimize the balancing process in terms of the time required.

V. Conclusion

This paper proposes a novel modular voltage balancing topology for an active battery management system (BMS). The principle of operation of the proposed topology is described in detail, namely, the switches network and the digital control system. The proposed topology was validated through experimental results with a developed laboratorial prototype. The experimental results allow to conclude that the voltage balancing is faster in the beginning, and slower in the ending of the process. It was also possible to conclude that the initial voltage unbalance should be the lower possible in order to optimize the time required to perform the voltage balancing and to minimize the currents. The experimental results were obtained to validate the proposed topology, i.e., the voltage balancing process. In the final application, the voltage of each battery will be continuously measured and when is detected that the voltage unbalance is greater than a predefined threshold, the voltage balancing process is performed.

ACKNOWLEDGMENT

This work has been supported by FCT – Fundação para a Ciência e Tecnologia in the scope of the project: PEst-UID/CEC/00319/2013. Mr. Vítor Monteiro was supported by the doctoral scholarship SFRH/BD/80155/2011 granted by the FCT agency.

REFERENCES

[1] João C. Ferreira, A. Silva, Vítor Monteiro, João L. Afonso. "Collaborative Broker for Distributed Energy Resources," in Computational Intelligence and Decision Making, 1st ed., A.Madureira, C.Reis, V.Marques, Ed. Springer, 2013, pp.367-378.

[2] Vítor Monteiro, Bruno Exposto, João C. Ferreira, João Luiz Afonso, "Improved Vehicle-to-Home (iV2H) Operation Mode: Experimental Analysis of the Electric Vehicle as Off-Line UPS," IEEE Trans. Smart Grid, vol.x, no.x, pp.x-x, Feb. 2016.

[3] S. R. Bull, "Renewable Energy Today and Tomorrow," Proc. IEEE, vol.89, no.8, pp.1216-1226, Aug. 2001.

[4] Shuai Lu, Keith A. Corzine, Mehdi Ferdowsi, "A New Battery/Ultracapacitor Energy Storage System Design and Its Motor Drive Integration for Hybrid Electric Vehicles," IEEE Trans. Veh. Technol., vol.56, no.4, pp.1516-1523, July 2007.

[5] Ala Al-Haj Hussein, Issa Batarseh, "A Review of Charging Algorithms for Nickel and Lithium Battery Chargers," IEEE Trans. Veh. Technol., vol.60, no.3, pp.830-838, Mar. 2011.

[6] Álvaro Cunha, F. P. Brito, Jorge Martins, Nuno Rodrigues, Vitor Monteiro, João L. Afonso, "Assessment of the Use of Vanadium Redox Flow Batteries for Energy Storage and Fast Charging of Electric Vehicles in Gas Stations," ELSEVIER Energy, vol.x, no.x, pp.x-x, Mar. 2016.

[7] Vítor Monteiro, J. G. Pinto, João L. Afonso, "Operation Modes for the Electric Vehicle in Smart Grids and Smart Homes: Present and Proposed Modes," IEEE Trans. Veh. Tech., vol.65, no.3, pp.1007-1020, Mar. 2015.

[8] Vítor Monteiro, João Paulo Carmo, J. G. Pinto, João L. Afonso, "A Flexible Infrastructure for Dynamic Power Control of Electric Vehicle Battery Chargers," IEEE Trans. Veh. Technol., vol.X, no.X, pp.X-X, Oct. 2015.

[9] Vítor Monteiro, João C. Ferreira, Andrés A. Nogueiras Meléndez, João L. Afonso, "Electric Vehicles On-Board Battery Charger for the Future Smart Grids," in Technological Innovation for the Internet of Things, 1st ed., Luis M. Camarinha-Matos, Slavisa Tomic, Paula Graça, Ed. Springer, 2013, Chapter 38, pp.351-358.

[10] Habiballah Rahimi-Eichi, Unnati Ojha, Federico Baronti, Mo-Yuen Chow, "Battery Management System - An Overview of Its Application in the Smart Grid and Electric Vehicles," IEEE Ind. Electron. Mag., vol.7, no.2, pp.4-16, June 2013.

[11] H. L. Chan, D. Sutanto, "A New Battery Model for use with Battery Energy Storage Systems and Electric Vehicles Power Systems," IEEE Power Engineering Society Winter Meeting, vol.1, pp.470-475, Jan. 2000.

[12] Philip T. Krein, "Battery Management for Maximum Performance in Plug-In Electric and Hybrid Vehicles," IEEE VPPC Vehicle Power and Propulsion Conference, pp.2-5, Sept. 2007.

[13] Antonio Manenti, Andrea Abba, AlessandroMerati, Sergio M. Savaresi, Angelo Geraci, "A New BMS Architecture Based on Cell Redundancy," IEEE Trans. Ind. Electron., vol.58, no.9, pp.4314-4322, Sept. 2011.

[14] Chol-Ho Kim, Moon-Young Kim, Gun-Woo Moon, "A Modularized Charge Equalizer Using a Battery Monitoring IC for Series-Connected Li-Ion Battery Strings in Electric Vehicles," IEEE Trans. Power Electron., vol.28, no.8, pp.3779-3787, Aug. 2013.

[15] Jurgen Garche, Andreas Jossen, "Battery Management Systems (BMS) for Increasing Battery Life Time," IEEE Telecommunications Energy Special Conference, pp.81-88, May 2000.

[16] Waraporn Puviwatnangkurn, Bundit Tanboonjit, Nisai H. Fuengwarodsakul, "Overcurrent protection scheme of BMS for Li-Ion battery used in electric bicycles," IEEE ECTI-CON International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, pp.1-5, May 2013.

[17] Laxman Maharjan, Shigenori Inoue, Hirofumi Akagi, Jun Asakura, "State-of-Charge (SOC)-Balancing Control of a Battery Energy Storage System Based on a Cascade PWM Converter," IEEE Trans. Power Electron., vol.24, no.6, pp.1628-1636, June 2009.

[18] Juan Carlos Álvarez Antón, Paulino García Nieto, francisco Javier de Cos Juez, Fernando Sánchez Lasheras, Cecilio Blanco Viejo, Nieves Roqueni Gutiérrez, "Battery State-of-Charge Estimator Using the MARS Technique," IEEE Trans. Ind. Electron., vol.28, no.8, pp.3798-3805, Aug. 2013.

[19] IL-Song Kim, "A Technique for Estimating the State of Health of Lithium Batteries Through a Dual-Sliding-Mode Observer, IEEE Trans., Power Electron., vol.25, no.4, pp.1013-1022, Apr. 2010.

[20] Jian Cao, Nigel Schofield, Ali Emadi, "Battery Balancing Methods: A Comprehensive Review," IEEE VPPC Vehicle Power and Propulsion Conference, pp.1-6, Sept. 2008.

[21] Mohamed Daowd, Noshin Omar, Peter Van Den Bossche, Joeri Van Mierlo, "Passive and Active Battery Balancing comparison based on MATLAB Simulation," IEEE VPPC Vehicle Power and Propulsion Conference, pp.1-7, Sept. 2011.

[22] Lukas Valda, Kamil Kosturik, "Comparison of Li-ion Active Cell Balancing Methods Replacing Passive Cell Balancer," IEEE AE International Conference on Applied Electronics, pp. 267-270, Sept. 2015.

[23] Gianfranco Pistoia, "Electric and Hybrid Vehicles Power Sources, Models, Sustainability, Infrastructure and The Markey," 1st ed., 2010, Elsevier.