Battery Management System Simulation using SystemC

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***Abstract*—One of the major problems with electric vehicles is the battery. The battery must be adequately monitored in order to optimize its performances and to maximize its life, to know when it's time to recharge it, or when the charging has been completed, or it's time to buy a new one. The battery's monitoring is the goal of the battery management system (BMS), which must be carefully designed. Moreover, the BMS must report its data to the outer world, and this means that it cannot work alone. If we want to use some kind of simulation to help the design of an effective BMS, we need a simulation model that can be easily attached to other hardware simulation models, such as CAN bus' or Bluetooth models. In this work we present and validate a BMS SystemC simulation model. Both the design and the validation of this BMS are carried on using real-world scenarios and data.**

Keywords— BMS, battery, SystemC, CAN

I. INTRODUCTION

Research on Electric Vehicles (EVs) is a long time work-in-progress. In the last decade, we have seen the commercialization of the first Hybrid Electric Vehicles (HEVs), cars with an internal combustion engine and an electric motor powered by batteries. HEVs use the batteries only for very short travels, for example low speed city traffic, and the battery is charged by the internal combustion engine. Plug-in Hybrid Electrical Vehicles (PHEVs) can be recharged using the power grid and their autonomy is greater. Several car manufacturers such as Nissan, Mitsubishi, General Motors and Chevrolet have recently begun to sell Plug-in Hybrid Electric Vehicles (PHEVs).

Full Electric Vehicles (FEVs), also called Plug-in Electric Vehicles (PEVs), are solely powered by batteries and electric motors. Nowadays the FEVs have some serious limitations, such as the high batteries cost, the limited driving range, the high recharge time and the lack of an adequate electrical infrastructure for charging purposes [1]. The FEVs' costs keep decreasing with the increase of petrol costs, and hence we can expect that FEVs market penetration will grow and will be soon able to sustain itself, but the other limitations keep standing. For example, there is a lack of FEV charging infrastructure in spite of the large diffusion of electrical infrastructure. The reason is (obviously) that this infrastructure requires investment from both the private and public sectors.

Energy efficient, safe and intelligent road transport system is one of the objectives of the European Work Program in Smart, green and integrated transport. Moreover, the 'European Green Cars Initiative' work program concentrates on research on electric and hybrid vehicles with the aim of strong reduction in CO2 emissions.

In this context, the problem we want to address is the battery monitoring problem. If we want to make a FEV reliable, we must be able to control the battery state of charge, that tells us if we need to stop and recharge the car; the battery state of health, that tells us if the battery is still good or if we need to buy a new one, and the battery temperature, that must be kept inside a well-defined range of safe values. Moreover, if we are charging the battery, we want to be able to know how long the charging will require, and we want to be warned when the charging ends. In a FEV, next to the battery there is a so-called battery management system (BMS), that controls the state and utilization of the battery, and that can tell us all these information. With a well-designed BMS simulation model we can test the performances of a hypothetical battery without actually plugging it in a car, whether the car is moving or is charging. Predictive and adaptive BMS models are important the integration of electric vehicles in a smart grid [2-3].

In literature several BMS simulation models exist ([4-6]). They are mainly related to the model of the battery and the characterization of model itself. The battery model is fundamental to estimate the state of charge. But the models used in the literature cannot be easily integrated in the enviroment used for system level design of electronic systems, such as SystemC. In [7] a SystemC-AMS model of the analog behaviour of the battery has been used. SystemC-AMS [8] and SystemC-WMS [9] are SystemC libraries used to model analog components and can be easyly integrated in the SystemC environment.

In this work, we present a SystemC model of the BMS that can be easily interfaced with other hardware models such as for example the CAN bus, or a Bluetooth device for the data transmission to the end user. To prove the effectiveness of our model, we test it with several real driving scenarios.

Section II presents the BMS architecture. The SystemC model is reported in Section III. Section IV reports some simulation results.

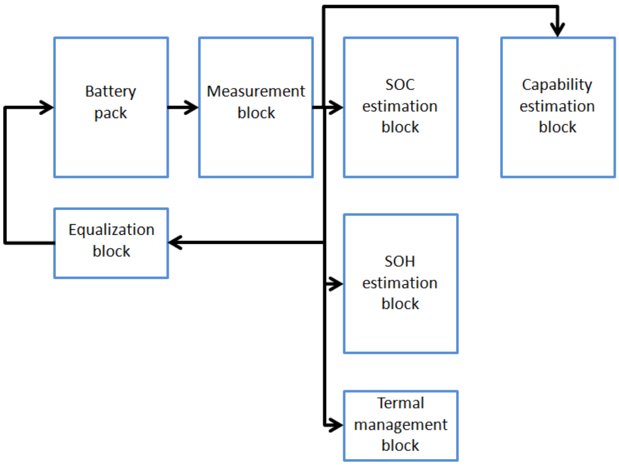

Fig. 1. BMS block diagram.

II. BMS ARCHITECTURE

A Battery Management System (BMS) is an interface between the real battery pack, and the outer world. A BMS must rule and check the energetic car's behavior, reporting to the user all the relevant information about the battery, whether the car is moving or not. In today's cars, we can easily assume that this BMS is connected to the remaining car's electronics via a CAN bus.

The main goals of a BMS are the following [5-6]:

- Battery voltage and current monitoring during the charging and discharging processes;
- Battery and battery cells temperature monitoring;
- Battery state of charge (SOC) and state of health (SOH) monitoring;
- Battery cells voltage balancing;
- Battery current levels monitoring during the charging and discharging processes;
- Battery cells protection against out-of-scale operating conditions.

A block diagram of a BMS is shown in Fig. 1. The battery pack is the actual battery, located outside the BMS but close to it, and it is generally composed by several series-connected smaller elements called "cells". The battery pack contains sensors that read the voltage and the temperature on each cell, and the current of the whole pack, and that pass them to the BMS. These signals are digitally converted by the measurement block [5].

The SOC and SOH estimation blocks take the digital signals coming from the measurement block and use them to evaluate the battery pack's SOC and SOH. The SOC is defined as the battery's remaining capacity percentage, and it's affected by temperature, and battery's life and discharge rate. The SOC is extremely important to avoid the overcharging problem during the battery's re-charge [5]. There are several techniques to evaluate the SOC. Among them, the most used are those based on a look-up table, the Coulomb counting integration method, and several mixed methods [5].

The SOH gives an estimation of the general "health" condition of the battery, with respect to its nominal performances. The reason behind the SOH is that the battery condition falls down during its life, and the SOH gives an idea about "how good" the battery still is, and whether is time to buy a new one. The SOH estimation is basically an empirical measure, usually based on the battery's loss of capacitance or on the counting of charge/discharge cycles.

The capability estimation block is used to estimate the maximum charge/discharge currents that the battery can use in any time. This value is used by the Electronic Control Unit (ECU) of the car to manage the charge/discharge of the battery. Rules to obtain this value can be found in [5].

The cell equalization block is used to equalize the voltage on each cell of the battery pack. Due to manufacturing inaccuracies, it usually happens that the cells in the same battery pack don't have the same capacitance or the same nominal voltage. This can lead to (for example) too high charge current, or too high current drawing, and a consequent damage for the battery.

Finally, the thermal management block is used to stabilize the temperature of the battery pack. If the temperature is too high, this block enables a cooling fan, while if the temperature is too low, the block enables a resistor. If the temperature is beyond acceptable limits, the block sends a warning message to the ECU.

III. THE BMS SYSTEMC MODEL

The BMS has been modeled using SystemC [10]. We made this choice mainly because the SystemC simulations are fast and we can change the BMS' parameters in a pretty easy way. Moreover, using SystemC we connected th BMS model with a CAN bus model we already developed, in order to simulate a more sophisticate system.

The architecture of the BMS reported in Fig. 1 has been implemented in SystemC including Application Interface to CAN, CAN controller and CAN BUS, as reported in Figs.3-4.

The following modules has been used:

- BATT.h and .cpp: module external to the BMS, emulating the battery pack.
- MEAS.h and .cpp : Measurement Block
- SOCE.h and .cpp: SOC Estimation Block
- SOHE.h and .cpp: SOH Estimation Block
- CAPE.h and .cpp: Capability Estimation Block
- EQUA.h and .cpp : Equalization Block
- THERM.h and .cpp : Thermal Management Block
- APP.h and .cpp : CAN Application Layer
- LLC.h and .cpp : CAN Link Controller Layer
- MAC.h and .cpp : CAN MAC Layer
- PHL.h and .cpp : CAN Physical Layer

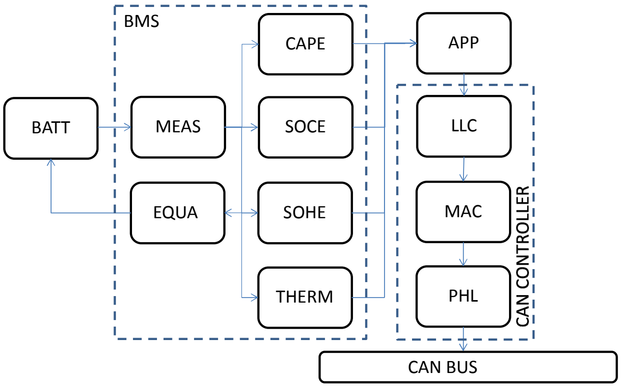

Fig. 2. Block diagram of the SysemC modules of Battery pack model, BMS, Application Interface to CAN, CAN controller and CAN BUS

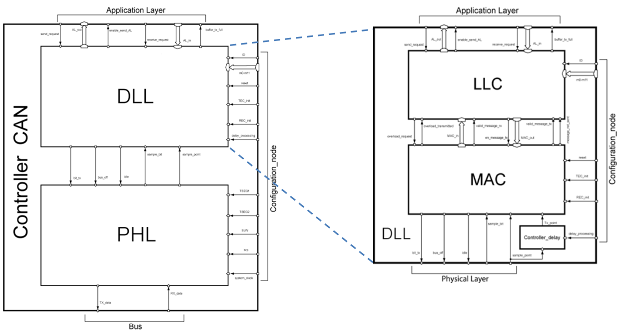

Fig. 3. Detail of the SystemC model of the CAN controller

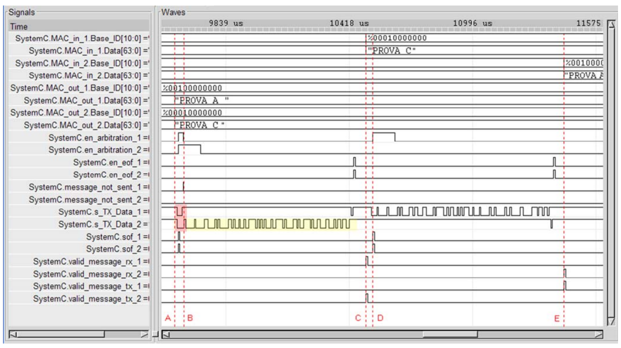

Fig. 4. Simulation of the transmission of BMS data in the CAN bus

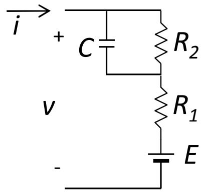

Fig. 5. Battery electrical model.

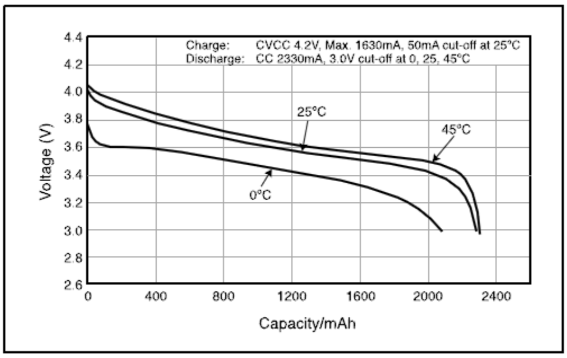

Fig. 6. Battery Discharge characteristics [11]

The BMS has been connected through an interface acting as application layer of the CAN protocol that converts the information coming from the BMS into a string of bits of the data field of the CAN bus: SOC (1 byte), SOH (1 byte), Temperature (2 bytes), Available Power (2 bytes), Voltage (2 bytes), Current (2 bytes). The complete system allows the simulation of the transmission of BMS data in the CAN bus for a clock accurate analysis.

The battery pack has been modeled as 50 parallel modules with 100 cells each. The prototype for a single cell is the Panasonic CGR-18650DA Lithium-Ion Battery.

The nominal voltage of each cell is 3.6 V, and the nominal capacitance is 2.33 Ah. The maximum and minimum charge voltages are 4.3 and 3.0 V, respectively. Hence, each battery's module will have a nominal voltage of 360 V, and a nominal capacitance of 2.33 Ah [11].

The thermal behavior has been modeled as described in [12], where the authors present a dynamic energy balance that can approximate the temperature change of the battery during the charge/discharge phases.

The authors of [12] present also an electrical model, shown in Fig. 5, which we used to evaluate the static SOC. The electrical model described in [12] requires the use of the battery's discharge characteristics, which can be found on the battery datasheet [11] and which are shown for convenience in Fig. 6. Figure 6 evidences the dependence of the battery voltage with the temperature. The method used for the evaluation of the SOC is mixed, i.e. it uses the Coulomb counting integration method with a look-up table to correct the estimations [12].

The SOH can be estimated in a rather simple way starting from the decrease of capacitance with the number of charge/discharge cycles, as that shown in [13].

To increase the accuracy of our BMS model, we also added a voltage difference among the battery *modules*. Even though in a real battery pack this voltage difference would be among the battery *cells*, for simulation purpose a random difference among the modules will suffice. In real battery packs, this variation can rise up to 15% of the nominal voltage, and hence we added to each module random multiplicative factors between 0.996 and 1.004.

IV. Results

To test the BMS behavior and effectiveness, we need data about the actual current demand from an electric vehicle. This demand depends on the route the vehicle is following, on the number of stops it does, on the speed it is running at, and so on. The United States Environmental Protection Agency (EPA) provides records about the speed of cars and light trucks in different street conditions. In [14] the speed of the vehicle and the associated current demands are given for the EPA SC03 driving cycle and for the EPA US06 driving cycle. The SC03 driving cycle is an urban track characterized by several stops and limited velocities, while the US06 is a more highway-like situation, with higher speeds and less stops. Moreover, we simulated two constant-current demand, with the 20% and 50% of the maximum current available, respectively.

The simulation of the complete system of Fig. 2 has been performed with four driving cycles (SC03, US06, 0.2C and 0.5C) and the results are reported in Figs 7-14. The current demand to the battery pack for each driving cycle has been derived from the data in [14].

From each simulation we reported the average battery pack voltage (Vpack), the open circuit voltage (OCV), the temperature and the State of Charge (SOC).

Figs. 7-10 show the results when the battery is initially fully charged and the environment temperature is 0°. Even though the battery is initially charged, Vpack and OCV are initially quite low, and then they increase almost steadily. The reason is the strong battery dependence from the temperature, which experiments a strong increase with the simulation time. The temperature dependence affects the SOC, too, rising the US06 SOC above the 0.2C curve.

The temperature dependence is also clear in Figs. 11-14, where we show the same results but with an environmental temperature of 25°. The values for the Vpack and the OCV are higher than those in Figs. 7-8, while the temperature increase follows almost the same way, but the initial value is higher.

V. Conclusions

The paper presents a SystemC model of the battery pack of the Battery Management System with an interface with a CAN bus. The simulation environment has been tested with preliminary test cases. The model developed allows a system exploration and it will be useful for an optimization of the algorithms of the BMS in different test conditions.

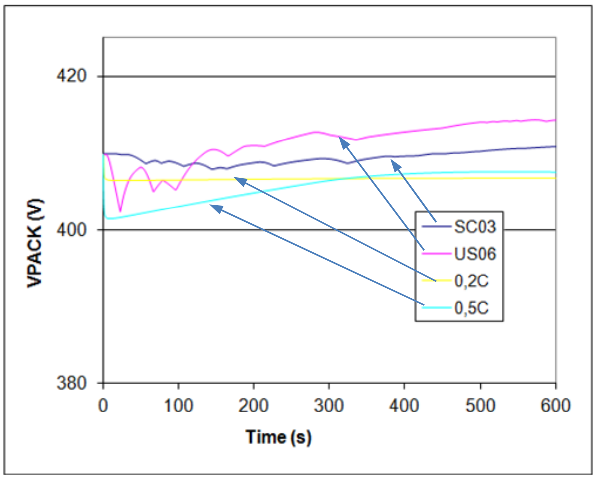

Fig. 7. Vpack of the battery with environmental temperature of 0°.

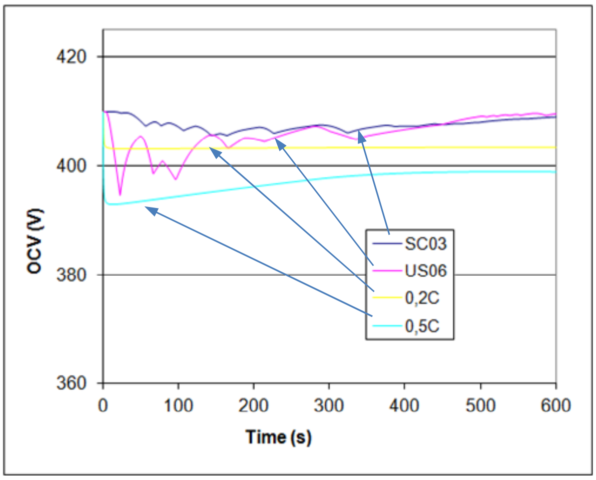

Fig. 8. OCV of the battery with environmental temperature of 0°.

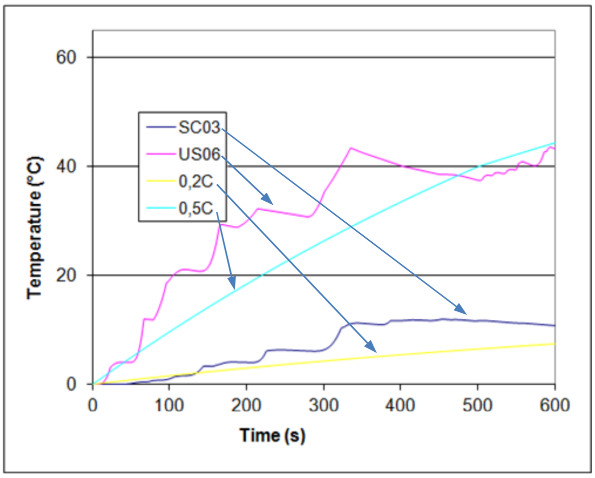

Fig. 9. Temperature of the battery with environmental temperature of 0°.

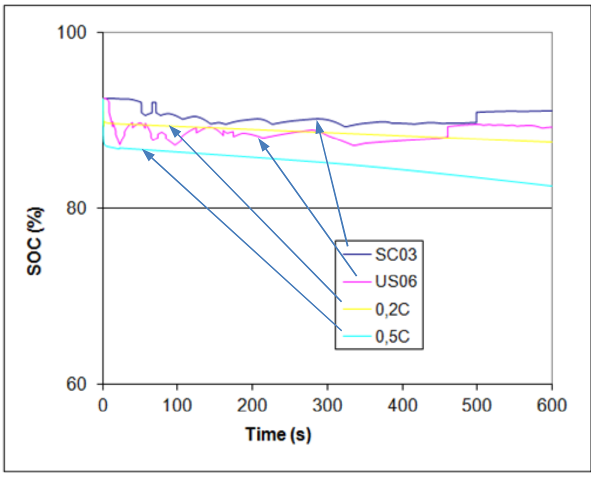

Fig. 10. SOC of the battery with environmental temperature of 0°.

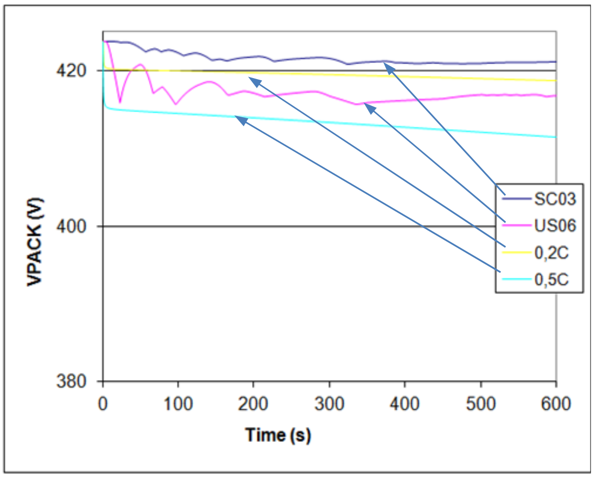

Fig. 11. Vpack of the battery with environmental temperature of 25°.

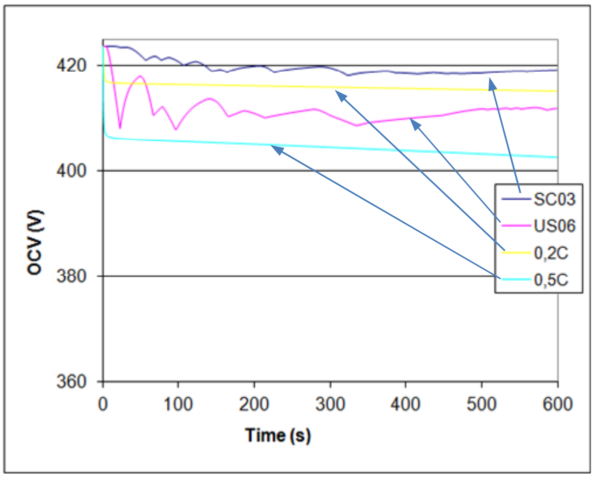

Fig. 12. OCV of the battery with environmental temperature of 25°.

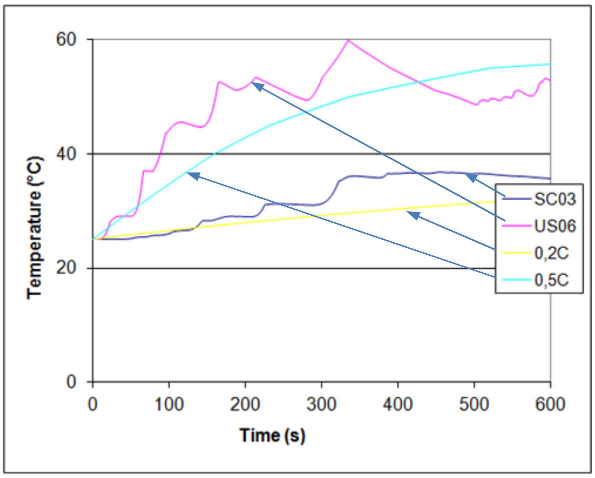

Fig. 13. Temperature of the battery with environmental temperature of 25°.

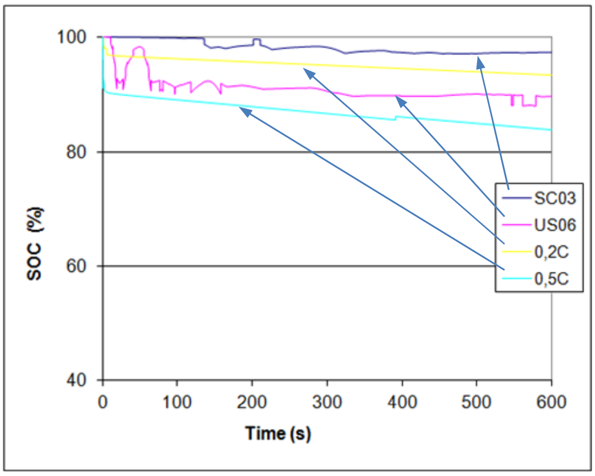

Fig. 14. SOC of the battery with environmental temperature of 25°.

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