Battery Management System (BMS) Simulation Environment for Electric Vehicles

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***Abstract*— The wide diffusion of Full and Hybrid Electric Vehicles is stimulating research on electric energy storage systems and Battery Management Systems (BMS). The Battery management system must ensure many complex features such as charge control, battery-capacity monitoring, remaining run-time information and charge-cycle counting. An optimization of the BMS can allow an improvement on security of the vehicle, performance of the engine, energy optimization and extension of the life of the battery. The main objective of this work is to develop a simulation environment based on SystemC to design and optimize the Battery Management System including a lithium-ion battery model and CAN communication interface. The BMS has been validated using real-world scenarios and data.**

Keywords*— *BMS, battery, SystemC, CAN

I. INTRODUCTION

After years of discussions, scientific evidence shows that climate change is occurring, mainly due to human activities. Worldwide public opinion and decision makers are moving in the direction of doing something to overcome this problem. Global warming is mainly due to the emissions of CO_2 caused by the combustion of fossil fuels (coal, natural gas, and oil) for energy production and transportation. Producing more energy from renewable sources is a way to reduce carbon emissions. The combustion of fossil fuels to transport people and goods (highway vehicles, air travel, marine transportation, and rail) is the one of the largest source of CO_2 emissions in industrialized countries. As an example, the 'European Green Cars Initiative' work program concentrates on research on electric and hybrid vehicles with the aim of strong reduction in CO_2 emissions.

On the basis of these considerations, a lot of research, prototypes and commercial products of low emission engine for transportation are now available. 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. In order to make hybrid, plug-in hybrid and fully electric vehicles fit for the mass market, the energy density and efficiency of battery packs need to increase. Besides research on advanced electro-chemistries, the integration of batteries primary cells into battery packs has great role to play.

Furthermore the impact of the recharge of FEV on the grid and the lack of an adequate electrical infrastructure for charging purposes is a relevant aspect to be faced [1-3].

Many aspects must be faced for the energy optimization in a FEV, for example:

- system integration of electric machines with transmissions;
- optimization of energy recovery with the integration of braking systems;
- integration of power electronics with battery charging functions;
- creation of models the components (motor, batteries, inverters, fuel-cells) that can be used for design, simulation, diagnosis and testing.
- creation of a simulation environment for the simulations of the electric digital-analog components and the mechanical and chemical components

In this context, an aspect to be faced is the battery monitoring system. 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. In a FEV, the battery management system (BMS) controls the state and utilization of the battery.

In literature several BMS simulation models exist [4-9]. 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. SystemC is a consolidated design language and environment, based on C++, used for system level description of electronic systems. SystemC is very well suited to the design and refinement of HW/SW systems from system-level down to register-transfer-level (RTL). However, for a broad range of applications, the digital parts of an electronic system closely interact with the analog chimical and mechanical parts and thus with the continuous-time environment. SystemC-WMS [10] has been used for this type of applications with digital and analog analog parts for example a Bluetooth transceiver, modeling of a wireless channel and solid state dimming [11-12].

In this work, we present, in Section II a SystemC model of the BMS that can be easily interfaced with other hardware models such as for example the CAN bus. To prove the effectiveness of our model, in Section III we report the application of the model in several real driving test scenarios.

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II. BMS MODEL

A Battery Management System (BMS) is becoming the most important component of a FEV. A BMS must rule and check the energetic car's behavior, reporting to the user all the relevant information about the battery. It must maximize the runtime per discharge and the number of life cycles. Usually BMS is connected to the remaining electronic systems via a CAN bus.

The BMS performs the following actions:

- Monitoring of battery voltage, current, temperature, state of charge (SOC), state of health (SOH);
- Balancing of battery cells voltage;
- Protection of battery cells against out-of-scale operating conditions.

The BMS must ensure:

- Safety: isolate the cells under abnormal conditions;
- Long life and efficient charging using an appropriate charging algorithm;
- Maintenance: using SOH measurements.

Fig. 1 reports the block diagram of a BMS. In this work the BMS has been modeled using SystemC. We made this choice mainly because the SystemC simulations are fast and we can change the BMS parameters in an easy way. Moreover, using SystemC we connected the BMS model with a CAN bus model we already developed, in order to simulate a more sophisticated system. The single blocks are described in detail.

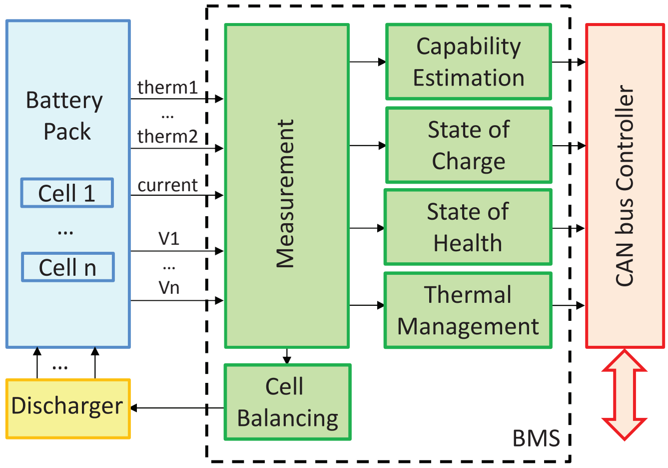

Fig. 1. BMS block diagram.

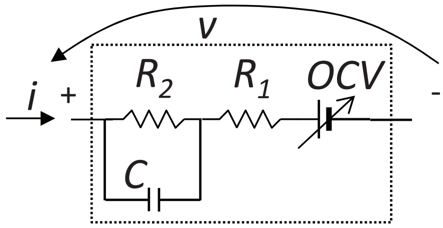

Fig. 2. Electric model of a single cell.

Battery Pack

The battery pack is composed M modules connected in parallel, each module consists of N series-connected smaller elements called "cells". The model used to describe the behavior of the single cell is reported in Fig. 2 and it is simple and widely used, as for example in [13-14]. The parameters of the model are the open circuit voltage (OCV), an internal resistance with two components R_1 and R_2 and a capacitance C, that characterizes the transient response. The OCV has a complex dependence on time t, temperature T and current i [13]. The model used is reported in the following equations:

$$i(t) = \frac{1}{R_2}(v(t) - OCV(t) - i(t)R_1) + C\frac{d}{dt}(v(t) - OCV(t) - i(t)R_1) \qquad (1)$$

$$OCV(T(t), i(t), t) = \sum_{k=0}^{n} c_k\, SOD^k(T(t), i(t), t) + \Delta E(T) \qquad (2)$$

$$SOD = \frac{1}{Q_r}\int_0^t \alpha[i(\tau)] \cdot \beta[T(\tau)]\, d\tau \qquad (3)$$

where SOD is the state of discharge, c_k are the coefficients of the polynomial, ΔE is potential correction term used to compensate for the variation of equilibrium potential that is induced by temperature variations.

In our model we used n=11, and

$$SOD = \frac{1}{Q_r}\int_0^t [\alpha_1 i(\tau) + \alpha_2]\, d\tau \qquad (4)$$

The thermic model of the battery is obtained, as indicated in [13], by the energetic balance between the Joule heating and the thermal conduction, reported in eq. (5)

$$h(T(t) - T_{amb}) + m\frac{dT}{dt} = i^2(t)R_1 + \frac{1}{R_2}(v(t) - OCV(t) - i(t)R_1)^2 \qquad (5)$$

Where h is the thermic conductance and m is the thermic capacitance.

In the simulations the battery pack has been modeled as 50 parallel modules with 100 cells each, with the coefficients of the single cell estimated from a 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 V and 3.0 V, respectively.

In order to simulate the behavior of the cell balancing system, we emulated the mismatch among the modules adding a random variation on the OCV with a maximum of $4\ {}^{0}/_{00}$.

Measurement

The functionalities of the measurements, A/D conversion and serial transmission are simply emulated in the SystemC block. The voltage, current and temperature of each module of the battery pack are sent to the cell balancing, capability estimation, SOH, SOC and thermal management blocks.

Cell Balancing

The cell balancing block is used to equalize the voltage on each cell of the battery pack. Due to manufacturing inaccuracies, usually the cells in the same battery pack don't have the same capacitance or the same nominal voltage. In the battery pack the mismatch among the modules have been emulated with a random generator. The cell balancing block emulates the system that forces the cells to have the same voltage. The cell balancing block evaluates the medium or minimum value and then overwrites the voltage of each cell.

Capability Estimation

The capability estimation block estimates the maximum charge/discharge currents that the battery can support/provide in any time. This value is sent by the BMS using the CAN bus to the Electronic Control Unit of the car that manages the battery charge/discharge of the battery. In the charging phase, the capability depends and decreases with temperature, SOC and OCV. Conversely, in the discharge phase the capability depends and decreases with temperature, SOC and SOH. The model used in the SystemC implementation is the one reported in [5].

State of Charge (SOC)

The State of Charge (SOC) is the battery's remaining capacity expressed in percentage, and it is affected by the temperature, the battery's life and the discharge rate. The SOC of a battery, is defined [15-20] as reported in equation (6), as the ratio between the residual charge available $Q(t)$ and the nominal capacity Q_{nom}, that is given by the manufacturer.

$$\mathrm{SOC}(t) = \frac{Q(t)}{Q_{\mathrm{nom}}} \qquad (6)$$

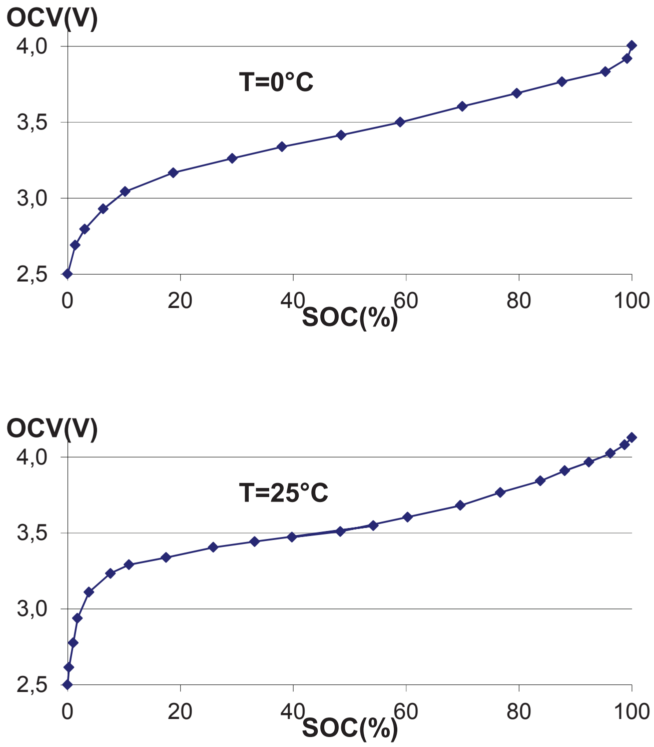

Fig. 3. OCV dependance on SOC at different temperatures

The SOC estimation is fundamental for the management of a battery. Two methods are generally used: the OCV method and the coulomb counting method. Both methods have been implemented in the SystemC model.

The OCV method [15-16] is based on the estimation of the relation between OCV and SOC. The charge-voltage curve is nonlinear and varies considerably according to the specific battery, to the operating conditions, such as life of the battery, temperature, etc. A battery look up table have been derived from the datasheet of the Panasonic CGR-18650DA and the results are shown in Fig. 3.

The coulomb counting method [17-20] measures the discharging current and integrates it over time. This amount must be subtracted to the previous capacity of the battery so obtaining the residual charge, as expressed by

$$\mathrm{SOC}(t) = \mathrm{SOC}(t_0) - \int_{t_0}^{t} \frac{I(t)}{Q_{\mathrm{nom}}} dt \qquad (7)$$

In the SystemC code, the integral has been approximated with the sum of the values of the current measured by the measurement block with a constant time interval.

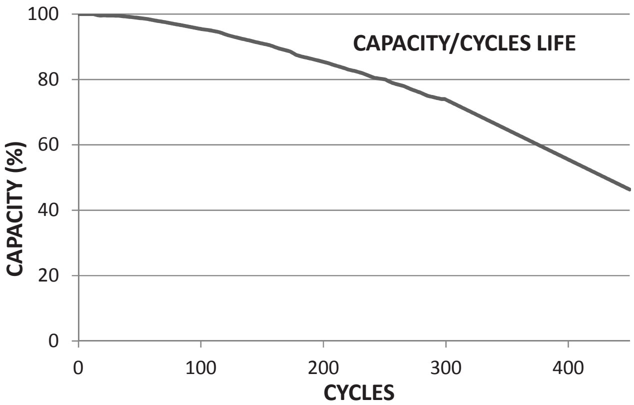

Fig. 4. SOH as a function of the recharging cycles

State of Health (SOH)

The maximum capacity on the battery (expressed in mAh) decreases every time the battery is recharged. The SOH is defined as the actual capacity of the battery normalized to the initial capacity, as reported in equation (8)

$$\mathrm{SOH}(k) = \frac{Q_{nom}(k)}{Q_{nom}(0)}\% \qquad (8)$$

The SOH gives an estimation of the general health condition of the battery, with respect to its nominal performances. The SOH gives an idea about how good the battery still is, and whether itis time to buy a new one. The SOH estimation can be performed from experimental measurements.

We used the datasheet of the Panasonic CGR-18650DA battery to derive a look up table and the results are shown in Fig. 4. Other methods, see for example [7], derive an estimation of the SOH from the measurements of the internal resistances R_1, R_2 of the model in Fig. 2.

Thermal Management

Being the battery pack performances strongly related to the temperature, it is fundamental to keep the temperature of each cell of the battery under control and activate heaters or coolers to maintain the temperature under defined limits. This action is performed by the thermal management block. If the temperature is too high, this block enables a cooling fan, while if the temperature is too low, the block enables a resistor.

In the model of the battery pack implemented in the SystemC code the temperature decreases or increases depending on the activation of the cooler/heater modifying the coefficient h in (5)

CAN Controller

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.

III. Results

The SystemC model of the complete system in Fig. 1 has been developed and tested with constant current absorption from the battery.

A more complete test with a real case requires 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 [21] 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.

We used the data of EPA SC03 and EPA US06 to estimate the current absorbed by the battery. The simulation of the complete system of Fig. 1 has been performed with two driving cycles (SC03, US06). The current demand to the battery pack for each driving cycle has been derived from the data in [21] and reported in Fig. 5. In the highway cycle the vehicle absorbs high currents when it accelerates to reach high values of speed. During deceleration the system is able to partially recharge the battery, with negative values of the current. All the parameters of the system have been monitored in particular OCV, current absorbed, SOH, SOC, temperature.

We reported the normalized average battery pack voltage (Vpack) in Fig. 6, the temperature in Fig. 7 and the SOC in Fig. 8. The battery is initially fully charged and the external temperature is 25°C.

The simulation environment developed has been tested and it will be used in future work to develop control strategies of the BMS.

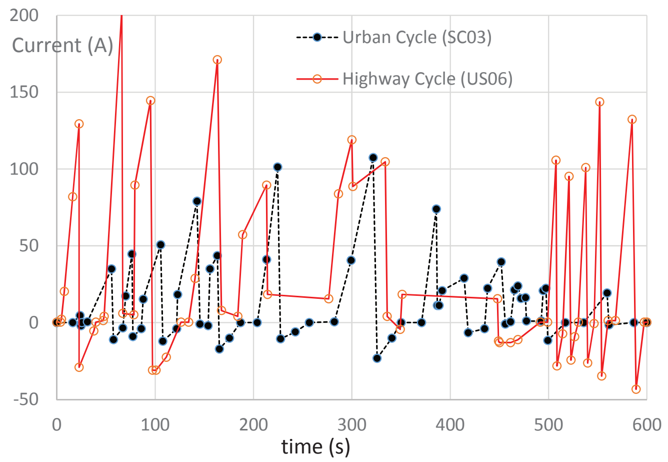

Fig. 5. Current absorbed by the engine in the two scenarios: urban Cycle and highway cycle.

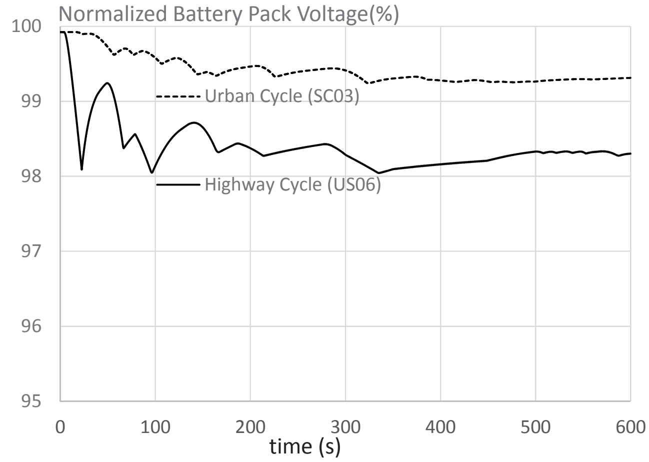

Fig. 6. Normalized Voltage of battery pack with external temperature of 25°.

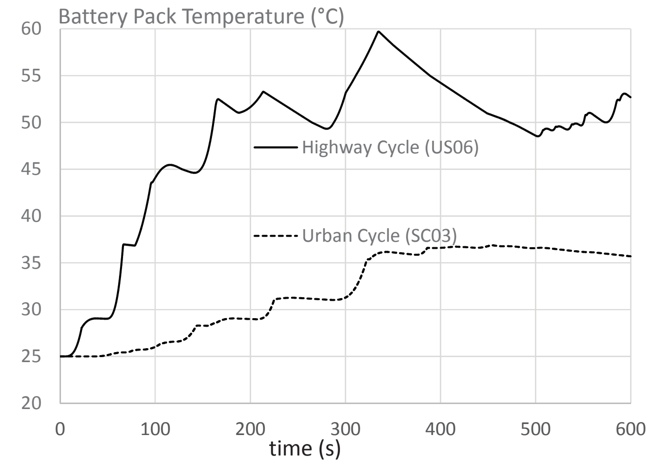

Fig. 7. Temperature of the battery with external temperature of 25°.

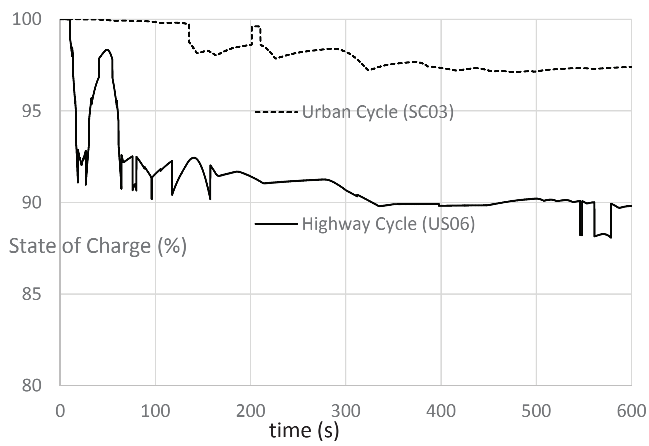

Fig. 8. State of Charge of the battery with external temperature of 25°.

IV. Conclusions

The paper presents a design framework based on SystemC with the model of the battery, of the Battery Management System and an interface with a CAN bus.

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.

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