Modeling an Electric Vehicle Lithium-Ion Battery Pack Considering Low Temperature Behavior

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Abstract—This paper deals with the modeling and simulation of an electric vehicle lithium-ion battery pack considering low temperature behavior. The initial part is focused on the impact of considering the thermal dynamics. To this end, experimental data is used to evaluate the parameters behavior due to the operation at low temperatures. The second part is devoted to study the thermal distribution in the complete pack. In this analysis, the advantage of using a structural approach such as Bond Graph becomes crucial. The complete thermal model is obtained graphically thus creating a direct correspondence between the topology of the system and its representation. Simulation results are provided in order to illustrate the importance of considering the thermal dynamics and the degradation produced when the cells within the battery pack are not equalized.

Keywords—Simulation, Lithium-Ion Battery, Bond Graph.

I. INTRODUCTION

Transportation solutions have been thoroughly investigated to improve fuel economy and reduce vehicle emissions. Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) have been proposed as a solutions to meet these goals. One of the most important elements within HEV/EV is the energy storage system. For this reason in recent years there is a growing interest in the battery technology [1] [2].

Lithium-ion batteries became the first choice in automotive products related to HEV and EV. This technology provides high efficiency, less self-discharge rate, long life cycles, high specific energy and energy density whereas their maintenance is considerably low [3]. A well known disadvantage of this type of technology is the reduction of the energy density at low temperatures [4] – [6]. In [7] the authors compare the thermal effect on the three most popular energy storage devices: lead-acid, lithium-ion and NiMH. As a conclusion, even if NiMh appears to have a lower sensitivity to ambient temperatures, lithium-ion remains the greatest potential for HEV/EV due to its longer life and power-to-energy ratio.

In order to understand the batteries behavior at low temperatures the modeling and simulation is an important task. It is a useful tool for testing novel concepts and helps in the design stage. It allows the evaluation of different battery pack configurations, inexpensively and without implementing a prototype. In most operation modes cold temperature is not a major issue: when the vehicle is plugged the grid is used to heat the battery and during a run, the exothermic discharge process maintains the temperature of the cell. However, the thermal management gets difficult if the vehicle is parked unplugged or when it is not a plugin vehicle. This fact is the motivation of the present article where the modeling of an EV lithium-ion battery pack considering low temperature behavior is presented.

Electro-thermal modeling of battery pack considering low-temperature behavior has been investigated in previous works [8] – [10]. A remarkable contribution of this article is the development of a Bond Graph-Based model of the complete battery pack. Bond Graph (BG) modeling is best suited to model large scale physical systems independently of their nature [11] [12]. That is why this tool becomes fundamental for modeling multi-domain systems in general and the electrical/thermal nature of the lithium-ion battery pack in particular. By using this formalism the resulting representation of the system presents a direct correspondence with the topology of the system [13] and the coupling with the model of a complete electric vehicle can be accomplished in a straightforward manner.

II. MODEL OF A SINGLE CELL

The first step of this study is focused on the modeling of a single cell. In order to capture the electrochemical dynamic behavior, an impedance-based model of the cell is presented. It is based on previous works [14] – [16] where different types of batteries are analyzed and modeled in terms of equivalent electrical networks. The idea is to find an electrical model that interpolates at best the battery behavior as seen from the terminals. The cell simulated in this paper is a 3.3V/100Ah rectangular LiFeMnPO4 cell, with a working voltage between 2.5V and 3.8V. The weight of the cell is 3kg and the size is 236x125x65mm. The energy density is 167 Wh/L.

A. Electric Equivalent Model

The lithium-ion batteries electric equivalent circuit is characterized by a voltage source ($V_{oc}$), R-C electric parallel arrangement ($R_1/C_1$) and an output resistance ($R_o$). The equivalent electric circuit is presented in Fig. 1(a).

![Electric equivalent circuit](image)

Fig. 1. (a) Electric equivalent circuit, (b) Bond Graph representation.
This electric equivalent circuit can be systematically represented using BG. This formalism facilitates the construction of models that represent the dynamics of multi-domain systems. The representation using BG presents a direct correspondence with the physical toplogy of the system, see Fig. 1.(b). Due to this property the BG representation allows an easy visualization of the physical system topology and power flow.

In the proposed model, each parameter depends on the state of charge (SOC). The SOC is obtained based on the total charge delivered by the cell and the initial state of charge (SOC\textsubscript{ini}) as follows:

\[ \text{SOC} = \text{SOC}_{\text{ini}} - \int \frac{I_{\text{batt}}}{C} \, dt \]  

(1)

where \( I_{\text{batt}} \) is the output current of the cell and \( C \) is the capacity of the cell in Ah.

In order to fully describe the behavior of the cell, the dependence of the parameters with respect to the SOC must be provided. These curves are obtained experimentally at ambient temperature of 25°C. The variation of \( R_0 \) and \( R_1 \) as function of SOC is depicted in Fig. 2 whereas the variation of \( C_1 \) and the open circuit voltage \( (E_0) \) is shown in Fig. 3. The curve that characterizes \( C_1 \) is fitted from experimental data [17].

![Fig. 2. Variation of \( R_0 \) and \( R_1 \) as function of SOC.](image)

![Fig. 3. Variation of \( C_1 \) and \( E_0 \) as function of SOC.](image)

**B. Thermal Dependent Model**

When the battery operates at extreme low temperatures the proposed isothermal model is not sufficient. A much better characterization of the electrochemical behavior can be obtained by considering the thermal dependence of the parameters [18] [19]. To this end, the thermal model of the cell must be included. Fig. 4.(a) shows the coupling of the electric equivalent circuit and the thermal model.

The total dissipated electric power is absorbed by the core of the cell which represents the active material. The core is connected to the casing of the battery characterized by the crust, with a conductive resistance in between. The power generated in the core is mainly transferred to the crust through the conductive resistance while the crust dissipates heat to the ambient. Again, the representation using BG presents a direct correspondence with the physical toplogy of the system, as seen in Fig. 4.(b).

To incorporate the power dissipated into the thermal model each resistive element is replaced by a resistive source element \( \text{“RS”} \) (see Fig. 5.(a)) whose relation between primary and secondary bonds is given by:

\[ e_1 = R \cdot f_1 \]  

(2)

\[ f_2 = f_1 e_1 / e_2 \]

Primary bond (indicated with subscript 1) belongs to the electric domain while secondary bond (subscript 2) enters the thermal model as a source of entropy. Parameter \( R \) represent the electric resistance.

Heat transfer by conduction or convection is represented with a thermal resistance element \( \text{“Rth”} \) (see Fig. 5.(b)) whose relationship between primary and secondary bonds is:

\[ f_1 e_1 = \frac{1}{\theta_c} (e_1 - e_2) \]  

(3)

\[ f_2 e_2 = f_1 e_1 \]

where \( \theta_c \) represents the thermal resistance. In the proposed model \( \theta_c \) and \( \theta_a \) represent the core-to-crust and ambient-to-crust resistances. The product \( f_1 e_1 \) is the rate of heat flow \( (\partial Q / \partial t) \) and (3) becomes equivalent to the experimental Fourier law for the thermal conductivity.

Heat storage is represented as shown in Fig. 5.(c) with a thermal capacity element \( \text{“Cth”} \). It inherits the relationship from a capacitor \( (C \dot{e} = f) \) but here the value of the capacity is inversely proportional to the element’s temperature (i.e. \( \dot{C} = \gamma_1 / e \)). With this substitution and knowing that the product \( f e \) is the rate of heat flow \( (\partial Q / \partial t) \), the relationship becomes

\[ \gamma_1 \Delta T = \Delta Q \]  

(4)

that corresponds to the first law of thermodynamics when neither phase change nor net work occur in the core.
Within the thermal model the evolution of the temperature of the core ($T_c$) and the crust ($T_r$) are calculated. In this model, the parameters of the equivalent electric circuit depends on the SOC and $T_c$. Additional experiments were conducted in order to capture the behavior at low temperature ($T_c = 0^\circ C$ and $T_c = -20^\circ C$). Each parameter is obtained from SOC and $T_c$ by bilinear interpolation [17] [20]. To illustrate this procedure, the dependence of $R_0$ and $R_1$ are shown in Fig. 6 and Fig. 7.

### III. Model of the Complete Pack

The model of the complete pack corresponds to the actual lay-out of the system. The pack is composed by four independent cells connected in series. The thermal model is constructed according to the real geometry of the system, as shown in Fig. 10.(a). Each crust has an independent temperature and dissipate heat towards the ambient. Also, the crust of each cell interchanges heat with its neighbors by conduction (which is represented by a thermal contact resistance).

Fig. 10.(b) shows the BG representation of the complete system which present a direct correspondence with the real topology. This property makes apparent the power interchange between sub-systems and gives an overall idea of the energy distribution within the system.

### IV. Simulation Results

Simulation results are obtained from the developed BG models. The first part presented in Section IV-A shows the importance of considering the thermal dependence when the battery operates at low temperatures. Simulation results presented in Section IV-B correspond to the complete battery pack.

#### A. Simulation of a Single Cell

The cell is discharged at constant current of 100 A during 3000 seconds, see Fig. 8.(a). For the model considering thermal dynamics the evolution of the temperatures are depicted in Fig. 8.(b).

The comparison of the isothermal model with the thermal dependent model is presented in Fig. 9. It can be seen that the degradation of the output voltage and the SOC is deeper when the thermal dependence is considered.
B. Simulation of the Complete Pack

First a balanced scenario is simulated. In this case all the cells are identical (i.e. the parameters are exactly the same). Then the capacity ($C$) and output resistance ($R_0$) of the first cell are modified considering aging according to [21]. The current extracted to the battery is the same for both scenarios, see in Fig. 11.(a). As expected, the output voltage is degraded when the battery pack is unbalanced, see Fig. 11.(b).

When the pack is balanced the symmetry produces same evolution for cells 1-4 as well as for cells 2-3. The temperatures of cores 1 and 4 are presented in Fig. 12.(a) for both scenarios. It can be seen that for the unbalanced scenario these temperatures are no longer the same. Fig. 12.(b) shows the temperature difference between core 1 and 4 for the unbalanced scenario. The evolution of the $SOC$ for both scenarios and the heat transferred between crust 2 and 3 are presented in Fig. 13.(a) and Fig. 13.(b), respectively. Naturally there is not heat transference for the balanced scenario whereas the heat transferred for the unbalanced scenario reaches 30 W.

V. Conclusion

The present work addressed the modeling of lithium-ion battery dynamics considering low temperature behavior. The first part is focused on the impact of considering the thermal dynamics. Experimental data is used to evaluate the parameters degradation at low temperatures. The simulation of a single cell proved that the operation at low temperatures reduces considerably the performance of the electric variables.

The second part is devoted to study the thermal distribution in the complete pack during normal and unbalanced operation. In this analysis, the advantage of using Bond Graph becomes crucial. The complete thermal model is obtained graphically and any further modification is introduced without rewriting any mathematical equation. Also, further works oriented to couple the battery model with the model of a complete hybrid electric vehicle can be accomplished in a straightforward manner using this graphical formalism.
REFERENCES


