



**HAL**  
open science

# Reduced Model for Fast Simulation of a Lithium-Ion Battery Pack Taking Into Account Current and State of Charge Dispersion

Fernanda Vendrame, Christophe Forgez, Marie Sayegh

► **To cite this version:**

Fernanda Vendrame, Christophe Forgez, Marie Sayegh. Reduced Model for Fast Simulation of a Lithium-Ion Battery Pack Taking Into Account Current and State of Charge Dispersion. 2022 IEEE Energy Conversion Congress and Exposition (ECCE), Oct 2022, Detroit, United States. hal-03852884

**HAL Id: hal-03852884**

**<https://hal.science/hal-03852884v1>**

Submitted on 15 Nov 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Reduced Model for Fast Simulation of a Lithium-Ion Battery Pack Taking Into Account Current and State of Charge Dispersion

Fernanda Vendrame<sup>1,2,\*</sup>, Christophe Forgez<sup>1</sup>, and Marie Sayegh<sup>2</sup>

<sup>1</sup>*Université de Technologie de Compiègne, Roberval (Mechanics, Energy and Electricity) , Centre de Recherches Royallieu, CS 60319, 60203 Compiègne Cedex, France*

<sup>2</sup>*Safran Electrical & Power , 70-80 Rue Auguste Perret, 94000 Créteil, France*

\*Corresponding author: fernanda.vendrame@safrangroup.com

## Abstract

Modeling the electrical behavior of a battery is essential for obtaining information that cannot be directly measured, such as the state of charge (SOC), or that needs a complex instrumentation, such as the individual cell current. Each cell in a battery pack behaves differently, creating dispersion of current, SOC, voltage and temperature. In this paper, we propose a method to estimate the current and the SOC of each cell in the pack, taking into account differences in temperature and connection resistances from one cell to another. To reduce computation time, what makes the algorithm more suitable for real-time applications, we simulate only a few cells in detail. For all the other cells, we use a simplified calculation of their resistances based on their temperatures to estimate current and SOC dispersions. Our method reduces the computation time by 60%, while preserving the accuracy of the model.

## 1 Introduction

When a battery pack is operating, each cell in the pack has a slightly different behavior. For this reason, they have different voltages, currents and states of charge (SOC). Quantifying these dispersions is important to monitor the limiting cells, to get better estimations of each individual cell, to evaluate the need for a balancing system or even to rethink the pack design.

Several authors have worked on the electrical modeling of battery packs. Li *et al.* [1] combined the electrical, thermal and aging models in order to find an optimal recharging strategy. He *et al.* [2] also proposed an electrothermal model to predict the temperature of each cell in the pack. Huang *et al.* [3] developed a method to estimate the SOC of the pack from the SOC of the cells, taking into account capacity dispersion. Kim *et al.* [4] proposed a combined SOC and SOH real time estimator. However, all mentioned works present only packs with cells in series. So, the effect of current dispersion between cells in parallel cannot be studied. Other authors studied the case of cells connected in parallel. Ye *et al.* [5] compared the performance of two connection types of battery packs, whether they were connected first in parallel and then in series or first in series and then in parallel. Zhang *et al.* [6] modeled a battery pack in order to explain the impact of temperature on current unbalance. Gong *et al.* [7] investigated the influence of cell inconsistency due to heterogeneous aging in cells connected in parallel. In these three works, the authors show a concern similar to ours, i.e. the cell to cell dispersion, and they propose very relevant models to simulate it.

The main contribution of our work compared to the existing literature is an algorithm that reduces computation time. Indeed, in the mentioned works, each cell of the pack has to be simulated in detail, which is not necessarily desirable if we want to simulate a pack composed of a large number of cells and even less desirable in the perspective of implementing the pack model in real time applications. To reduce computation time, our method requires only a few cells in the pack to be simulated in detail. For all the other cells, a simplified calculation of their resistances based on their temperatures allows the current distribution to be calculated, so that we can estimate current and SOC dispersion.

In this paper, our goal is to validate the proposed method through simulation. In the future, we intend to implement it on a BMS (Battery Management System) to run it in real time. In section 2, we present the electrical model of the cell and the pack, explaining how to obtain the cell parameters as well. In section 3, we explain how to estimate the temperature distribution from a few measurement points in the pack. In section 4, we present our simulation algorithm, step by step. In section 5, we validate our method (only a few cells simulated in detail) by comparing its performances in terms of computation time and accuracy with those obtained when all the cells of the pack are simulated in detail.

## 2 Proposed modeling method

### 2.1 Cell model

The electrical behavior of the pack depends on the electrical behavior of the cells that constitute it, so the starting point for modeling the pack is modeling the cells. For that, we chose an equivalent electrical circuit model [8] (see the cell zoom in Fig. 3), composed of:

- $U_{oc}$ : a voltage source representing the OCV (open-circuit voltage), which is the voltage measured when the cell is at rest and completely relaxed;
- $R_s$ : a series resistance representing all purely resistive contributions (electrolyte, current collectors and contact resistances);
- $R_{surf}$ : a surface resistance related to the voltage drop between the surface of the active material and the electrolyte due to charge transfer and SEI (Solid Electrolyte Interphase);
- $\tau_{surf} = R_{surf} \cdot C_{surf}$ : a time constant related to the surface phenomena, which are associated with charge transfer, double layers and SEI. It represents a very quick dynamic, of the order of a few milliseconds;
- $R_{diff}$ : a diffusion resistance related to the phenomena of lithium ions diffusion in the electrolyte and lithium atoms in both electrodes;
- $\tau_{diff} = R_{diff} \cdot C_{diff}$ : a time constant related to the diffusion phenomena. It represents a slower dynamic, of the order of a few seconds or minutes.

All these parameters are obtained from previously determined look-up tables as a function of temperature, SOC and current.

#### 2.1.1 Parameters identification

To identify the look-up tables, two tests were performed:

- **EIS (Electrochemical Impedance Spectroscopy)**: consists in applying a sine current wave to the cell and measuring its voltage variation in order to compute its impedance [9].

- Frequencies: 10 kHz to 10 mHz
- Current : sinus with a peak value of  $\pm 500mA$
- SOC: 100% to 0%, every 10%
- Temperatures: 0°C, 10°C, 25°C, 50°C

• **GITT (Galvanostatic Intermittent Titration Technique)**: combines transient and steady-state measurements, by applying small current steps followed by a relaxation period [10].

- Current : +1C, +C/2, -1C, -3C, -5C
- SOC: 100% to 0%, every 10%
- Temperatures: 0°C, 10°C, 25°C, 50°C

From EIS tests, we directly identify  $R_{surf}$  at a near-zero current and  $R_s$ , which is assumed not to depend on the current, as shown in Fig. 1.

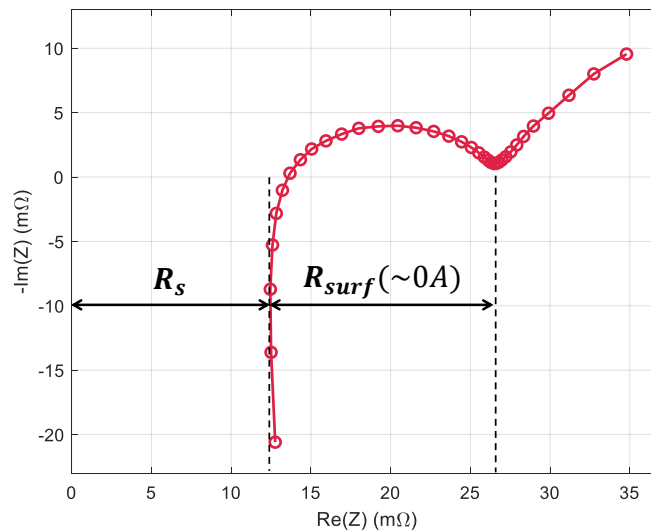


Figure 1: Parameters identification from EIS test

From GITT tests, we directly identify  $U_{oc}$ , which is the voltage when the cell is relaxed. Once  $U_{oc}$  is identified, we fit the voltage response to obtain the surface and diffusion parameters ( $R_{surf}$ ,  $\tau_{surf}$ ,  $R_{diff}$ ,  $\tau_{diff}$ ). Fig. 2 shows the GITT protocol, as well as the contribution of each parameter on the voltage response.

## 2.2 Pack model

The pack is modeled as shown in Fig. 3. It presents  $n_p$  cells in parallel and  $n_s$  cells in series. The cells are connected to each other by a metal strip, modeled by resistances in series with each cell. These resistances may change from cell to cell because the current has to travel different paths depending on the position of each cell.

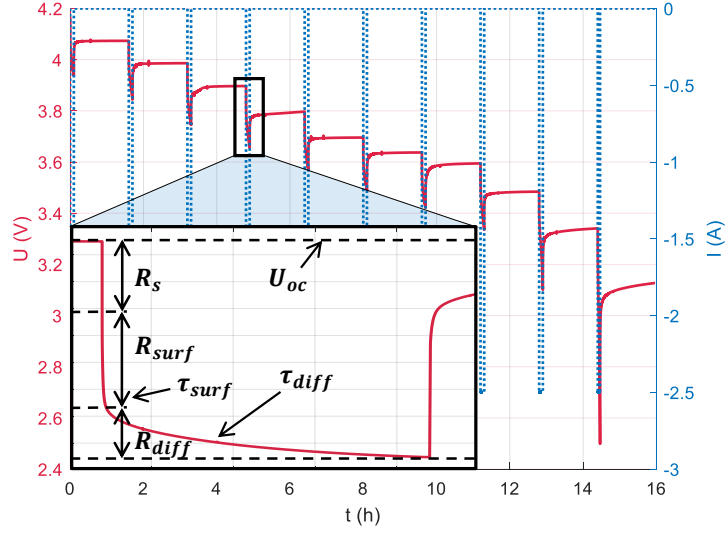


Figure 2: Parameters identification from GITT test

For the simulation of the pack model, we decided to neglect the dynamics of the surface phenomena in the cells, represented by  $\tau_{surf}$ , since they are very quick ( $< 100ms$ ) and even lower than the acquisition sampling of the pack sensors.

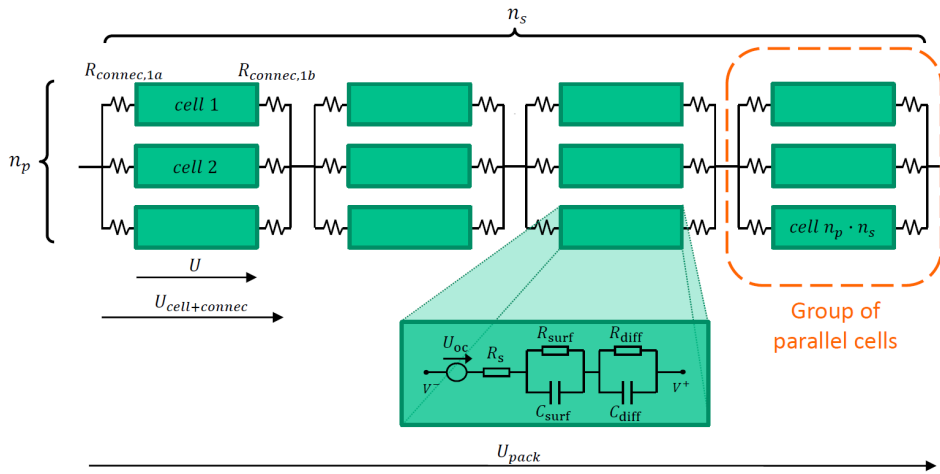


Figure 3: Cell and pack models

### 3 Estimation of the temperature of all cells from a few measurements in the pack

Our method requires a temperature input for each cell in the pack. However, only a few cells are equipped with temperature sensors. It is therefore necessary to estimate the temperatures of all the cells in the pack based on the few temperatures readings available. To do so, we make a 2D interpolation of the sensor data using the function *griddedInterpolant* on Matlab. Fig. 4 shows an example of interpolation.

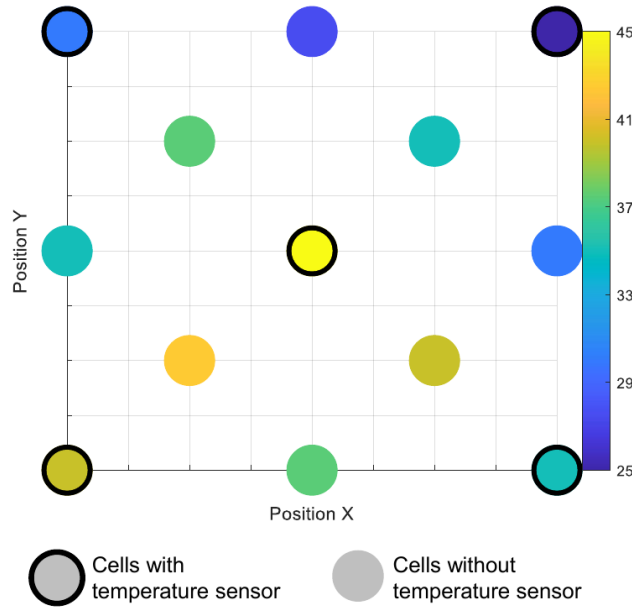


Figure 4: Example of a 2D interpolation of temperatures measured by the sensors

Once a temperature value is assigned to each cell in the pack, we calculate a vector of  $n_s \cdot n_p$  temperature ratios :

$$r_T(i, j) = \frac{T(i, j) - T_{min}}{T_{max} - T_{min}}, i \in [1, n_s], j \in [1, n_p] \quad (1)$$

Since the internal resistance of the cells decreases as temperature increases, we assume that a resistance ratio can be defined as follows:

$$r_R(i, j) = 1 - r_T(i, j) \quad (2)$$

At any given moment, the temperature of all the cells in the pack can then be estimated from the measurements ( $T_{ref}$ ) as:

$$T(i, j) = T_{ref, min} + r_T(i, j) (T_{ref, max} - T_{ref, min}) \quad (3)$$

During experimental tests, we found that the hottest cell at a given moment tended to remain the hottest throughout the test and was also the hottest or second hottest during other tests. The same was found for the coldest cells. Based on this observation, we assumed that the temperature ratios  $r_T$  remained constant throughout the mission profile, i.e. the hottest cell is always the hottest, the coldest

is always the coldest and the temperatures of all cells change at the same rate. This assumption allows the temperature ratios to be calculated only once, in a pre-simulation step, which reduces the calculation time. However, if one wishes to be more precise and take into account the different heating and cooling dynamics of the cells, it is also possible to perform a temperature interpolation every few seconds or minutes.

## 4 Simulation algorithm

Once a temperature ratio  $r_T$  has been assigned to each cell, the algorithm presented in the end of this section is used to compute the current and the SOC of each cell.

Through step 1, we obtain the highest and lowest cell resistances. In step 2, we obtain the total resistance (internal resistance plus connection) related to each cell in the pack by using the ratios calculated in (2), their temperature with the ratio determined in (1) and the temperature measurements ( $T_{ref}$ ), as well as their OCV. In step 3, we simulate in detail one cell per group of parallel cells, which is necessary to calculate the pack voltage and current in step 4. To have a good estimation of the global behavior of the pack, we recommend choosing the cells to be simulated in detail so that their temperature distribution is representative to that of all the cells in the pack. In step 5, we use the total resistances and the OCVs from step 2 and the pack current from step 4 to calculate the current distribution within each group of parallel cells and update the SOC of each cell in the pack.

The equations of the equivalent open-circuit voltage  $U_{oc,eq}$  and the cell current  $I$  in step 5 were presented by Juston [11, p. 31-34]. The calculation of the current at cell level must take into account not only the distribution of the pack current between the cells in parallel according to their resistances, but also the effect of rebalancing between the cells, which is present even in the absence of external current.

### STEP 1: Obtain highest and lowest cell resistances.

$$R_{max} = f(T_{min}, I_{min}, SOC_{max})$$

▷ From look-up tables

$$R_{min} = f(T_{max}, I_{max}, SOC_{min})$$

▷ From look-up tables

▷  $R_{max/min}$  is the sum of  $R_{s,max/min}$ ,  $R_{surf,max/min}$  and  $R_{diff,max/min}$

### STEP 2: Estimate one global resistance for each cell and its connections. Estimate its temperature and its OCV.

**for**  $i = 1, n_s$  **do**

**for**  $j = 1, n_p$  **do**

        ▷ Index  $t-1$  indicates the previous time step

$$R(i, j) = R_{min} + r_R(i, j) \cdot (R_{max} - R_{min}) + R_{connec}(i, j)$$

$$G(i, j) = 1/R(i, j)$$

$$T(i, j) = T_{ref,min} + r_T(i, j) \cdot (T_{ref,max} - T_{ref,min})$$

$$U_{oc}(i, j) = f_{U_{oc}}(T(i, j)_{t-1}, SOC(i, j)_{t-1})$$

**end for**

**end for**

### STEP 3: For one cell per group, calculate its resistance and voltage in detail.

$$selectedCells = [cell_{group1}, \dots, cell_{groupn_s}]$$

**for**  $i = selectedCells$  **do**

$$\begin{aligned}
R_s(i) &= f(T(i)_{t-1}, SOC(i)_{t-1}) \\
R_{surf}(i) &= f_{R_s}(T(i)_{t-1}, I(i)_{t-1}, SOC(i)_{t-1}) \\
R_{diff}(i) &= f_{R_{diff}}(T(i)_{t-1}, I(i)_{t-1}, SOC(i)_{t-1}) \\
\tau_{diff}(i) &= f_{\tau_{diff}}(T(i)_{t-1}, I(i)_{t-1}, SOC(i)_{t-1}) \\
U_{diff}(i) &= U_{diff}(i)_{t-1} \left(1 - \frac{\Delta t}{\tau_{diff}(i)}\right) + R_{diff}(i)I(i)_{t-1} \left(\frac{\Delta t}{\tau_{diff}(i)/R_{diff}(i)}\right) \\
U(i) &= U_{oc}(i) + (R_s(i) + R_{surf}(i)) \cdot I(i)_{t-1} + U_{diff}(i) \\
U_{cell+connec}(i) &= U(i) + R_{connec}(i) \cdot I(i)_{t-1}
\end{aligned}$$

**end for**

**STEP 4: Calculate pack voltage and current.**

$$\begin{aligned}
U_{pack} &= \sum_{i=1}^{n_s} U_{cell+connec}(i) \\
I_{pack} &= P_{pack}/U_{pack}
\end{aligned}$$

▷  $P_{pack}$  is an input

**STEP 5: Calculate the current and the SOC of each cell.**

**for**  $i = selectedCells$  **do** ▷ Each group of parallel cells

$$U_{oc,eq}(i) = \frac{\sum_{k=1}^{n_p} U_{oc}(i,k) \cdot G(i,k)}{\sum_{k=1}^{n_p} G(i,k)}$$

**for**  $j = 1, n_p$  **do** ▷ Each cell in the group

$$I(i, j) = I_{pack} \cdot \frac{G(i,j)}{\sum_{k=1}^{n_p} G(i,k)} + G(i, j) \cdot (U_{oc,eq}(i) - U_{oc}(i, j))$$

▷  $G = 1/R$

$$SOC(i, j) = SOC(i, j)_{t-1} + I(i, j) \cdot \frac{\Delta t}{3600}$$

**end for**

**end for**

## 5 Validation

### 5.1 Experimental and simulation setup

We validated the proposed method using a battery pack (see Fig. 5) composed of 66 Samsung 18650-25R cylindrical cells (NCA+NMC/graphite+SiO, nominal capacity of 2.5 Ah, nominal voltage of 3.6 V). The pack is equipped with voltage sensors at the terminals of each cell and on the metal strips connecting the cells (one per group of cells in parallel, measuring the voltage over the cells and the connection resistance) and 18 temperature sensors on cells distributed over different areas of the pack. Although there is not an ideal number of sensors, there should be enough to measure extreme temperatures. In our case, it is the center for the hottest cells and the edges for the coldest. Other sensors are distributed over intermediate areas. To allow for good interpolation of the measurements, as described in section 3, it is better to scatter the sensors instead of aligning them.

For charging and discharging the pack, we used a power emulator composed of a power supply Regatron TCP 32.200.400S with 32 kW and an electronic load H&H ZS21030 with 21 kW. Both were connected to a dSPACE system, that sends the control input to the emulator and gathers the output values.

The results of the experimental tests were then used as a reference for our simulations. These simulations were performed on Matlab 2021a with the following PC configuration:

- Operating system: Windows 10 Pro
- Processor: Intel Core i5-7300U (base frequency of 2.60 GHz)



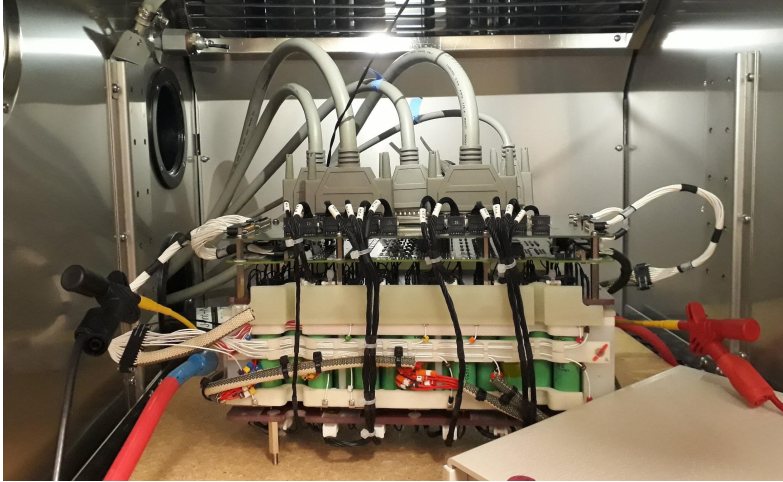


Figure 5: Battery pack

- RAM: 8 GB
- Disk: 256 GB

## 5.2 Simulation results

To validate the performances of our method, the pack was submitted to the mission profile of an aircraft presented in Fig. 6. This profile represents the following phases of the flight of a VTOL (vertical take-off and landing) aircraft: (1) ground, (2) climb, (3) hover, (4) cruise, (5) hover, (6) descent and (7) ground.

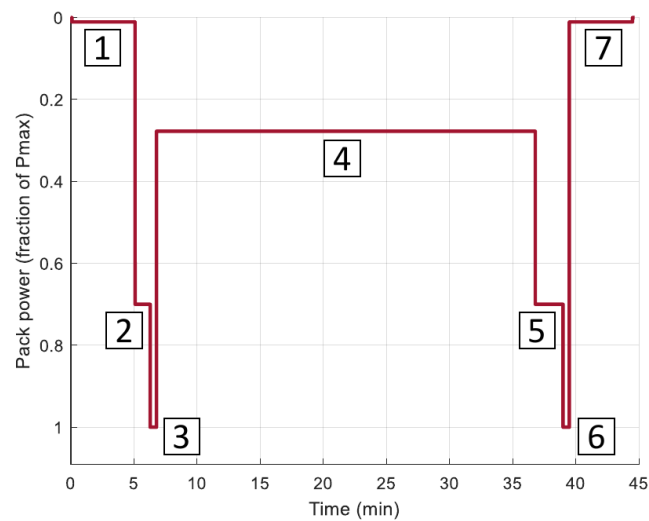


Figure 6: Validation profile

Three indicators are used to evaluate the performance of our method:

- The ability to correctly estimate **current and SOC dispersion**. The reference is the method where each cell is simulated in detail.
- The ability to correctly estimate the **voltage** (cells and pack). The reference is the measured voltage.
- The required **computation time**. The reference is the method where each cell is simulated in detail.

### 5.2.1 Current and SOC dispersion

Cell current and SOC cannot be directly measured. However, we need a reference to judge the consistency of our method. For this reason, we simulated the mission profile in Fig. 6 with two methods:

1. A **full model**, where all cells are simulated in detail (as presented in step 3 of our algorithm) to have maximum accuracy.
2. A **reduced model**, the method we propose in the present paper, where only one cell per group of cells in parallel is simulated in detail and all others are simulated using approximations of their resistance as a function of the temperature distribution.

Fig. 7a and 7b show the current and the SOC, respectively, simulated for each cell in the pack with both models. Considering the full model as the reference, the comparison between the two models leads to a RMSE (Root Squared Mean Error) of 102 mA for a current dispersion going up to 2500 mA, and a RMSE of 3.3 mAh for a SOC dispersion going up to 160 mAh. There is a good consistency between the two models, which shows that we can use the reduced model to obtain very similar results to what we could obtain with a more detailed but time-consuming model (see "*Computation time*" in the end of this section).

### 5.2.2 Accuracy of voltage estimation

Another performance indicator that is very important to evaluate our method is voltage, since it is the only indicator that can be compared to experimental measurements. Fig. 8a presents the measurements and simulated values of the voltages over the cells and the connection resistances ( $U_{cell} + U_{connec}$ ), showing a good consistency between simulation and measurements for both full and reduced models.

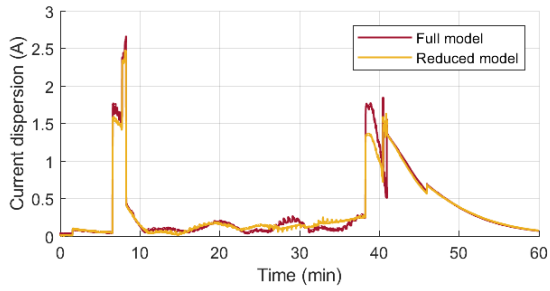
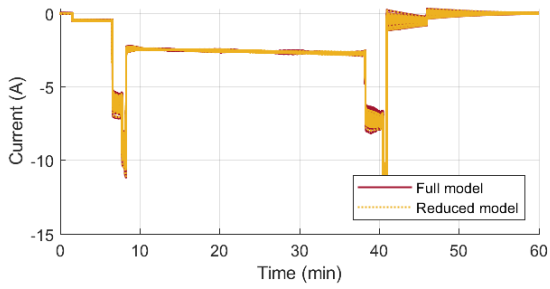
To compare the estimation errors of the two models, we can compare the measured and simulated pack voltages. Fig. 8b shows that the accuracy of the model is preserved, since the voltage errors obtained with the reduced model are very close to the errors obtained with the full model.

### 5.2.3 Computation time

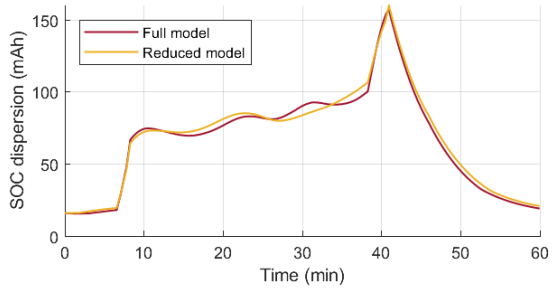
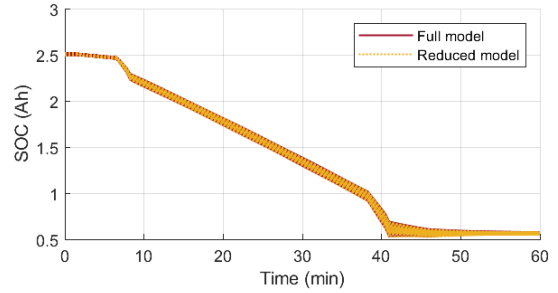
The simulation with the full model took 7.2 seconds to run, while it took only 2.9 seconds with the reduced model, a 60% reduction in computation time.

## 6 Conclusion

In this paper, we proposed a method to estimate the dispersion of current and SOC among all the cells of a battery pack, taking into account the temperature measured in different zones of the pack. First, we estimated the temperature of all cells in the pack from measurements of a few sensors. Then, we simulated in detail one cell per group of parallel cells to have an accurate estimation of pack voltage. To

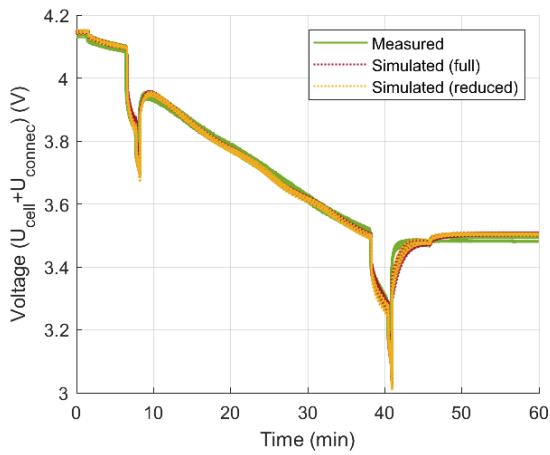


(a) Cell current

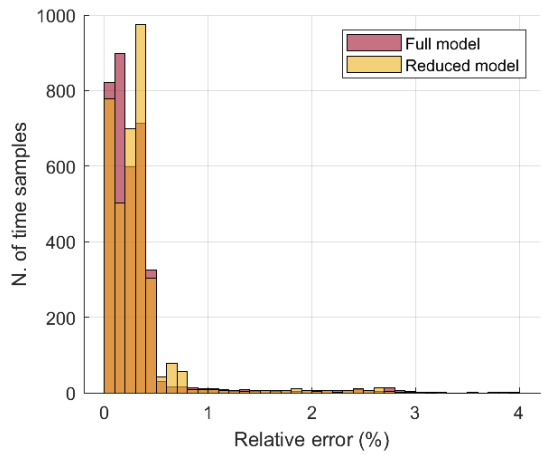


(b) Cell SOC

Figure 7: Simulation results : current and state of charge



(a) Cell voltage: simulation results and measurements



(b) Model errors (pack voltage)

Figure 8: Simulation results : voltage

avoid a detailed simulation of each cell in the pack, which can be very costly in terms of computing time, we used a simplified calculation of their resistances based on their temperatures to estimate their current and SOC.

Our method reduces computation time by 60% compared to the case where all cells are simulated in detail, while preserving the accuracy of the model.

The next step would be to implement the proposed model on a BMS to perform real-time estimation of current and SOC dispersion, which would improve battery safety.

## References

- [1] Y. Li, K. Li, Y. Xie, B. Liu, J. Liu, J. Zheng, and W. Li, "Optimization of charging strategy for lithium-ion battery packs based on complete battery pack model," *Journal of Energy Storage*, vol. 37, 5 2021.
- [2] F. He, A. A. Ams, Y. Roosien, W. Tao, B. Geist, and K. Singh, "Reduced-order thermal modeling of liquid-cooled lithium-ion battery pack for evs and hev," pp. 507–511, IEEE Transportation Electrification Conference and Expo (ITEC), 2017.
- [3] C.-S. Huang, B. Balagopal, and M.-Y. Chow, "Estimating battery pack soc using a cell-to-pack gain updating algorithm," pp. 1807–1812, IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, 2018.
- [4] T. Kim, W. Qiao, and L. Qu, "Online soc and soh estimation for multicell lithium-ion batteries based on an adaptive hybrid battery model and sliding-mode observer," pp. 292–298, IEEE Energy Conversion Congress and Exposition, 2013.
- [5] M. Ye, X. Song, R. Xiong, and F. Sun, "A novel dynamic performance analysis and evaluation model of series-parallel connected battery pack for electric vehicles," *IEEE Access*, vol. 7, pp. 14256–14265, 2019.
- [6] Y. Zhang, R. Zhao, J. Dubie, T. Jahns, and L. Juang, "Investigation of current sharing and heat dissipation in parallel-connected lithium-ion battery packs," pp. 1–8, IEEE Energy Conversion Congress and Exposition (ECCE), 2016.
- [7] X. Gong, R. Xiong, and C. C. Mi, "Study of the characteristics of battery packs in electric vehicles with parallel-connected lithium-ion battery cells," *IEEE Transactions on Industry Applications*, vol. 51, pp. 1872–1879, 3 2015.
- [8] N. Damay, K. M. Mbeya, G. Friedrich, and C. Forgez, "Separation of the charge transfers and solid electrolyte interphase contributions to a battery voltage by modeling their non-linearities regarding current and temperature," *Journal of Power Sources*, vol. 516, p. 230617, 12 2021.
- [9] F. Huet, "A review of impedance measurements for determination of the state-of-charge or state-of-health of secondary batteries," 1998.
- [10] W. Weppner and R. A. Huggins, "Determination of the kinetic parameters of mixed-conducting electrodes and application to the system li3sb," *Journal of The Electrochemical Society*, vol. 124, 1977.
- [11] M. Juston, *Suivi du vieillissement des batteries lithium embarquées, en usage ferroviaire*. PhD thesis, Université de Technologie de Compiègne, 2021.