The 27th INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION
BARCELONA
17th-20th November 2013

# Towards advanced BMS algorithms development for (P)HEV and EV by use of a physics-based model of Li-ion battery systems


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IFPEN, Lyon


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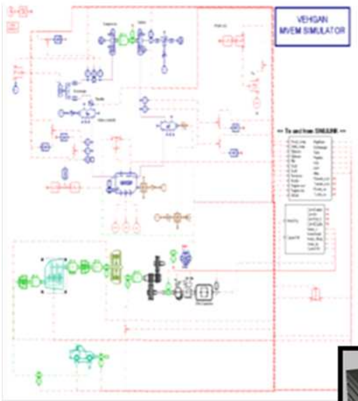
# IFPEN R&D
# Electrochemical storage system models

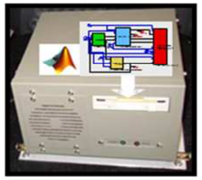
## A complete approach is developed

Vehicle and powertrain simulation

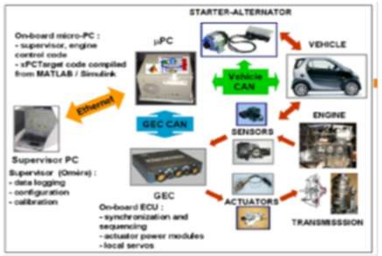
LMS AMESim



Real time simulation



Integrated powertrain control



Component testing and optimization

BMS

Energy storage system test bench

Engine test benches

Vehicle testing

Prototypes design, realization and optimization

# IFPEN R&D
# Electrochemical storage systems models

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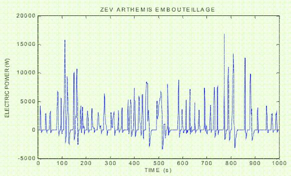
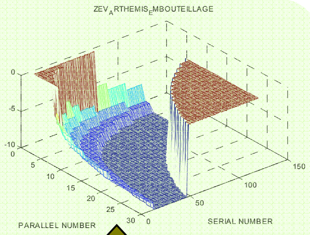
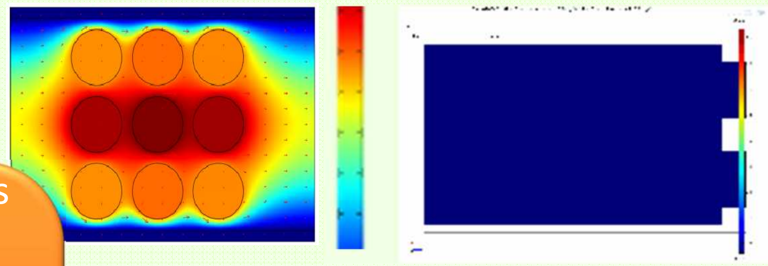
## Battery Pack Sizing



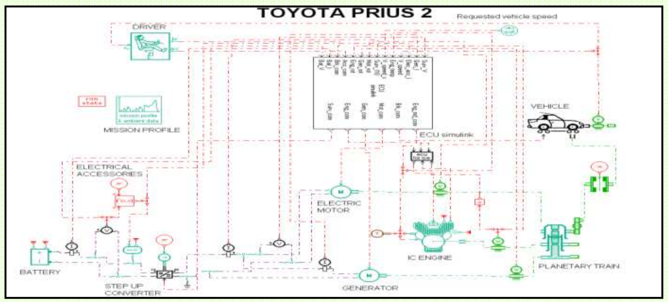

Power/Energy requirements
or vehicle mission profiles
Batch Simulations with
cell constraints
& vehicle constraints

## Thermal Management laws

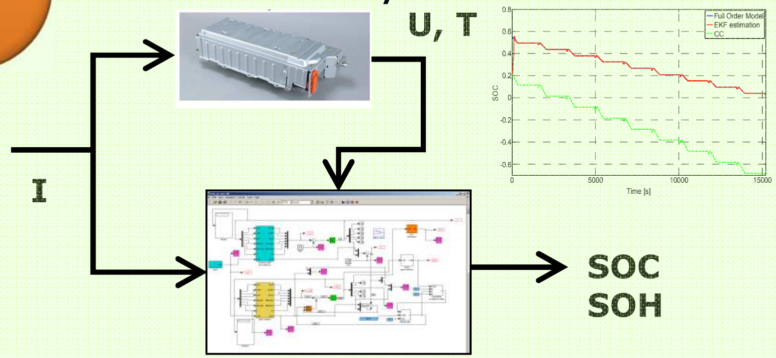


Battery and supercapacitors characterization
Multi-Physics & Multi-Dimensional Models
Electrochemical models,
Impedance-Based models
Aging

## HEV / PHEV / EV Simulators (Available LIBES sofware on AMESim)




## Model Based BMS estimators SOC / SOH

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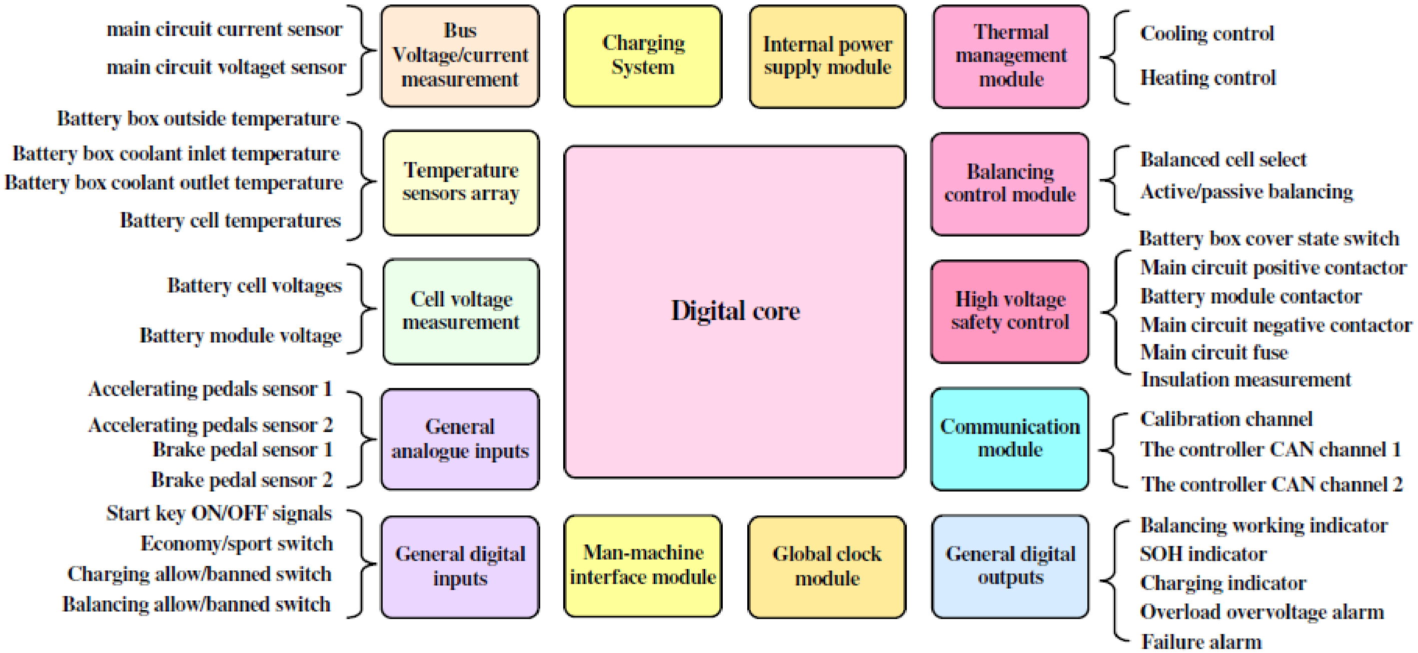
# Introduction to BMS functions

- The battery management system (BMS) has to ensure reliable and safe use of stored electrical energy onboard (P)HEV and BEV
- Different functions to monitor the battery: SOC




**➔ Herein, focus on a Battery Intensity Management Algorithm (BIMA) and the related methodology to design charge/discharge maximal intensity (CMI/DMI)**

# Outline

- I. Electrochemical and thermal model development
- II. Model calibration
- III. Model-based methodology for the design of BMS laws
- IV. Application of the methodology (P)HEV and EV BMS
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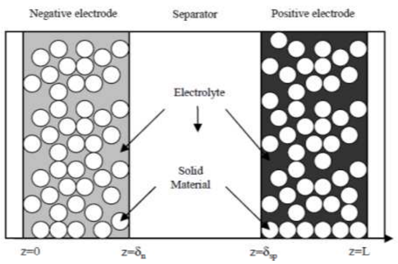
# Modified SP Electro-thermal model Prada et al. JES 2013

## Hypotheses and modeling approach




*The cell voltage (V) is expressed:*

*1) as the sum of kinetics and mass transport overpotentials in the electrodes and electrolyte*

*2) as a function of the design parameters (Porosity, Electrodes thicknesses...) and physical properties of electrodes and electrolyte (Diffusion coefficients, Electrochemical kinetics...)*

**Hypotheses and Set of Equations can be found in Prada et al. JES 159 (9) A1508-A1519 (2012), "A Simplified Electrochemical and thermal model of $LiFePO_4$-graphite Li-ion batteries for Fast Charge Applications"*

## Electrochemical sub-model

*Cell Voltage (V)*

$$V(t)=U_p\left(\frac{c^s_{s,p}}{c_{s,p,\max}}\right)-U_n\left(\frac{c^s_{s,n}}{c_{s,n,\max}}\right)$$

$$+\frac{RT}{\alpha F}\ln\left(\frac{\frac{-R_{s,p}}{6\varepsilon_{s,p}i_{0,p}A\delta_p}I+\sqrt{\left(\frac{R_{s,p}}{6\varepsilon_{s,p}i_{0,p}A\delta_p}I\right)^2+1}}{\frac{R_{s,n}}{6\varepsilon_{s,n}i_{0,n}A\delta_n}I+\sqrt{\left(\frac{R_{s,n}}{6\varepsilon_{s,n}i_{0,n}A\delta_n}I\right)^2+1}}\right)$$

$$+(1-t_+)\frac{2RT}{F}\ln\frac{c_e(L)}{c_e(0)}-\frac{I}{2A}\left(\frac{\delta_n}{\kappa_n^{eff}}+2\frac{\delta_{sep}}{\kappa_{sep}^{eff}}+\frac{\delta_p}{\kappa_p^{eff}}\right)-IR_{SEI}$$

*State of Charge of the (+) and (-)electrodes (%)*

$$\theta^s_p=\frac{c^s_{s,p}}{c_{s,p,\max}}\qquad \theta^s_n=\frac{c^s_{s,n}}{c_{s,n,\max}}$$

*State of Charge of the battery (%)*

$$SOC_{bat}=100\times\left(\frac{\theta^b_n-\theta^b_{n,0\%}}{\theta^b_{n,100\%}-\theta^b_{n,0\%}}\right)$$

## Thermal sub-model

$$\frac{dT_{skin}}{dt}=\frac{1}{mC_p}\left(Q_{irrev}+Q_{rev}-q_n\right)$$ *Energy Balance*

$$Q_{irrev}=-\left(V-(U_p-U_n)\right)I$$ *Irreversible Thermal power (W)*

$$Q_{rev}=-T_{skin}\frac{d\left(U_p-U_n\right)}{dT}I$$ *Reversible Thermal power (W)*

$$q_n=h_{conv}S_{cell}\left(T_{skin}-T_{cooling}\right)$$ *Exchange Thermal power (W)*

$$T_{centre}=T_{skin}\left(1+\frac{h_{conv}S_{cell}}{\lambda_{cell}r_{cell}}\right)-T_{cooling}\frac{h_{conv}S_{cell}}{\lambda_{cell}r_{cell}}$$ *Internal temperature (K)*

## Modified SP Electro-Thermal model OUTPUT

*Cell Voltage (V)*

*$SOC_{bat}$ (%)*

*$T_{skin}$ (K)*

*$T_{centre}$ (K)*

*A123 Systems Cell, 2,3 Ah*

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# Model calibration

- The Li-ion battery cell is a NCA/C
- The nominal capacity is 41Ah
- The cell is a mixed-typology for PHEV-EV


| | Voltage (V) | Temperature (°C) |
|---|---|---|
| Maximum | 4.1 | 60 |
| Minimum | 2.7 | -25 |

- Most of electrochemical and thermal model parameters are taken from literature data. Mass transport parameters are adjusted based on experimental tests

- Simulation results between experimental and model prediction at different continuous discharge rates (From manufacturer datasheet)

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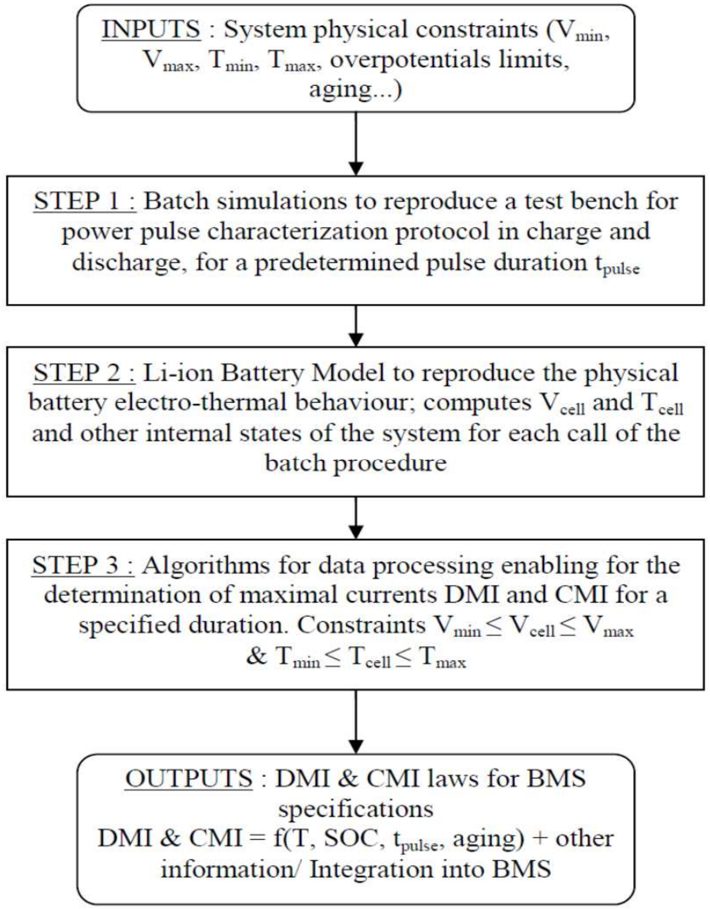
# Model-based methodology (1/2)

- Model-based methodology to design the allowable maximal charge and discharge current intensities (CMI & DMI)
- The battery electrochemical and thermal model is used as a virtual system to streamline experimental tests.
- The inputs are the cell voltage $V_{cell}$ and temperature $T_{cell}$ constraints (from manufacturer datasheet)

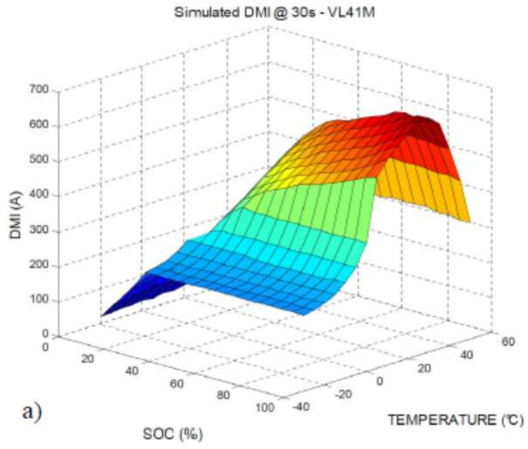
| | Voltage (V) | Temperature (°C) |
|---|---|---|
| Maximum | 4.1 | 60 |
| Minimum | 2.7 | -25 |

- Simu… Disc… & CMI) for a specified pulse duration

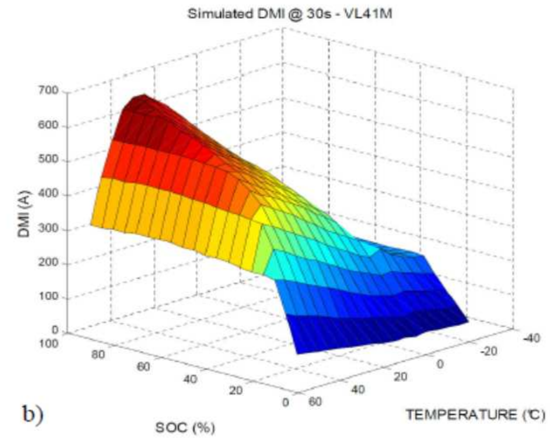


# Model based methodology (2/2)

- Results of the Model-based methodology to design the allowable maximal charge and discharge current intensities
- For a given pulse duration, the output is a map representing maximal intensity as a function of SOC and T.
- The map shows different zones:
  - Voltage-induced limitation between 5° C and 35° C due to solid-state diffusion mechanism
  - Intensity-induced limitation above 35° C due to thermal constraints
  - Intensity-induced limitation below 5° C due to electrolytic-phase diffusion mechanism



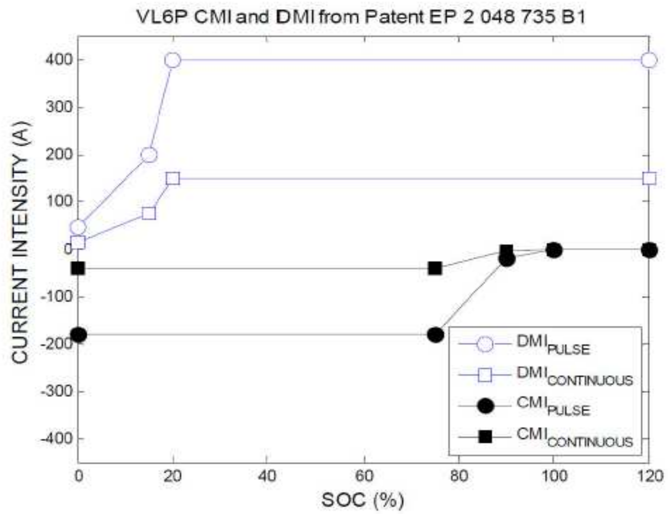
a)

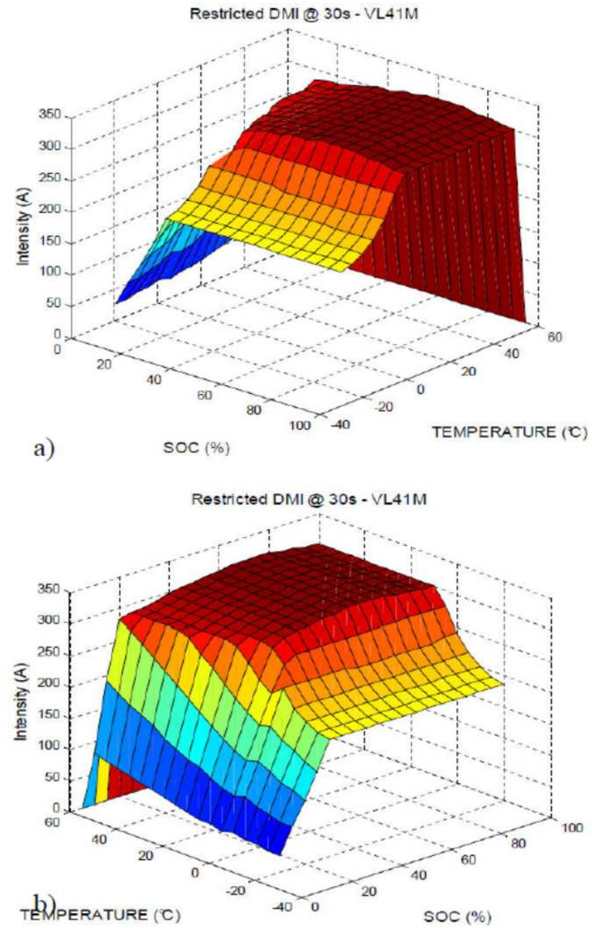


b)

# Comparison with the manufacturer specifications

- For (P)HEV & BEV BMS, the simulations results are compared with the manufacturer specifications (for another Li-ion cell)




- Presence of current plateaus as well
- By restricting the map at 55° C values, one can observed similar trends as a function of SOC
- Conservative option of the manufacturer?

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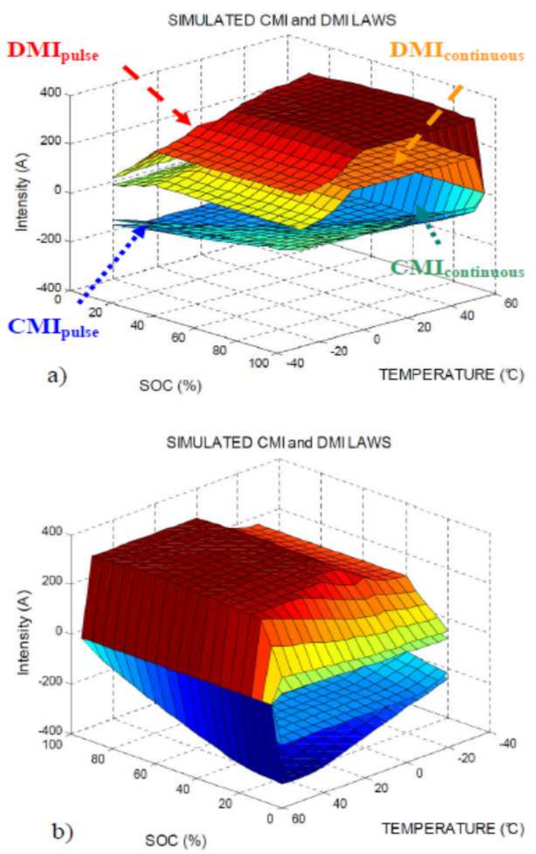
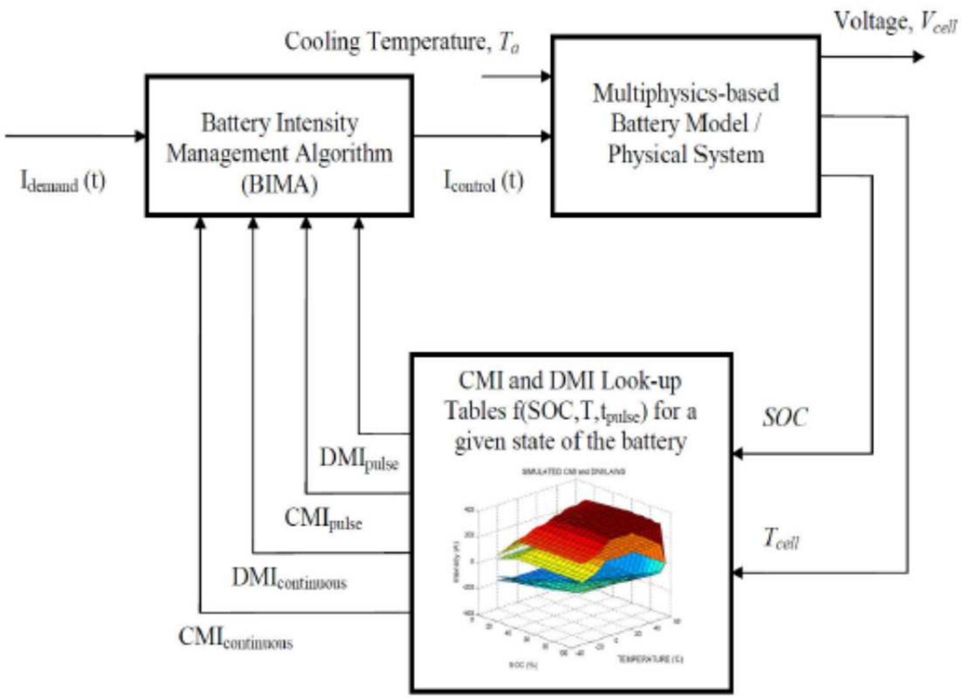
# Application of the methodology for (P)HEV & EV

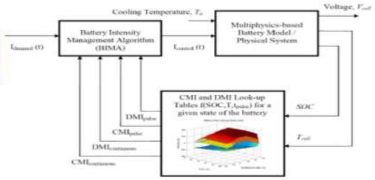
- Design of restricted DMI and CMI laws for pulse and continuous operations




- Design of a BIMA controller fed by the DMI and CMI maps

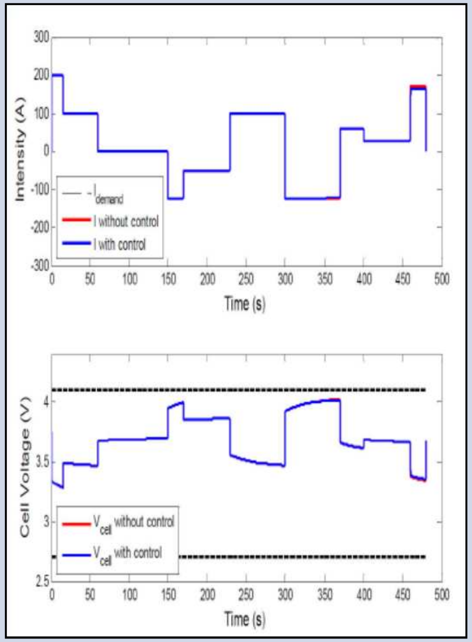
# Numerical validation of the BIMA



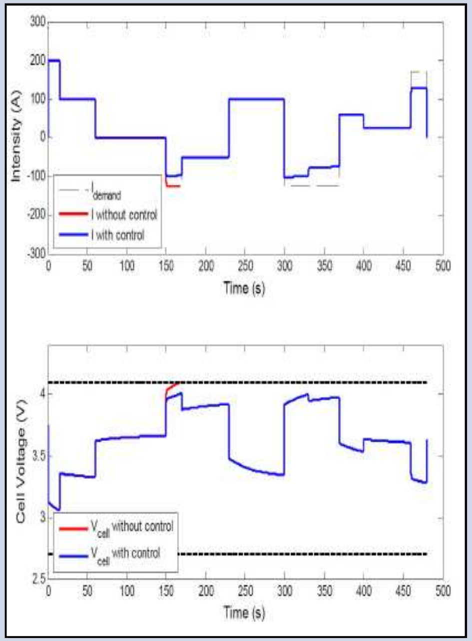
- Four cases are proposed to simulate different battery operations and to test the BIMA
- The demanded intensity is represented in dashed line, the intensity without control is in red line and the controlled intensity is in blue line.

| Simulation Case | Initial SOC (%) | Initial Temperature (°C) |
|---|---|---|
| N°1 | 70 | + 35 |
| N°2 | 70 | - 5 |
| N°3 | 10 | + 35 |
| N°4 | 100 | + 35 |

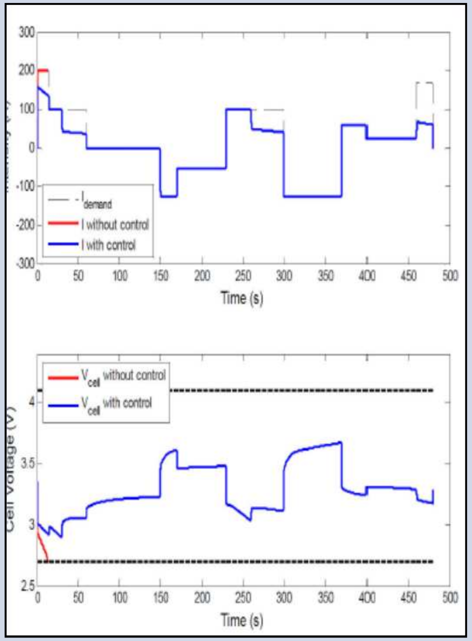
## Nominal case



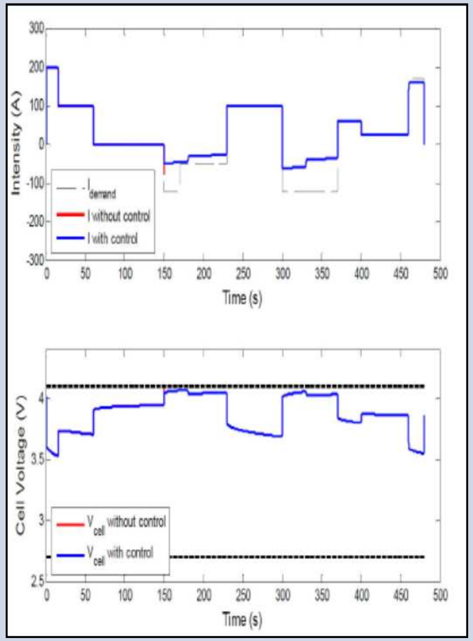

## Cold Battery




## Depleted Battery




## Fully charged Battery



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# Conclusions and perspectives

- A model-based methodology to design the maps of allowable charge and discharge currents (CMI/DMI) for Li-ion batteries is presented and used for (P)HEV and BEV
- The methodology allows for a rapid prototyping of CMI and DMI laws based on a simplified electrochemical and thermal model
- The CMI and DMI maps feed a Battery Intensity Management Algorithm that is numerically tested and validated for different case studies.
- Future work will deal with the integration of aging adaption within the preliminary BIMA presented herein

➔ **Need of a generic multi-physics (electrochemical, thermal, mechanical) and multi-chemistry aging model for Li-ion technologies to extend the methodology**

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Feel free to contact us for any questions and for the upcoming AGIL(ES)$^2$ Consortium*!


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* AGIL(ES)$^2$ : AGing modeling of Industrial Li-ion Electrochemical Energy Storage Systems

# Thank you for your attention

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