Li-ion battery models for HEV simulator

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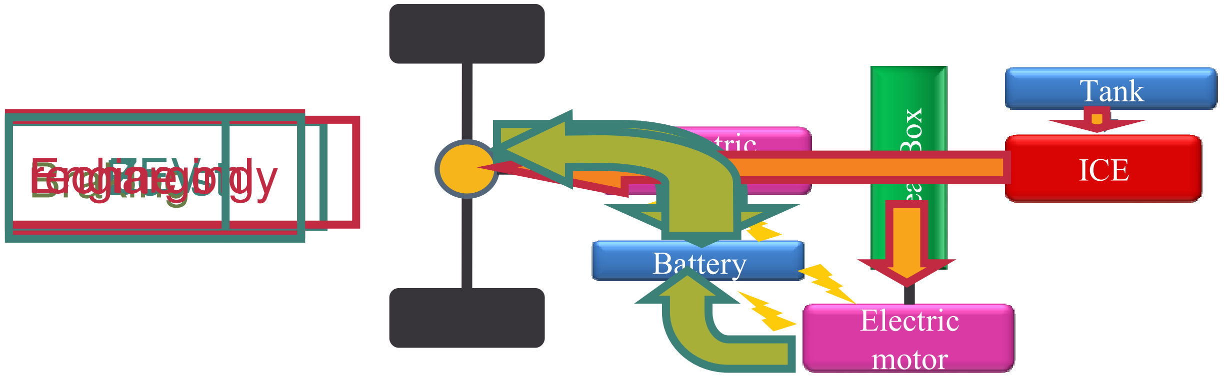
Contents

INTRODUCTION

- **Hybrid Electrical Vehicle is a solution to consume less fuel**
  - How can a hybrid vehicle consume less fuel?
    - By Downsizing the internal combustion engine (with the same performances)
    - By turning-off the engine when the vehicle is stopped (Start & Stop)
    - By optimizing the energy distribution between the sources



    - By recovering a part of the kinetic energy during deceleration

Energy Management

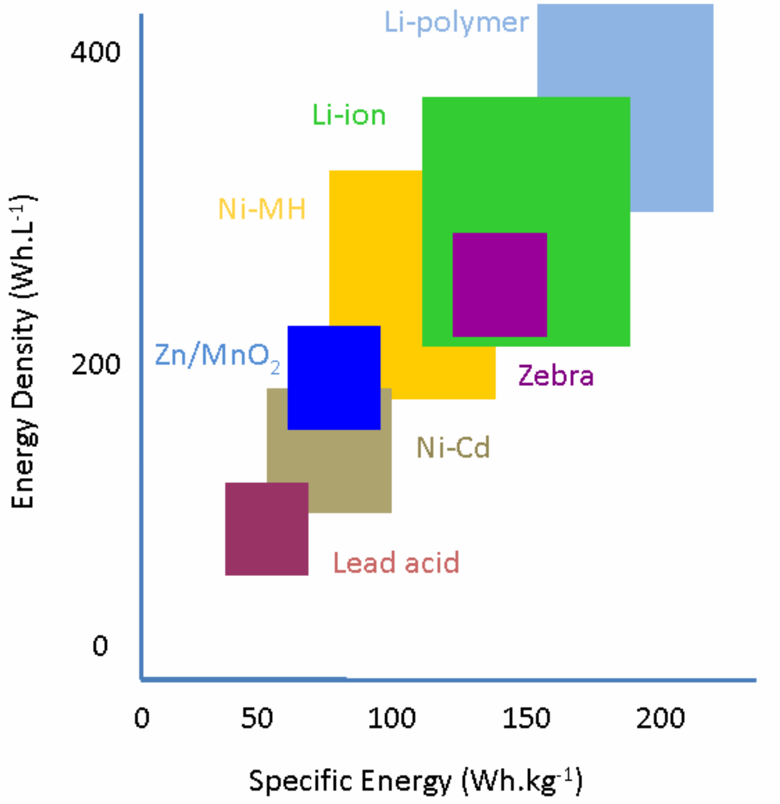
  - Drawback of this technology
    - The additional cost
    - The additional weight

INTRODUCTION

- **Simulation is useful for the Energy Management development**
  - The energy management performances are tested and compared in simulation
  - Some of these Energy management uses Battery State Of Charge (SOC)
- **HEV simulator requirement**
  - Good battery behaviour prediction
  - Reasonable time of simulation
  - Quick adaptation for different cells (constant innovation in cells technology)

INTRODUCTION

- **Why Li-ion?**
  - Li-ion has high Energy density
  - Li-ion has high Specific Energy*
  - Li-ion has no memory effect
  - Li-ion has a low self-discharge rate



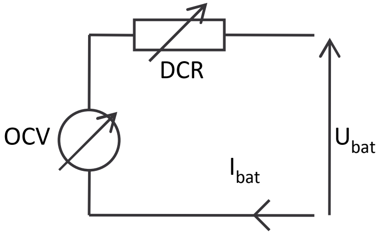
* i.e. : Gasoline has a Specific Energy of 13 kWH/kg

Batteries Models

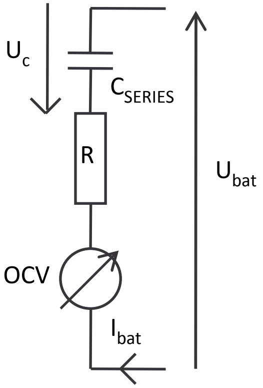
- **Usually transformed into equivalent circuit**
  - Overview of battery modeling for HEV simulator & thermal aspect
    - L.Guzzella A.Sciarretta, *Vehicle propulsion systems.*
  - Quasistatic modeling
    - VH. Johnson, *Battery performances in ADVISOR.*
  - Overview of battery dynamics
    - A. Jossen, *Fundamentals of battery dynamics.*
  - Dynamic modelling
    - A. Capel *Mathematical model for the representation of the electrical behaviour of a lithium cell.*
    - E. Kuhn, C. Forgez, P. Lagonotte, G. Friedrich, *Modelling Ni-mH battery using Cauer and Foster structure.*
    - *S. Buller, M. Thele, R. De Doncker, W. Karden, Impedance-based non-linear dynamic battrey modeling for automotive applications.*
- **Electrochemical models**
    - L.Guzzella A.Sciarretta, *Vehicle propulsion systems.*
- **Black box model**
- **Thermal Aspect**
    - A. Pesaran, *A Battery thermal models for hybrid vehicle simulations.*
    - N. Sato *Thermal behavior analysis of lithium-ion batteries for electric and hybrid vehicles.*

BATTERIES MODELS

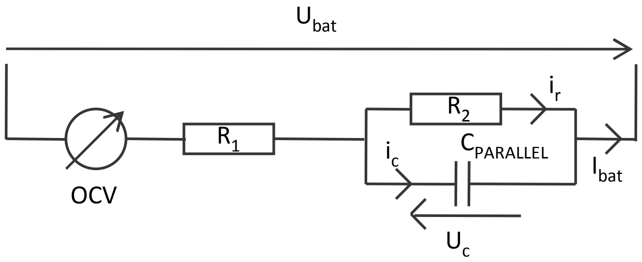
- **Three models tested**



R_{INT}



RC_{SERIES}



$RC_{PARALLEL}$

  - Battery State of Charge

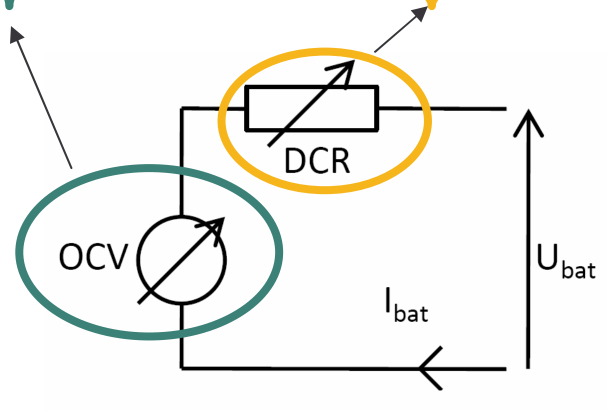
$$SOC(t) = \frac{1}{Q_{max}.NbCparallel} \int_0^t -I^*_{bat}(\tau)d\tau + SOC_{ini}$$

$$I^*_{bat}(t) = \begin{cases} I_{bat}(t) & \text{si } I_{bat}(t) >= 0 \\ \eta(SOC)I_{bat}(t) & \text{si } I_{bat}(t) < 0 \end{cases}$$

BATTERIES MODELS

- **R_{INT} model**

$$U_{bat}(t) = \underbrace{OCV(SOC(t))} - \underbrace{DCR(SOC(t), sign(I_{bat}))}.I_{bat}(t)$$



OCV: non linear function of battery State of charge

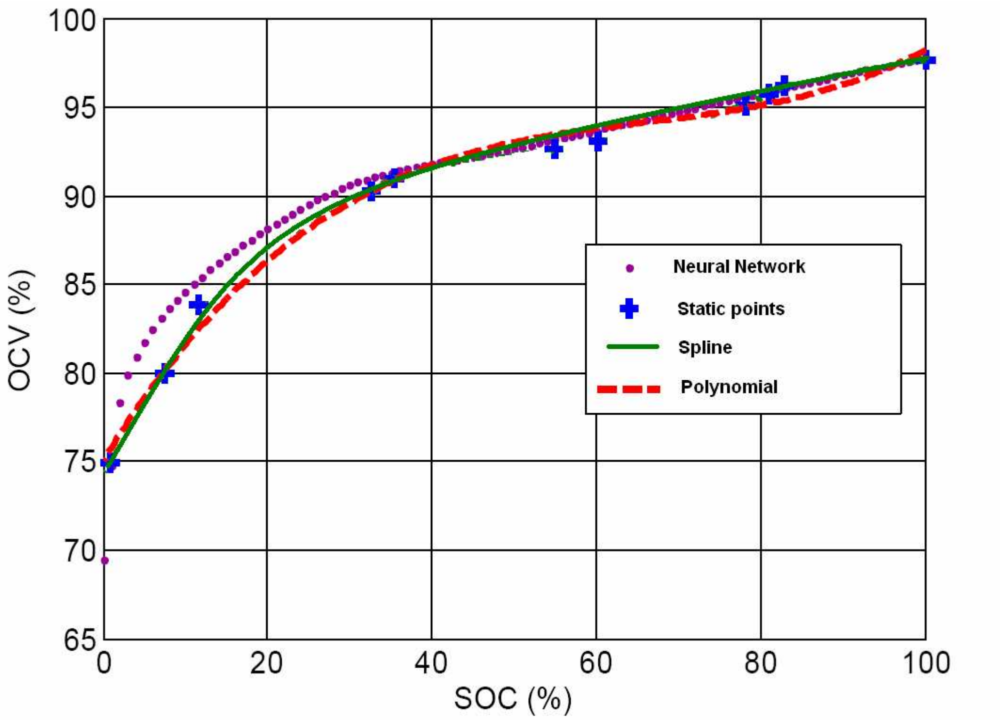
DCR: non linear function of battery State of Charge which is different in case of charge or discharge

BATTERIES MODELS

- ***Open Circuit Voltage (OCV)***
  - Polynomial fitting
    - On static points
  - Spline
    - On static points
  - Neural Network
    - Perceptron with one hidden layer
    - Sigmoïde for input layer
    - Linear for output layer

↓

$$\begin{cases} U_{bat} = f_{NN}(I_{bat}, SOC) \\ OCV = f_{NN}(0, SOC) \end{cases}$$



For confidential reasons battery cells voltage is normalised with respect to its maximum value (in %)

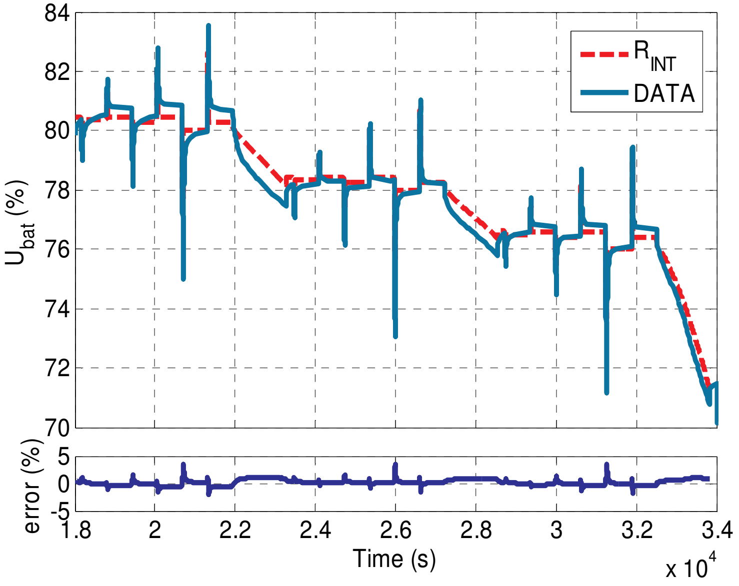
Batteries Models

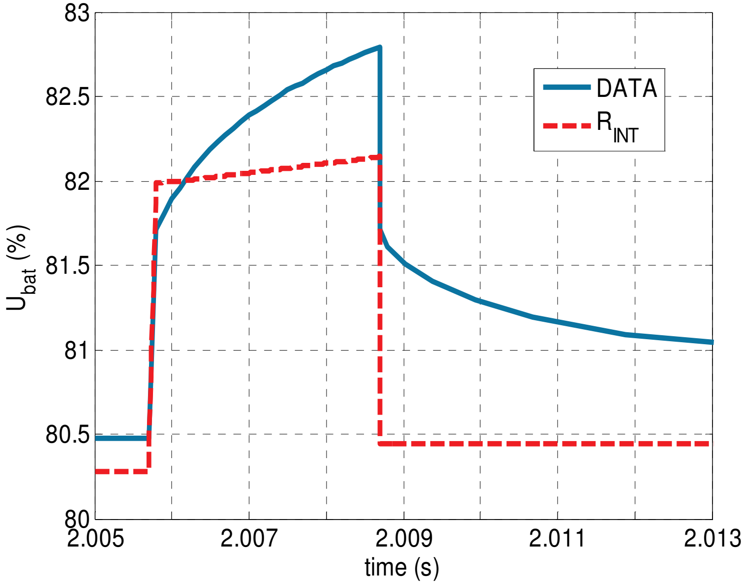
- **R_{INT} model results**
  - FIT criterion (evaluation of the correlation between model prediction and battery behaviour

$$FIT = 100.\left(\frac{1 - \|Y - Y_s\|}{\|Y - \overline{Y}\|}\right)$$

FIT= 85% (identification)

***FIT*= 79,3% (validation)**



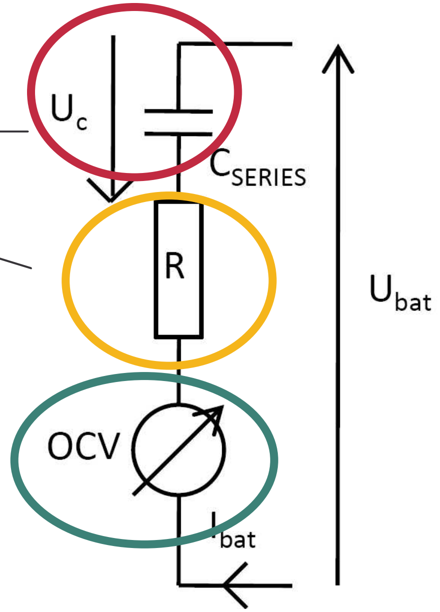


  - **Quasi-static model**

Batteries Models

- **RC$_{SERIES}$ model**

$$U_{bat}(t) = \underbrace{OCV(SOC(t))}_{} - \underbrace{R}_{}.I_{bat}(t) - \underbrace{U_c(t)}_{}$$



$$\left\{\begin{aligned} & U_c(t) = \begin{cases} sat_{max} & \text{if } X > sat_{max} \\ sat_{min} & \text{if } X < sat_{min} \\ X & \text{else} \end{cases} \\ & X = \int_0^t \frac{I_{bat}}{C_{SERIES}} dt \end{aligned}\right.$$

OCV: non linear function of battery State of charge

R: Constant which is different in case of charge or discharge

C$_{SERIES}$: Constant which is different in case of charge or discharge

Batteries Models

- **RC_{SERIES} models identification**

  6 undetermined parameters : $C_{SERIES}(ch/disch)$, R *(ch/disch)*, sat_{min}, sat_{max}

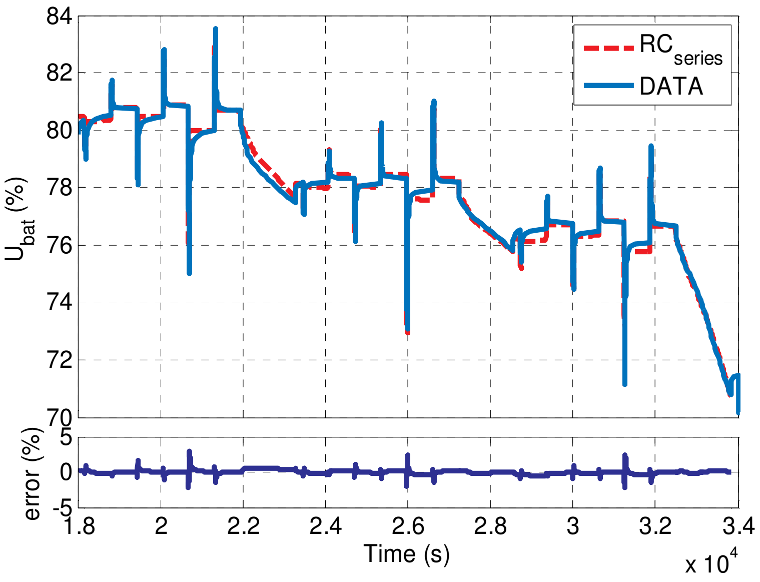
  A simplex algorithm find the solution which minimises the criterion :

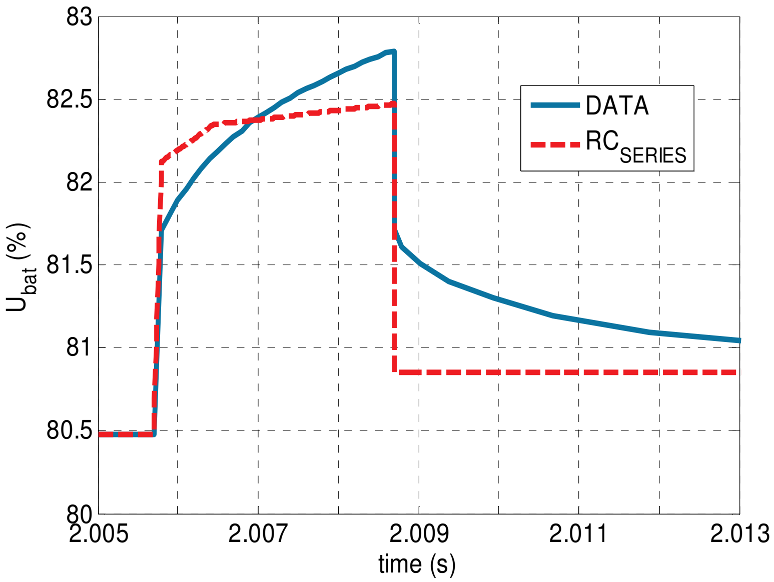
$$J = (100 - FIT)^2$$

- **RC_{SERIES} results**

FIT= 89.6%
(identification)

***FIT*= 89.5%**
(validation)



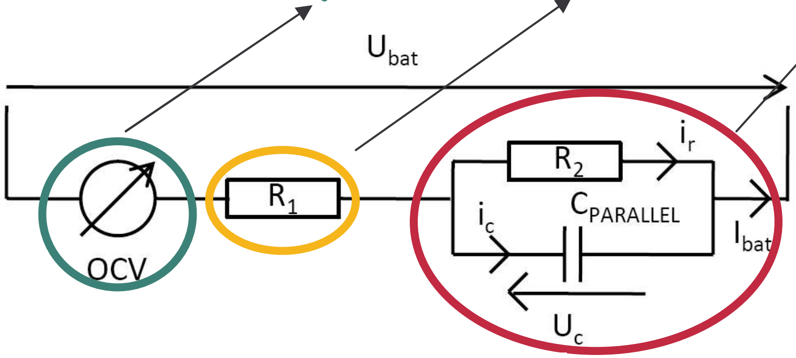


- **Non physical behaviour (due to the saturation)**

Batteries Models

- **$RC_{PARALLEL}$ models**

$$U_{bat}(t) = \underbrace{OCV(SOC(t))}_{} - \underbrace{R_1}_{}.I_{bat}(t) - \underbrace{U_c(t)}_{}$$

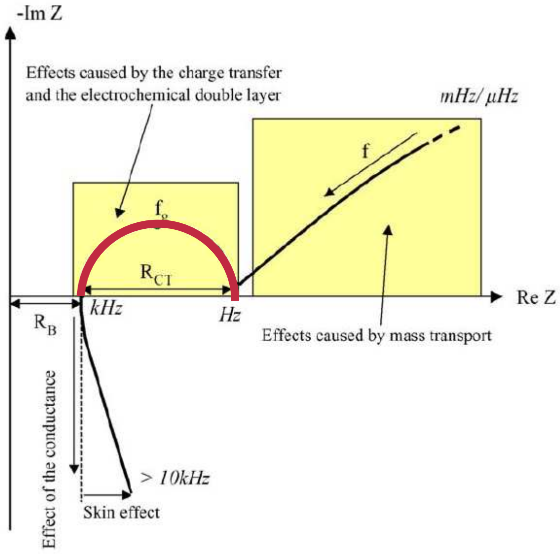


$$U_c(s) = \frac{R_2.I_{bat}(s)}{R_2.C_{PARALLEL}.s + 1}$$

$R_{1,}R_2$: Constant

C_{SERIES}: Constant

OCV: non linear function of battery State of charge



A. Jossen. Fundamentals of battery dynamics. *Journal of power sources,*

Hz < **Good behaviour** < kHz

Batteries Models

- **$RC_{PARALLEL}$ Identification**
  - Problem formulation
    - Normalisation
      - I_{bat}, *SOC* are centred around 0 and $\Delta U_{bat}(t) = U_{bat}(t) - OCV(t)$
    - New equation

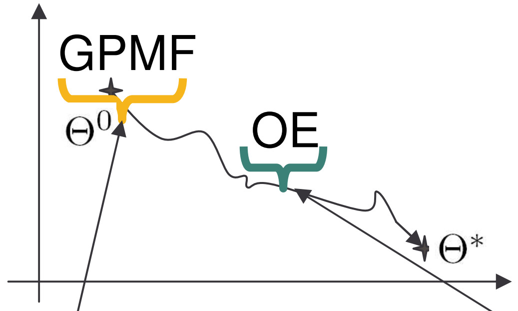
$$\Delta U_{bat} = Z.(SOC(t)) - (R_1 + Z_{rc}).I_{bat}(t)$$

$$\Delta U_{bat}(s) = \underbrace{Z(s)}.SOC(s) - \underbrace{\frac{C_{PARALLEL}.R_1.R_2.s + R_1 + R_2}{1 + C_{PARALLEL}.R_2.s}}.I_{bat}(s)$$

Continuous parametric model of type 'output error'

$$\Delta U_{bat}(s) = \overbrace{\underbrace{\frac{B_1(s)}{F_1(s)}}_{\text{N order which increases identification performances}}}.SOC(s) - \overbrace{\underbrace{\frac{B_2(s)}{F_2(s)}}_{\text{First order with one pole}}}.I_{bat}(s) + \underbrace{E(s)}_{\text{White noise}}$$

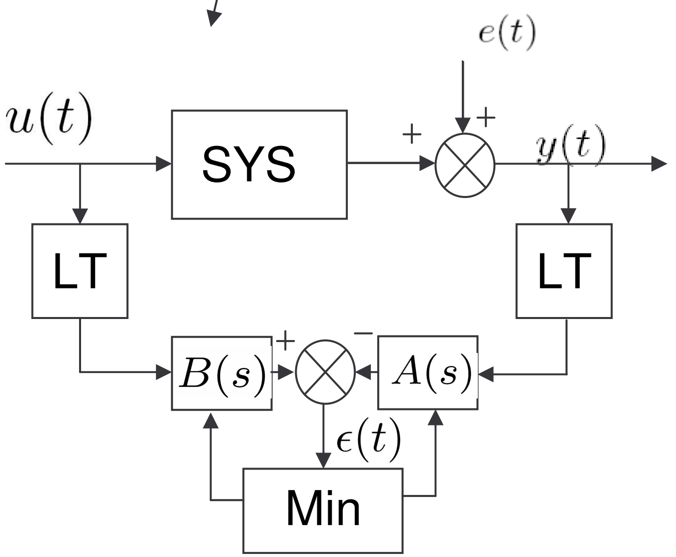
Batteries Models

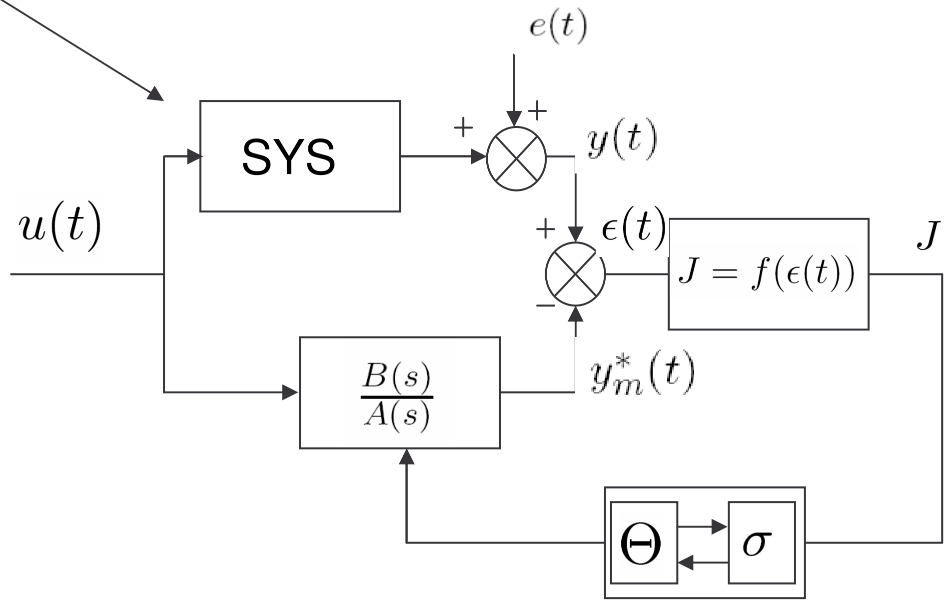


$$\frac{B(s)}{A(s)} = \frac{b_m.s^m+...+b_1.s^1+b_0}{a_n.s^n+...+a_1.s^1+a_0}$$

$$\Theta = [\theta_1...\theta_N]' = [a_1...a_n b_0...B_n]'$$

$$\text{with } a_0 = 1$$





Batteries Models ‘Output Error’

$$J=\sum_{k=0}^{N-1}(\epsilon(k)^2)=\sum_{k=0}^{N-1}(y(k)-y_m^*(k))^2$$

$$\Theta(i+1)=\Theta(i)+[(\underbrace{\nabla^2 J(\Theta)}+\mu.I)^{-1}\underbrace{\nabla J(\Theta)}]$$

$$\nabla^2 J(\Theta)=2\sum_{k=0}^{N-1}\underbrace{\sigma_\Theta(k)}.\sigma_\Theta(k)' \qquad \nabla J(\Theta)=-2\sum_{k=0}^{N-1}\epsilon(k).\underbrace{\sigma_\Theta(k)}$$

$$\sigma_\Theta(k)=[\sigma_{\theta_1}(k)\ldots\underbrace{\sigma_{\theta_i}(k)}\ldots\sigma_{\theta_{np}}(k)]'$$

$$\sigma_{\theta_i}(k)\triangleq\frac{\partial y_m^*(k)}{\partial\theta_i} \quad\Longleftrightarrow\quad \begin{cases}\sum_{i=0}^n a_{n-i}^*\,\sigma_{a_1^*}^{(i)}(t)=-y^{*\,(n-1)}(t)\\ \vdots\\ \sum_{i=0}^n a_{n-i}^*\,\sigma_{a_n^*}^{(i)}(t)=-y^{*\,(0)}(t)\\ \sum_{i=0}^n a_{n-i}^*\,\sigma_{b_0^*}^{(i)}(t)=u^{(m)}(t)\\ \vdots\\ \sum_{i=0}^n a_{n-i}^*\,\sigma_{b_m^*}^{(i)}(t)=u^{(0)}(t)\end{cases}$$

Batteries Models

$RC_{PARALLEL}$ Identification

$$\Delta U_{bat}(s) = \frac{B_1(s)}{F_1(s)}.SOC(s) - \underbrace{\frac{B_2(s)}{F_2(s)}}.I_{bat}(s) + E(s)$$

$$\longleftrightarrow \quad \frac{B_2(s)}{F_2(s)} = \frac{\alpha s + \beta}{s + \gamma}$$

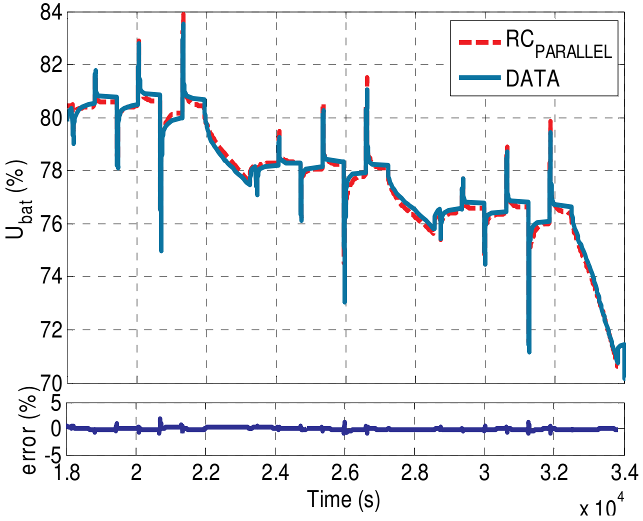
- Thanks to the continuous methods the analogy gives:

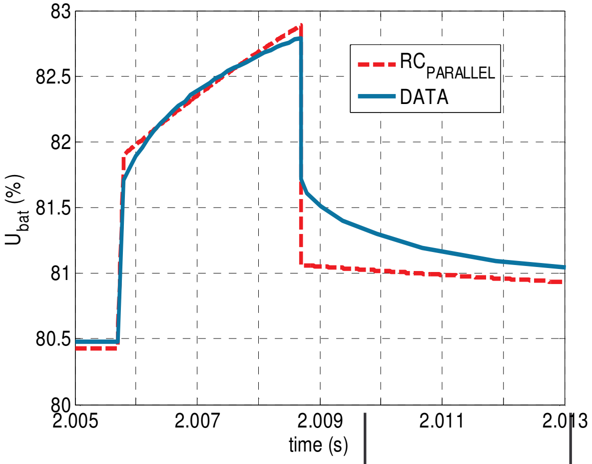
$$\begin{cases} R_2 + R_1 = \dfrac{\beta}{\gamma} \\ C_{PARALLEL}.R_2.R_1 = \dfrac{\alpha}{\gamma} \\ C_{PARALLEL}.R_2 = \dfrac{1}{\gamma} \end{cases} \Longrightarrow \begin{cases} R_1 = \alpha \\ R_2 = \dfrac{\beta - \alpha.\gamma}{\gamma} \\ C_{PARALLEL} = \dfrac{1}{\beta - \alpha.\gamma} \end{cases}$$

- Discrete identifications (ARX, ARMAX, Box Jenkins…) gives good results but the analogy is not direct and the solution depends on the sampling period.

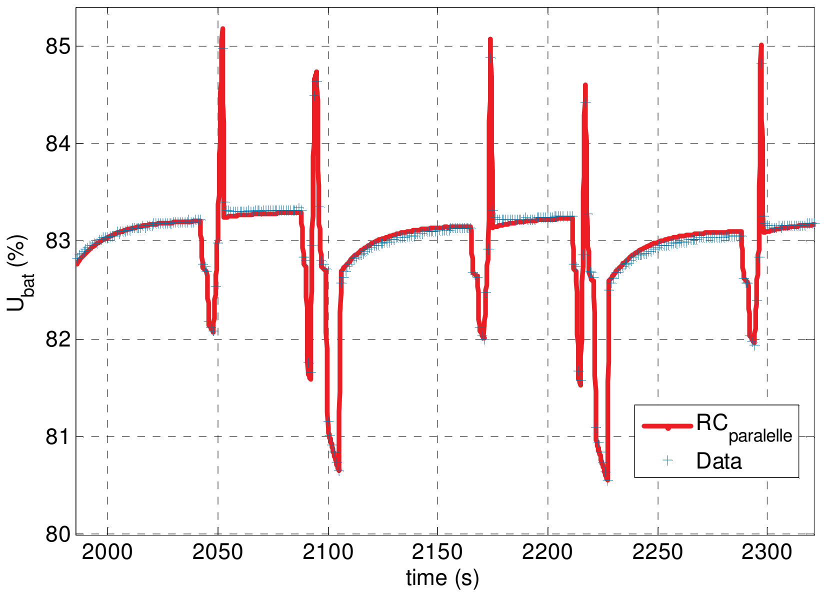
Batteries Models

- **RC$_{PARALLEL}$ Results**





Another experiments with this model and method



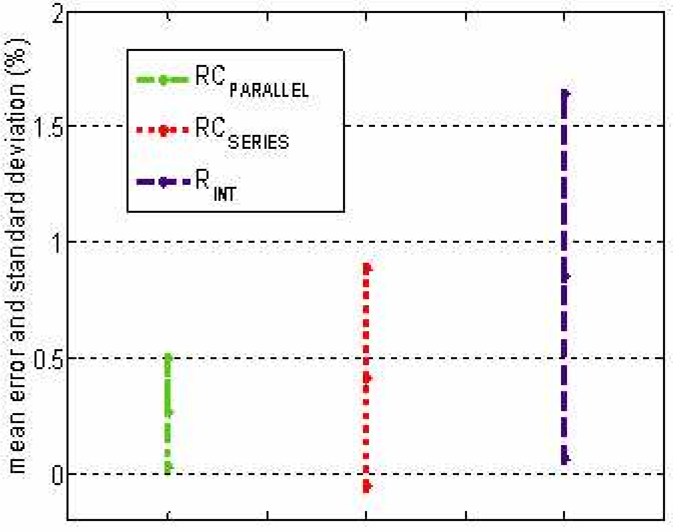
FIT= 91.7%
(identification)

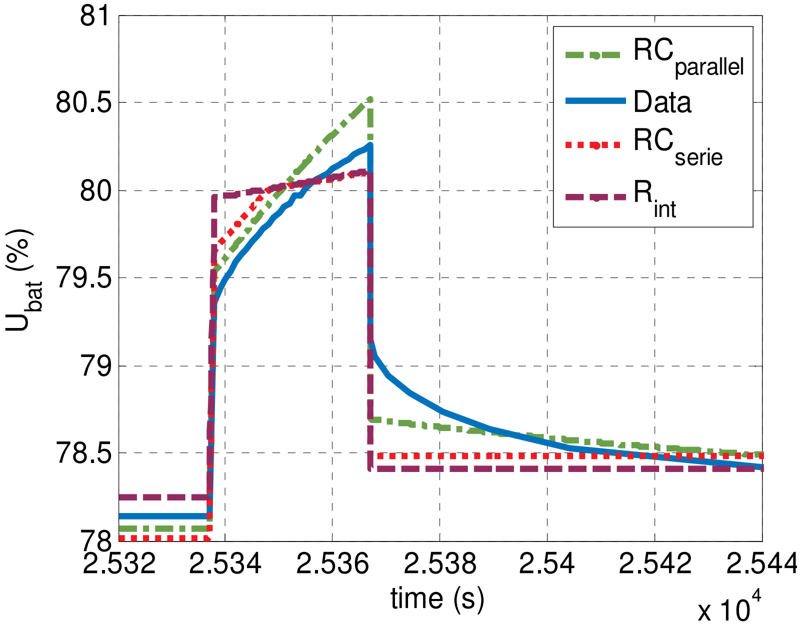
***FIT*= 91.6%**
(validation)

Batteries Models

- **Model performances**

FIT	**Identification data**	**Validation data**
R_{INT}	85%	79.3%
RC_{SERIES}	89,6%	89.5%
$RC_{PARALLEL}$	91.7%	91.6%

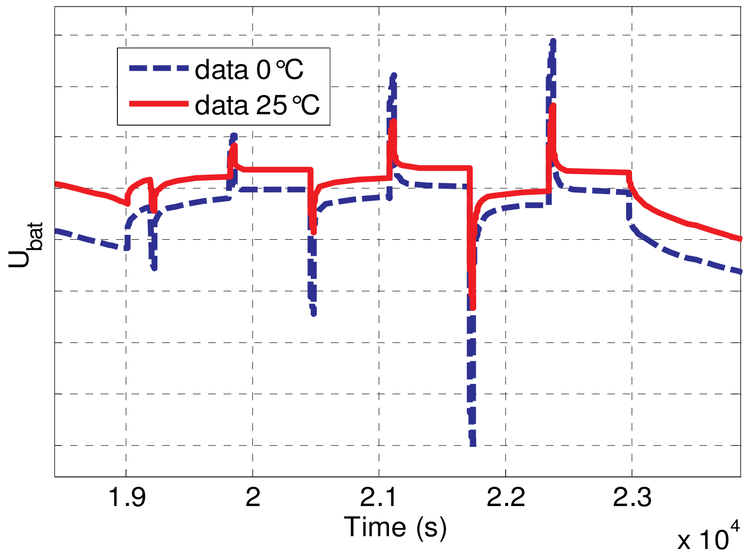




Improvement with temperature consideration?

THERMAL ASPECT

- **Temperature effect**
  - cold condition
    - Increase the internal resistance
    - Decrease the Open Circuit Voltage
    - Decrease the capacity
- **Temperature modelling**



$$T_{bat} = \int_0^t \frac{\underbrace{Q_{in}} - \underbrace{Q_{out}}}{m.c_p} dt$$

Integral of the difference between heat produced and heat exchange

$$\overbrace{Q_{in} = R.I_{bat}^2 + T_{bat}.\Delta S \frac{1}{nF}}$$

Joule effect + cells reaction (which can be neglected)

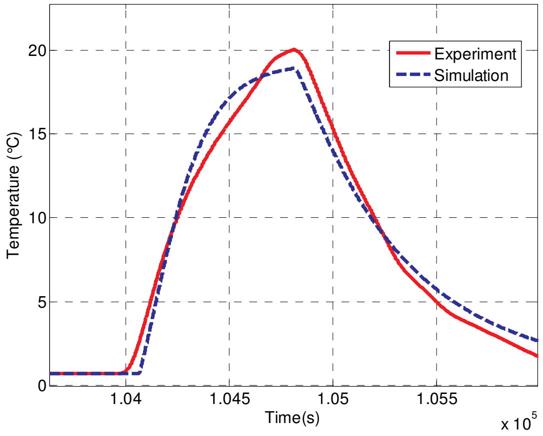
$$\overbrace{Q_{out}} = \frac{T_{bat} - T_{air}}{\underbrace{R_{eff}}}$$

$$R_{eff} = \frac{1}{h.A} + \frac{e}{k.A}$$

Convection & conduction

THERMAL ASPECT

Temperature model validation

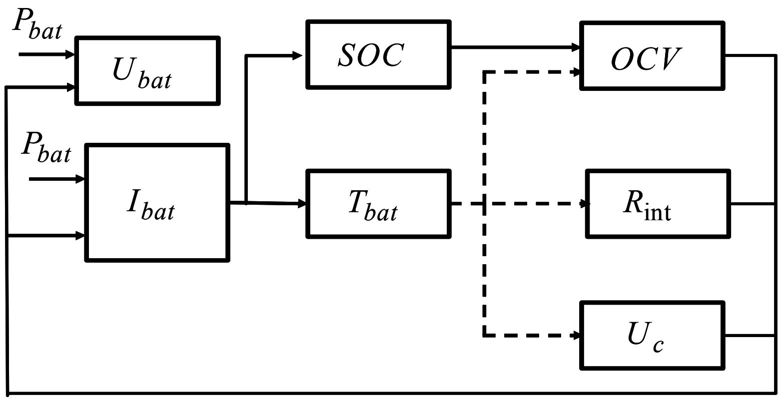


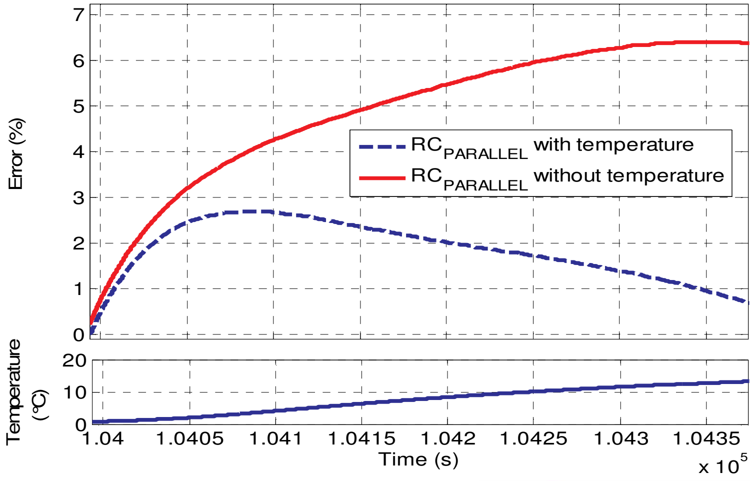
h and *Cp* are identified in a 4C discharge at 25℃ in initial condition

Temperature model validation is made with the same test but at 0℃ in initial condition

The prediction error is low ~3℃ max

Implementation & Results





CONCLUSION

- **$RC_{PARALLEL}$ model**
  - Improvement of the battery behaviour prediction for the HEV simulator
  - Most part of battery dynamic is represented
  - Fast identification with a continuous identification method
  - Temperature consideration
  - Cells are extrapolated to give battery pack

- **Improvements & future work**
  - Development of specific strategy in cold condition
  - Model with the effect of mass transportation (all frequencies represented)
  - Heating Interaction between cells in the battery pack
  - Battery pack model with n-cells (effect of dispersion, State Of health…)
  - Battery management system consideration
  - …