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# Proposal and Validation of a SOC Estimation Algorithm of $LiFePO_4$ Battery Packs for Traction Applications

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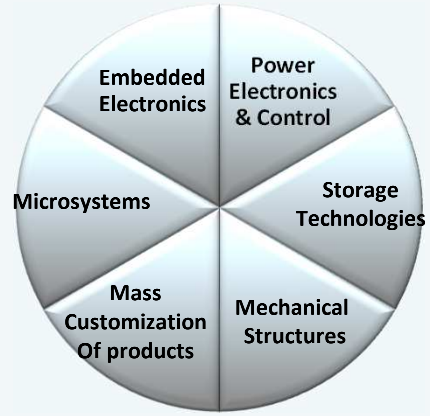
# IK4-Ikerlan

## Technology Research Centre

- Multidisciplinary Applied Research & Product Development
- 250 professionals
  - ≈ 84% doctors or higher degree holders
- 20.6M€ income
  - ≈ 65% public funding
  - ≈ 35% private funding
- Basque Country (Spain)


## Specialized in Multi-Technology Integration

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ESS solutions developer

Component → Cell → Module → Battery Pack → Integration → End user

# Motivation

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# Motivation

## Challenges of developing ESS

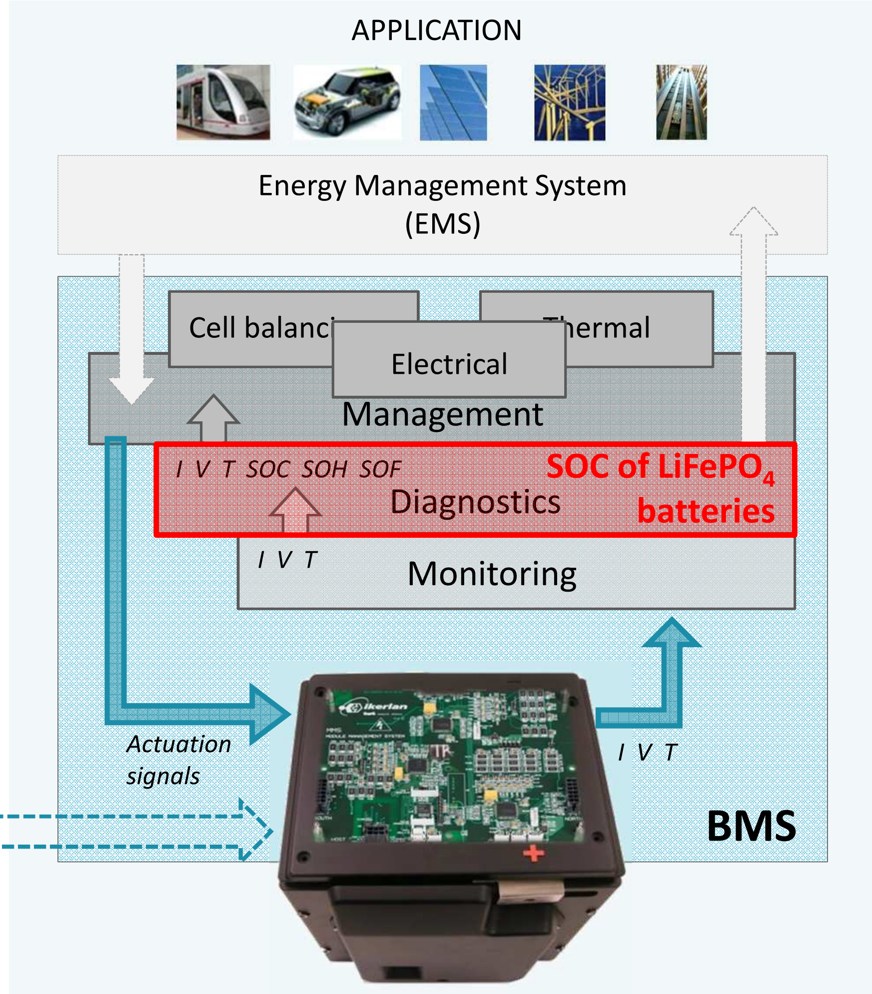
**CUSTOMIZED ESS**

- *Application adaptability*
- *Optimal sizing*
- *Reliability*
- *Lifetime guarantee*
- *User & system safety*
- *Efficiency*
- *Scalability & Maintenance*

Need of Precise battery diagnostic:

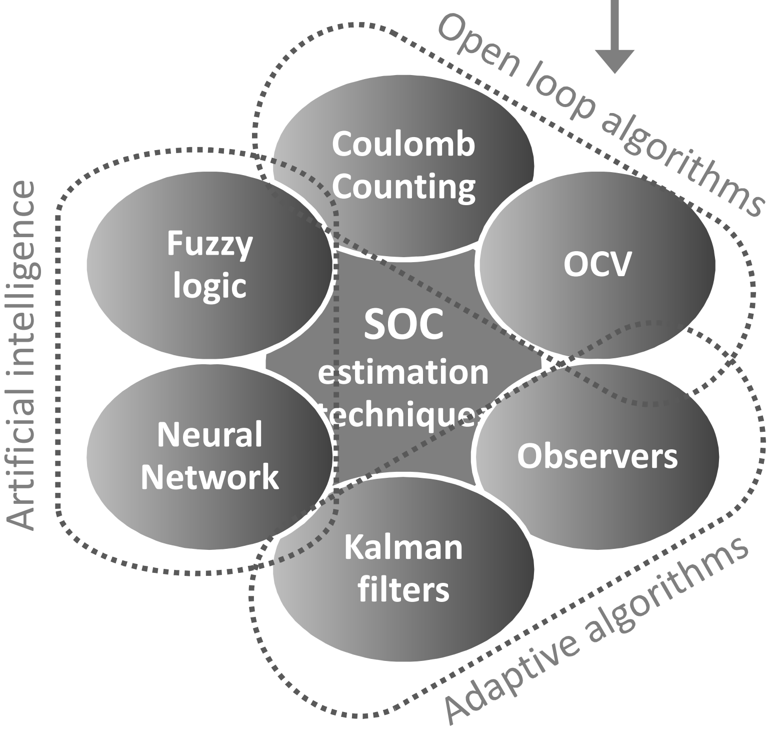
✓To avoid battery's unsafe operation

✓As a basis for Optimum Management



# Motivation

## SOC estimation for $LiFePO_4$ cells

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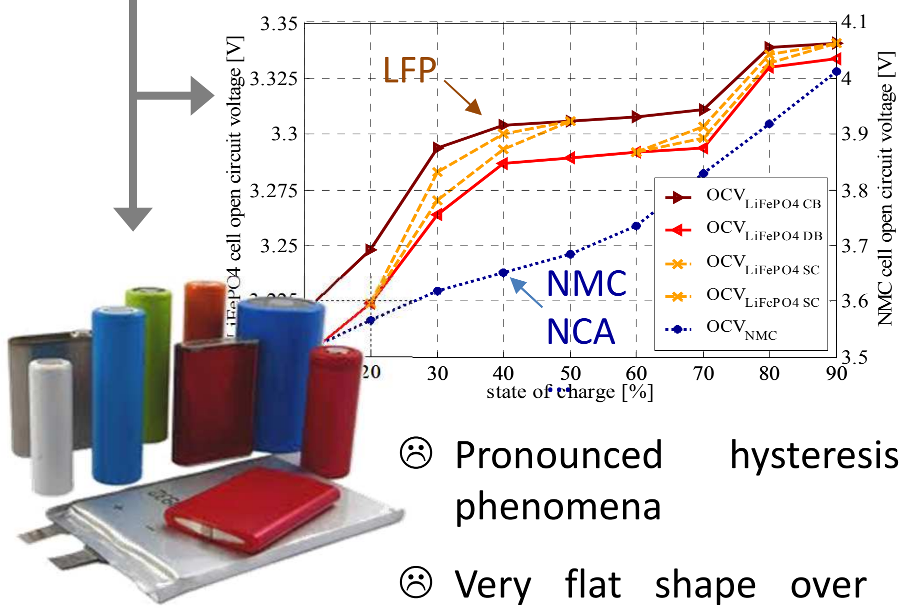



☹ Pronounced hysteresis phenomena

☹ Very flat shape over middle SOC range

# Contents

# SOC estimation algorithm

## Cell level SOC estimation

### Operating principle

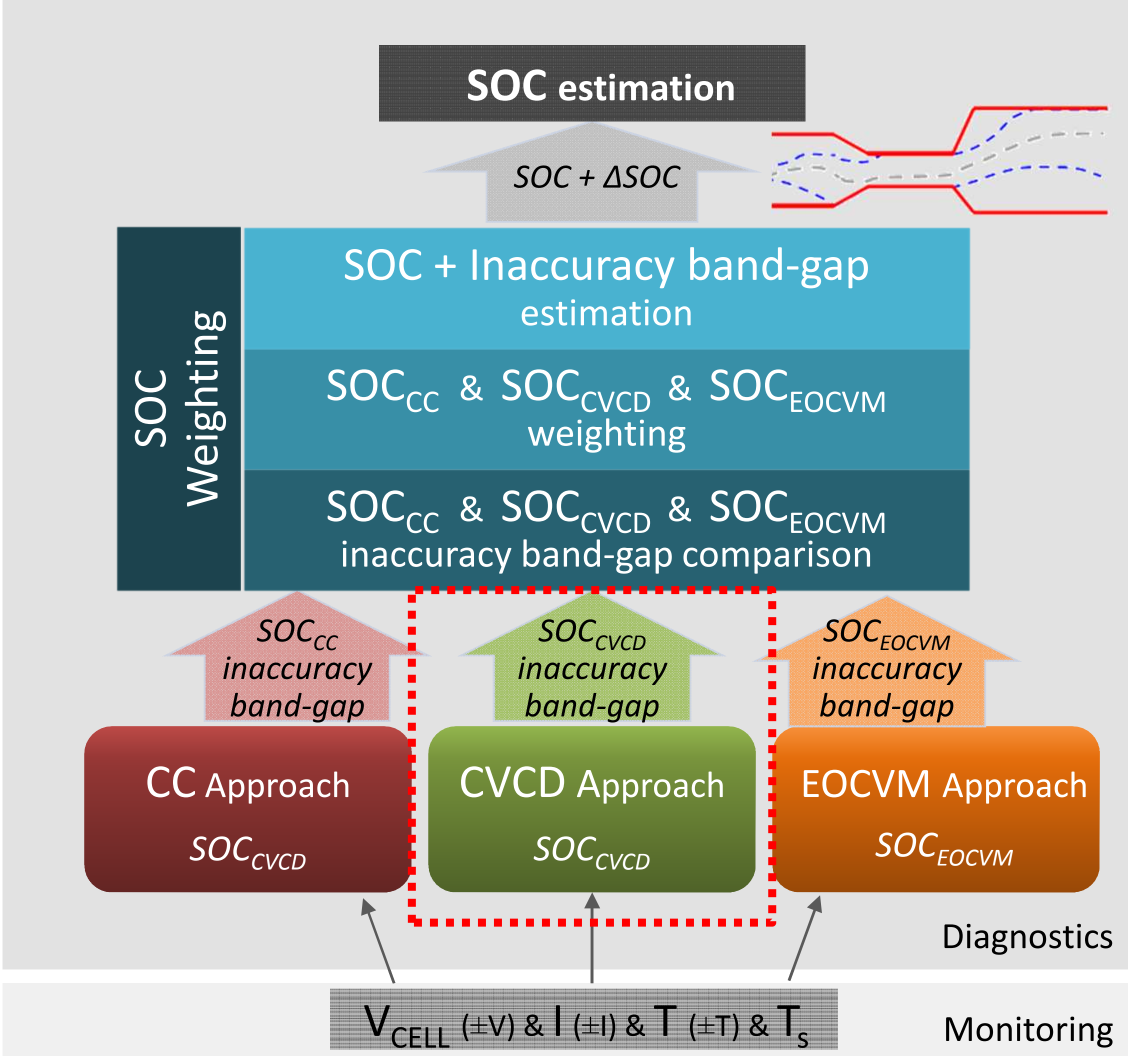
- Open loop algorithm
- Weighting of individual techniques ($T_n$) for reliable SOC estimation

### Present case

T1: *Coulomb Counting* [CC]

T2: *Const. Voltage Charge Detector* [CVCD]

T3: *Enhanced OCV Model* [EOCVM]

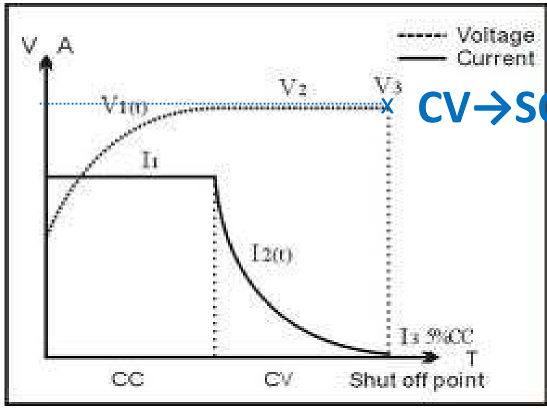


# SOC estimation algorithm

## Cell level SOC estimation

### Constant Voltage Charge Detector (CVCD) Approach

- Relates CC-CV end-of-charge voltage with SOC
- Requires CC-CV charge process of the cell
- Valid for wide operating conditions (I, T and all SOC range)
- Easily implementable in a BMS
  - Simple
  - Low parameterization & implementation efforts

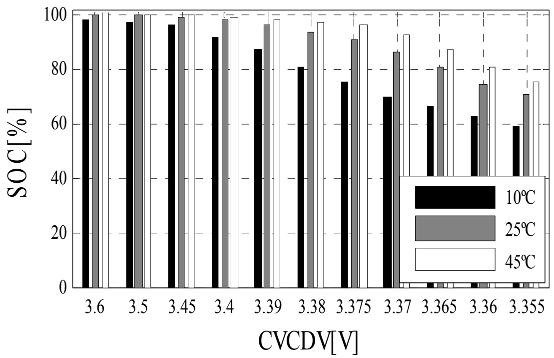



CV→SOC

Sensitivity Evaluation Tests $SOC_{CVCD}(CV, T)$ → Modeling $SOC_{CVCD}=f(CV, T)$ → CVCD approach $SOC_{CVCD} \pm \Delta SOC_{CVCD}$

Inaccuracy band-gap $\Delta SOC_{EOCV}=f(V, T, model)$

**Implementation Procedure**



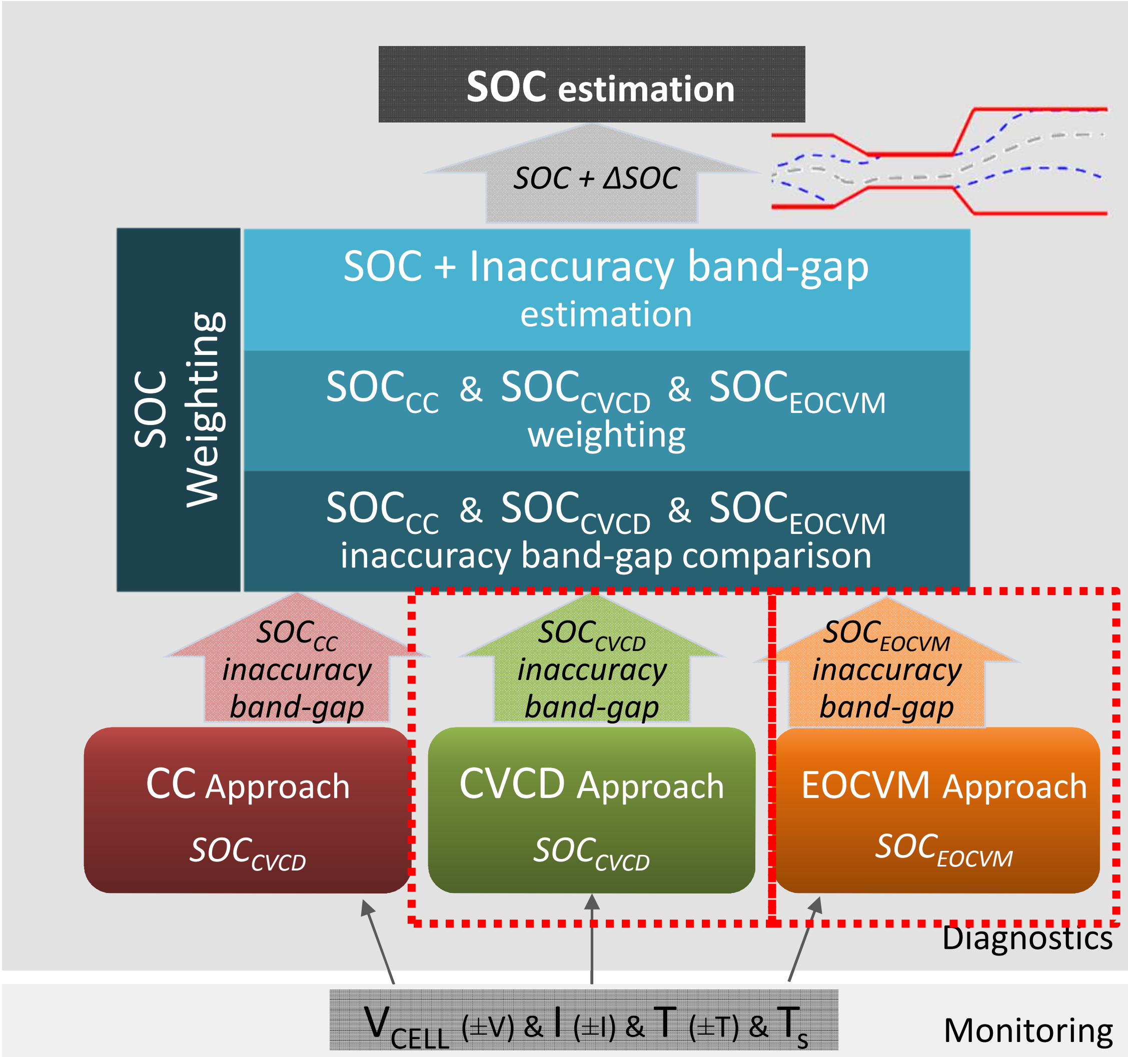

| CV [V] | T [ºC] 10 ºC | 25 ºC | 45 ºC |
|---|---|---|---|
| 3.60V | 97,80% | 100% | 100,09% |
| 3.45V | 95,65% | 99,16% | 99,40% |
| 3.38V | 80,55% | 93,27% | 97,05% |
| 3.375V | 74,67% | 90,11% | 95,59% |
| 3.365V | 66,27% | 80,59% | 87,03% |
| 3.355V | 59,12% | 70,27% | 75,08% |

Look-up tables with interpolation

- Tº & V sensors accuracy
- Modelling error
- Cell dispersion

# SOC estimation algorithm

## Cell level SOC estimation

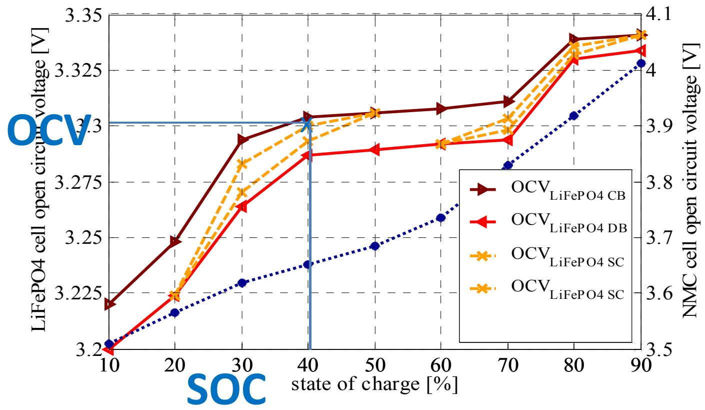


# SOC estimation algorithm

## Cell level SOC estimation

### Enhanced Open Circuit Voltage (EOCV) Approach

- Relates OCV measurements with SOC
- High Scope
  - Considers $LiFePO_4$ OCV hysteresis effect
  - Applicable under diverse operating conditions (I, T and all SOC range)
- Easily implementable in a BMS
  - Simple
  - Low parameterization & implementation efforts




Sensitivity Evaluation Tests

OCV(SOC, $T_r$, T)

OCV Modeling & Integration in SOC

EOCV=f(SOC, $T_r$ , T) → SOC=f(EOCV(SOC, $T_r$, T)

EOCV approach

$SOC_{EOCV} \pm \Delta SOC_{EOCV}$

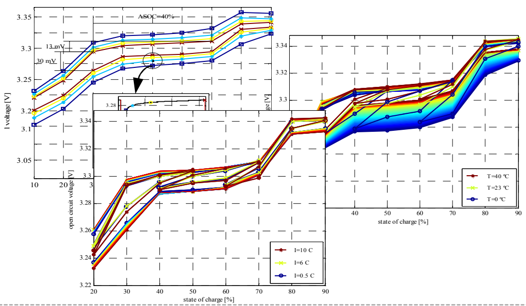
Inaccuracy band-gap

$\Delta SOC_{EOCV}$=f(V,T,model)

**Implementation Procedure**

***CONCLUSIONS***

- Relaxation time ($T_r$) impact → High
- Hysteresis effect impact → High
- Temperature effect impact → High
- Current effect impact → Low



- Tº & V sensors accuracy
- Modelling error
- Cell dispersion

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# SOC estimation algorithm

## Cell level SOC estimation

Sensitivity Evaluation Tests
$OCV(SOC, T_r, T)$

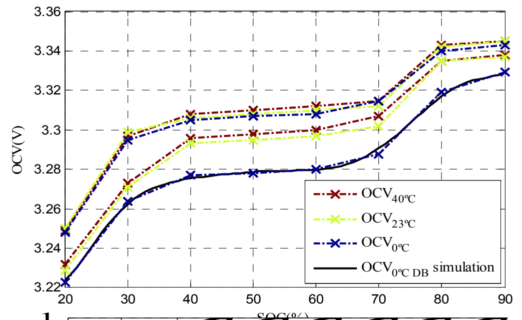
OCV Modeling & Integration in SOC
$EOCV=f(SOC, T_r, T)$ & $SOC=f(EOCV(SOC, T_r, T)$

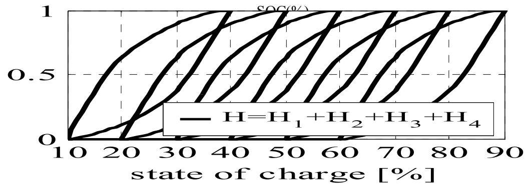
EOCV approach
$SOC_{EOCV} \pm \Delta SOC_{EOCV}$

### OCV Modeling

$$EOCV(SOC_k, T_k) = OCV_{CB\,k}(SOC_k, T_k) \cdot H_k + OCV_{DB\,k}(SOC_k, T_k) \cdot (1 - H_k)$$

1
0



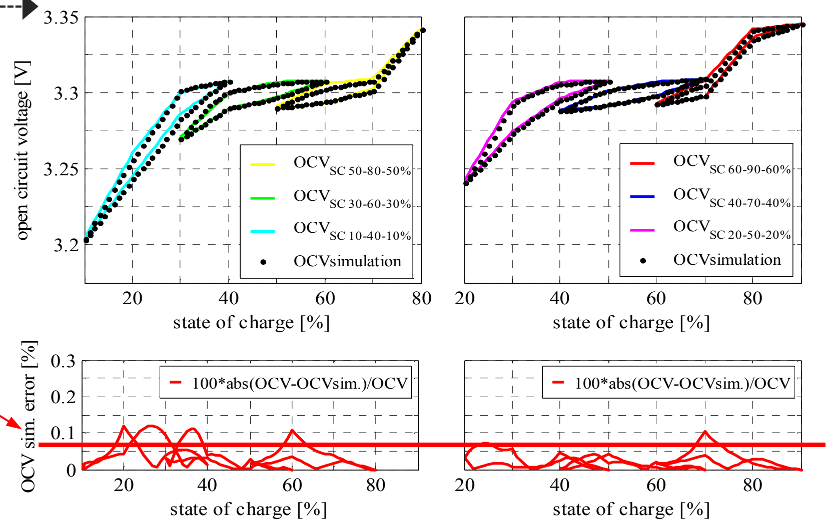




### Integration in SOC

$$\vartheta = [dEOCV_k(SOC_k)/dSOC_k]^{-1}$$

$$SOC_{EOCV\,k} = SOC_{k-1} + \vartheta \cdot (V_{cell\,k} - EOCV_{model\,k})$$

$\varepsilon < 0.1\%$

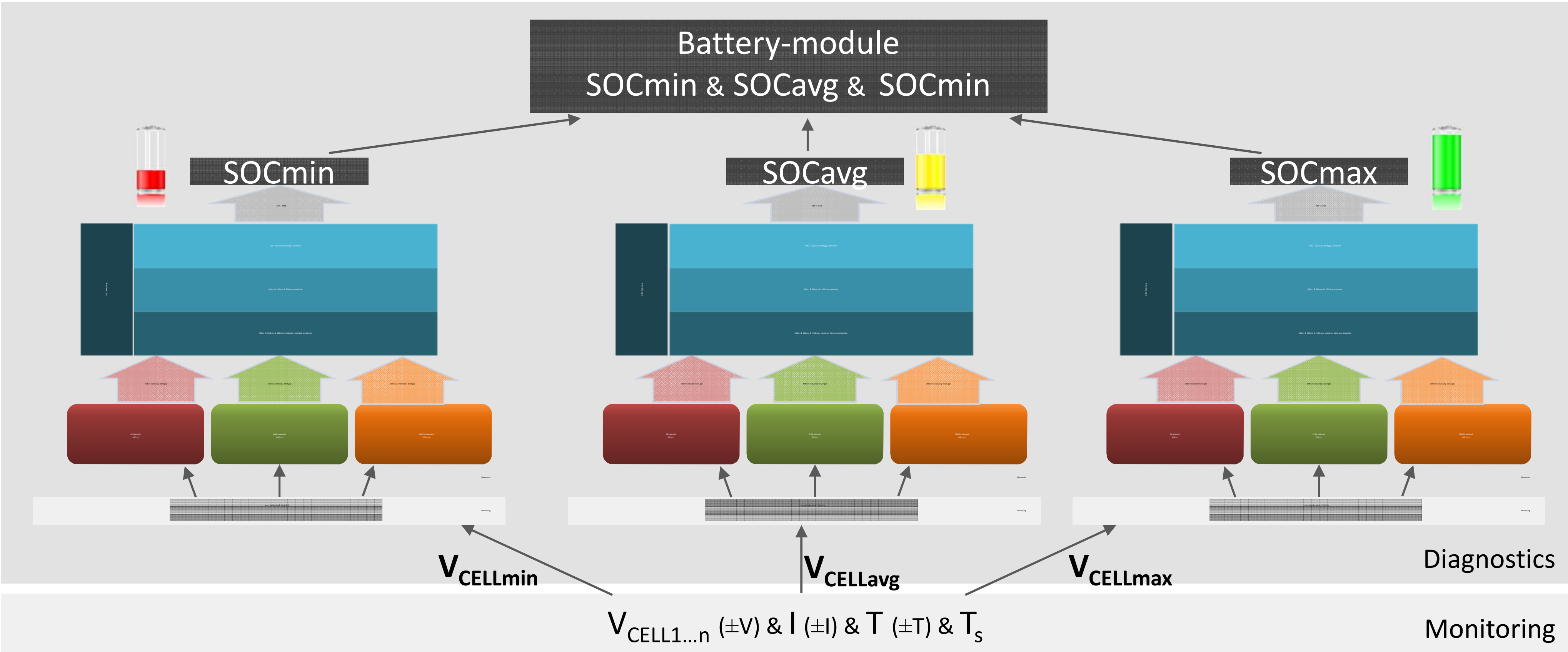


# SOC estimation algorithm

## Battery-module level SOC estimation

### Operating principle

- 3 SOC estimations: $SOC_{MAX}$ with $Vcell_{MAX}$
  $SOC_{AVG}$ with $Vcell_{AVG}$
  $SOC_{MIN}$ with $Vcell_{MIN}$



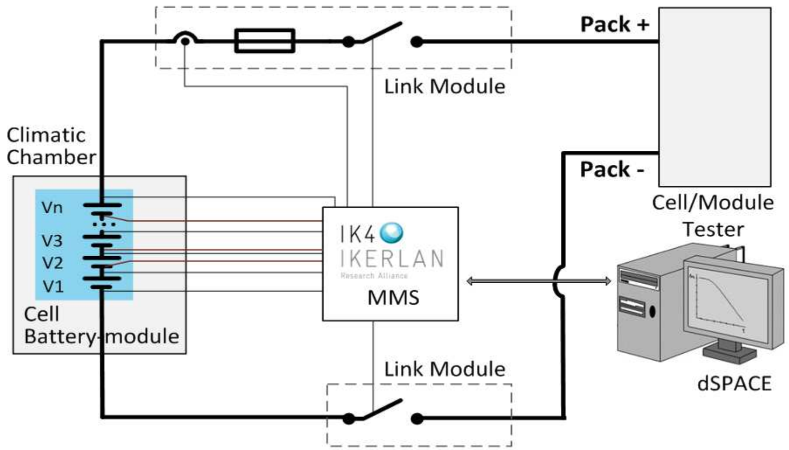
# Contents

# Applied experimental validation

## Objectives

### Objectives


- Check **SCOPE** and **VERSATILITY** at different:
  - **Cell design features**
    - Energy & Power
    - Format: cylindrical, pouch, prismatic
    - Manufacturer
    - …
  - **Operating conditions**
    - Load profiles
    - Temperature
    - SOC range
    - …

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# Applied experimental validation

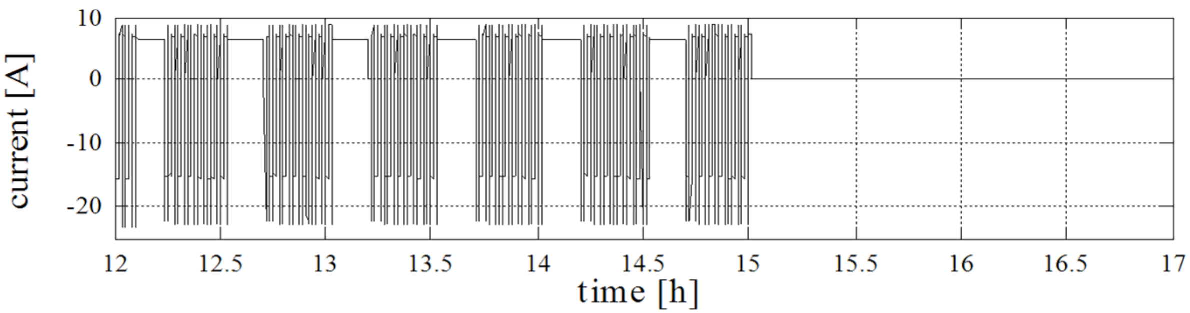
## Validation scenario 1: Residential elevator application

### Functionalities

- Cost saving reducing grid power peaks
- Efficiency increase saving braking energy
- Automatic rescue in case of power outage

| Cell Characteristics | |
|---|---|
| Manuf.: | A123 ANR26650M1-B |
| Nominal Voltage (V) | 3.3 |
| Capacity (Ah) | 2.4 |
| Energy (Wh) | 7.92 |
| Max. Dch. Power (W) | 200 |
| Weight (g) | 76 |

| Battery-module Characteristics | |
|---|---|
| Nº cells | 12s |
| Nominal Voltage (V) | 38.4 |
| Capacity (Ah) | 2.4 |
| Energy (Wh) | 92.16 |
| Max. Dch. Power (W) | 675.84 |
| Weight (kg) | 1.2 |




Accelerated one day current profile

### Validation test profile

- Elevator operating profile: Simulates 30 days of use
- Temperature = 25ºC

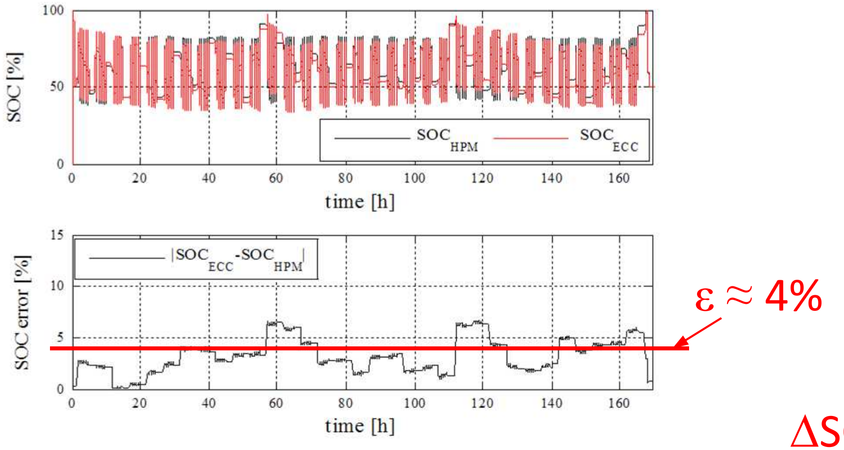
# Applied experimental validation

## Validation scenario 1: Residential elevator application

### CELL LEVEL RESULTS

✓ After 30 days:

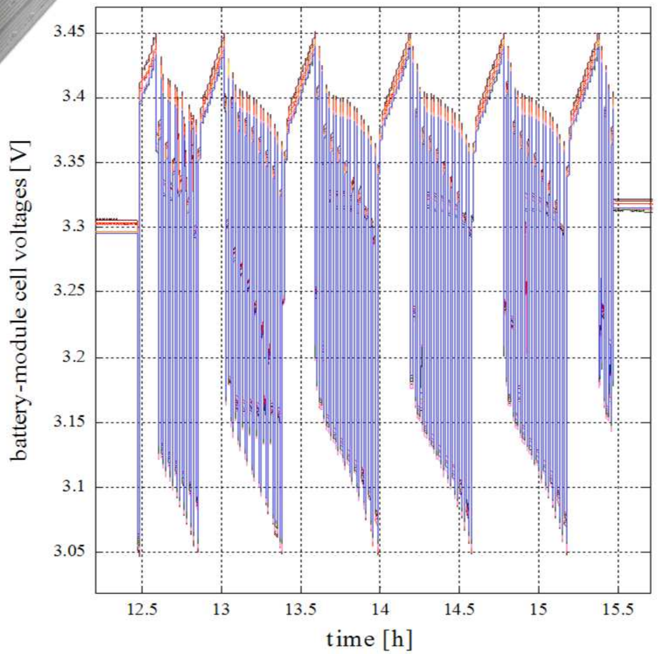
SOC inaccuracy ≈ 4 %

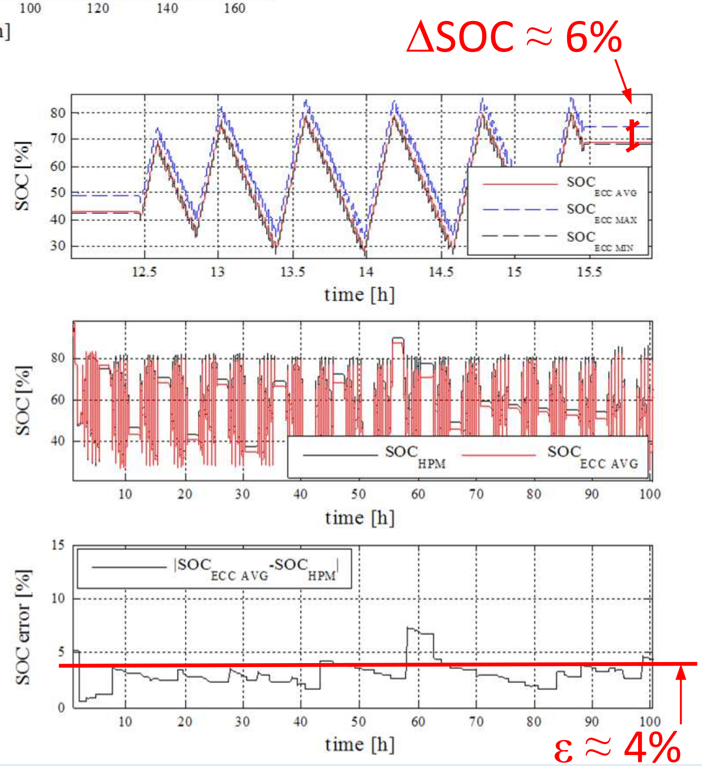



### BATTERY-MODULE LEVEL RESULTS

✓ After 20 days:

- Cells SOC dispersion ≈ 6%
- SOC inaccuracy ≈ 4%



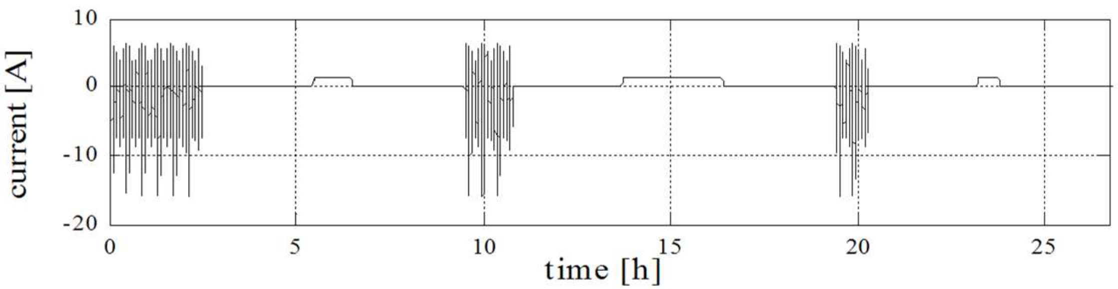
# Applied experimental validation

## Validation scenario 2: Electric on-road vehicle application

### Functionalities

- **Efficiency increase** of the overall traction system
- Reduce $CO_2$ emissions

| Cell Characteristics | |
|---|---|
| Manuf.: | OMT OMLIFE-8AHC-HP |
| Nominal Voltage (V) | 3.2 |
| Capacity (Ah) | 8 |
| Energy (Wh) | 25.6 |
| Max. Dch. Power (W) | 570 |
| Weight (g) | --- |


One day current profile of an on-road pure electric vehicle

### Validation test profile

- On-road vehicle operating profile:
  Simulates one day of use
  (FTP-75 test procedure + const. 5W CHs)
- Temperature = 0ºC & 25ºC & 45ºC

# Applied experimental validation

## Validation scenario 2: Electric on-road vehicle application

### CELL LEVEL RESULTS


! Temperature impact:

$V_{CELL}$ can vary up to ≈400mV

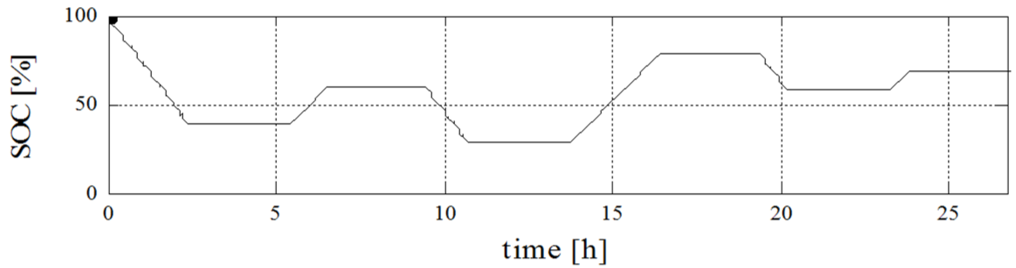
✓ After 1 day:

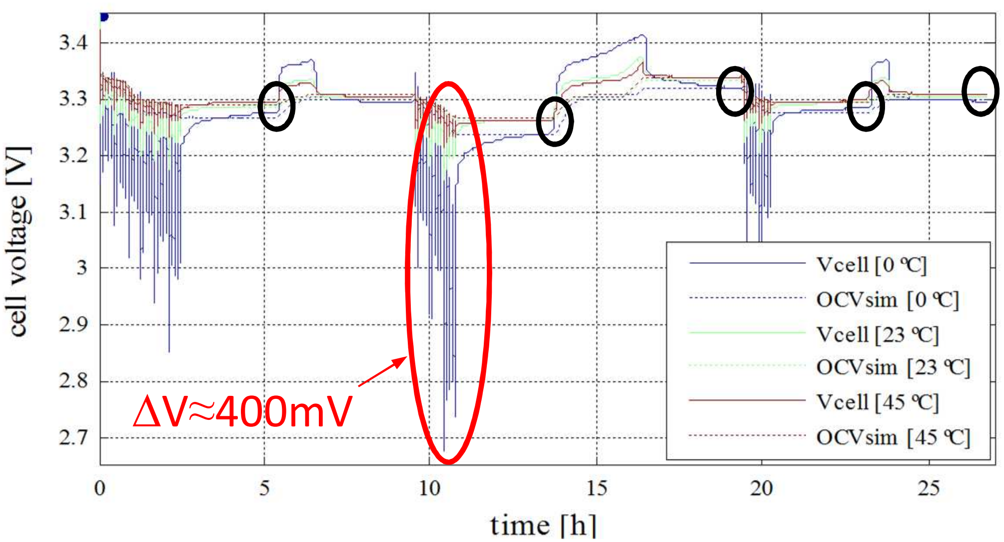
Max. SOC inaccuracy ≈ 2 %

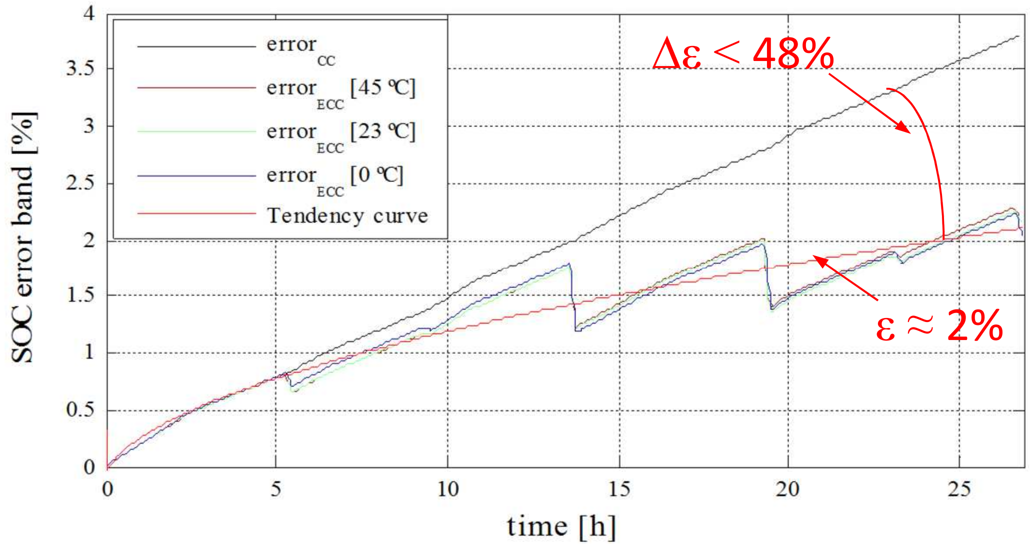
48% less error that with CC

✓ Algorithm considers temperature impact:

$avg(OCV_{MEASURED}\text{-}OCV_{EOCVM}) \approx 3mV$



# Applied experimental validation

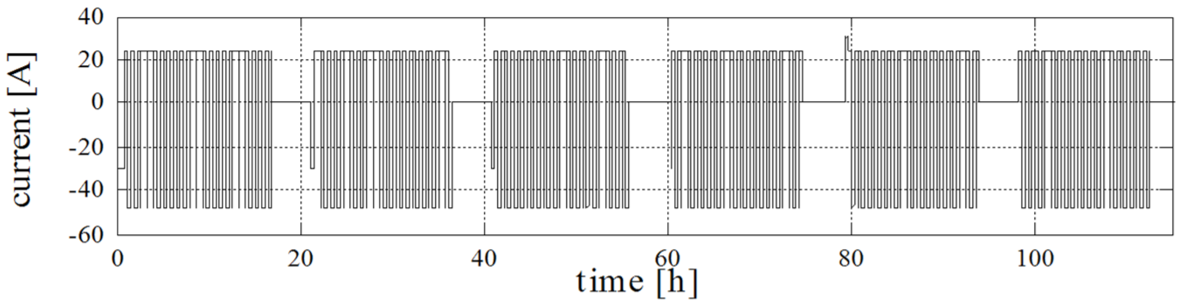
## Validation scenario 3: Electric railway vehicle application

### Functionalities

- **Cost saving** reducing power peaks from catenary
- **Efficiency increase** saving braking energy
- **Catenary-free** operation mode


| Cell Characteristics | |
|---|---|
| Manuf.: | CALB SE100AHA |
| Nominal Voltage (V) | 3.2 |
| Capacity (Ah) | 100 |
| Energy (Wh) | 320 |
| Max. Dch. Power (W) | 960 |
| Weight (kg) | 3.2 |

| Battery-module Characteristics | |
|---|---|
| Nº cells | 16s |
| Nominal Voltage (V) | 51.2 |
| Capacity (Ah) | 100 |
| Energy (kWh) | 5.12 |
| Max. Dch. Power (kW) | 15.36 |
| Weight (kg) | 59.6 |


One week current profile

### Validation test profile

- Railway vehicle operating profile: Simulates 1 week of use
- Temperature = 25ºC

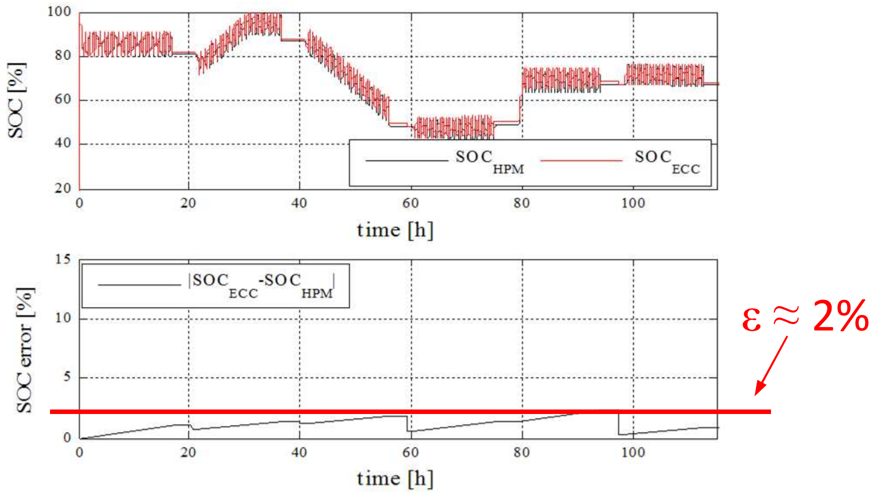
# Applied experimental validation

## Validation scenario 3: Electric railway vehicle application

CELL LEVEL RESULTS

✓ After 1 week:

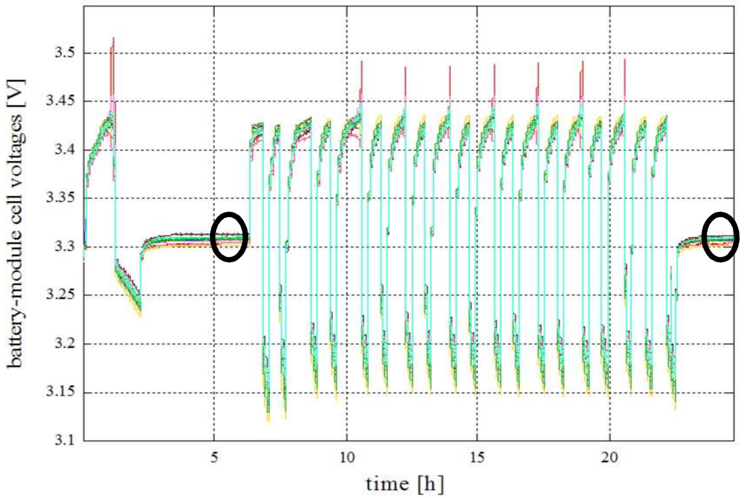
SOC inaccuracy ≈ 2 %

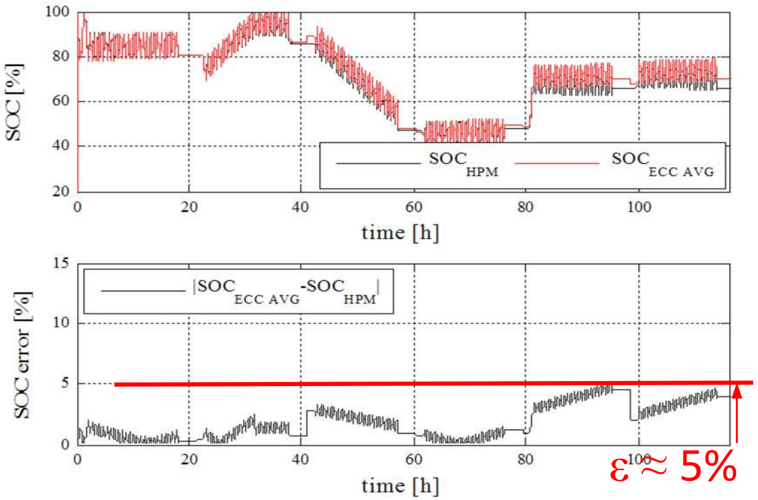



BATTERY-MODULE LEVEL RESULTS

✓ After 1 week:

SOC inaccuracy ≈ 5 %



## Contents

# Conclusions

## Summary and Conclusions

- Enhanced Coulomb Counting SOC algorithm for $LiFePO_4$ cells
  - Hybridization of 3 independent SOC techniques
  - Valid for cell and battery-module level
  - Accurate and simple for BMS
- Applied experimental validation
  - Real-time validation framework → Validation at final application conditions
  - 3 case studies:
    - Low capacity cells → residential elevator application
    - Medium capacity cells → on-road electric vehicle application
    - Large capacity cells → electric railway vehicle application
- SOC estimation error ≈< 5%

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Thank you

Moltes gràcies

Muchas gracias

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# Other IK4-Ikerlan Publications at EVS 27

Dialogue session: Monday 2013-11-18, 13:00-15:00
**THERMAL MANAGEMENT SYSTEMS' DESIGN METHODOLOGY FOR TRANSPORT APPLICATIONS**
Nerea NIETO

Session 1B: Monday 2013-11-18, 15:15-16:35
**MODELLING OF LI-ION BATTERIES DYNAMICS USING IMPEDANCE SPECTROSCOPY AND PULSE FITTING: EVS APPLICATION**
Unai VISCARRET

Session 2B: Monday 2013-11-18, 16:50-18:10
**VALIDATION OF THE METHODOLOGY FOR LITHIUM-ION BATTERIES LIFETIME PROGNOSIS**
Elixabet SARASKETA ZABALA

Session 7B: Wednesday 2013-11-20, 09:00-10:20
**PROPOSAL AND VALIDATION OF A SOC ESTIMATION ALGORITHM OF $LIFEPO_4$ BATTERY PACKS FOR TRACTION APPLICATIONS**
Maitane GARMENDIA