Mattia Ribera

Model-Based and Data-Driven SoH Estimation for Lithium-Ion Batteries: A Comparative Study with Deployment Guidelines

Tutor: *Prof. Diego Iannuzzi*

Cycle: XXXVIII Year: III

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Candidate's information

- MSc degree :
  Automation Engineering at the University of Naples Federico II
- DIETI Research group/laboratory:
  Electrical Machines And Drives (CRIAT group)
- PhD start date – end date:
  01/11/2022 to 31/10/2025
- Scholarship type :
  UNINA

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Summary of study activities

- **Targeted coursework (9 course, PhD ad-hoc + MSc Electrical)** to build a solid backbone in power systems, e-mobility and energy storage.
- **Methods & tools** — statistical data analysis, numerical modelling & simulation, optimization, deep learning;
- **Hands-on** (from ad-hoc PhD , seminars and lab activities): with MATLAB/Simulink, Python, TI C2000 toolchain, and SCPI-based instrument automation.
- **Research practice** — experimental design and data curation, result visualization, scientific writing and presentation.

PhD Year	Courses	Seminars	Research	Tutoring / Supplementary Teaching
1st	18.2	5.8	29	0
2nd	24.2	3.2	43	0
3rd	0	1	58	0

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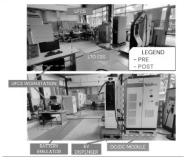
Research areas

- **Battery SoH estimation algorithm** – from data-raw to implementation/validation of estimation algorithms;
- **Datasets & collaborations** — FAAM gigafactory cycling protocols specified; collaborations (POLIMI, Michigan) → multi-chemistry datasets & co-authorships;
- **Power-electronics growth** — TI C2000 programming for embedded solution for Electrical Converters control; support to PNRR experimental benches for EMS of ESS for railway system; prototype resolver interface benchmarked vs commercial device;
- **UFCS work** — upgrade ultra-fast charging station with auxiliary battery to extend lifetime of EV charger system
- **Automation & test** — instrument control, SCPI scripting, faster and automated execution of experiments to support to teaching/research setups



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Research results

Core results (covered in the thesis)

- **SoH estimation pipelines**
  Model-based (IR/ARMAX with LUTs) and Data-driven (ANN on V-I-T sequences) validated across multiple chemistries (LFP/NMC/LCO); generated journal & conference outputs.
- **OCV modelling and Heat exchange analysis**
  OCV–SoC maps and temperature effects derived from lab data; promising features for SoC/SoH estimators (exploratory, not fully validated).

Additional results / pipeline to publications

- **Resolver interface prototype**
  First experimental results completed; 1 manuscript submitted (under review); next steps planned: extended experimental campaign + analytical verification to consolidate the design.
- **Single-inverter / multi-motor control**
  Papers in preparation; experimental activities to be scheduled.
- **UFCS aging & management**
  Simulator with embedded aging used to assess the extended life time of battery based charger; Results presented and recorded in I-STENTORE deliverables.

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Research products

International journal papers

- P. Franzese, D. Iannuzzi, R. Merolla, M. Ribera, I. Spina,
  Artificial Neural Networks for Residual Capacity Estimation of Cycle-Aged Cylindric LFP Batteries,
  Batteries, vol. 11 (7), 2025, Article 260, DOI: 10.3390/batteries11070260.
- Dannier, G. Brando, M. Ribera, I. Spina,
  Li-Ion Batteries for Electric Vehicle Applications: An Overview of Accurate State of Charge/State of Health Estimation Methods,
  Energies, vol. 18 (4), 2025, Article 786, DOI: 10.3390/en18040786.

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Research products

International conference papers

- G. Brando, D. Iannuzzi, M. Ribera,
  State of Health Estimation of Cycle-Aged Cylindric LFP Batteries using ARMAX Modeling,
  2024 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM 2024), 2024, pp. 668–673, DOI: 10.1109/SPEEDAM61530.2024.10609193.
- Andreotti, A. Di Pasquale, S. Meo, M. Pagano, M. Ribera,
  An AHP Approach for the Optimal Sizing of On-Board Energy Storage in DC Rail Transit Systems,
  2024 IEEE International Conference on Artificial Intelligence and Green Energy (ICAIGE 2024), 2024,
  DOI: 10.1109/ICAIGE62696.2024.10776749.
- S. Barcellona, M. Ribera, E. Fedele, L. Piegari, L. Codecasa, D. Iannuzzi,
  State of Health Estimation of $LiCoO_2$ Cells based on Impulse Response and ARMAX Identification,
  2024 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles and International Transportation Electrification Conference (ESARS-ITEC 2024), 2024,
  DOI: 10.1109/ESARS-ITEC60450.2024.10819863.

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Research products

International conference papers

- S. Barcellona, S. Colnago, E. Fedele, D. Iannuzzi, L. Piegari, M. Ribera,
  Cycle Aging Effect on the Open Circuit Voltage of a $LiFePO_4$ Battery,
  2023 IEEE Vehicle Power and Propulsion Conference (VPPC 2023) – Proceedings, 2023,
  DOI: 10.1109/VPPC60535.2023.10403323.
- D. Iannuzzi, M. Ribera, P. Satariano, E. Fedele, F. Pagliarini, P. Cennamo, F. Orsini, L. Petrazzuoli, M. Spinelli,
  Capacity Fade Estimation of LiFePO Cells Based on Improved Impulse Response Method: Experimental Results,
  2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles and International Transportation Electrification Conference (ESARS-ITEC 2023), 2023,
  DOI: 10.1109/ESARS-ITEC57127.2023.10114873.
- P. Franzese, M. Ribera, D. Iannuzzi,
  Design Comparative Analysis of Distributed and Concentrated Electrical Power Conversion Systems for Multi-Slot Ultra-Fast Chargers,
  IET Conference Proceedings, 2023 (18), pp. 182–190, 2023, DOI: 10.1049/icp.2023.2702
- M. Ribera, M. Coppola, A. Dannier, and D. Iannuzzi,
  Aging Effect on Temperature Behaviour in Li-ion Battery Cell: a Case of Study,
  31st International Workshop on Thermal Investigation of ICs and Systems (THERMINIC 2025), Naples, Italy, Sept. 24–26, 2025, to appear in the proceedings

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PhD thesis overview

Battery's problem

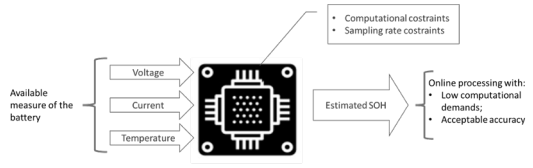
Lithium-ion batteries degrade during rest and operation; availability, safety and cost depend on an accurate State of Health (SoH) estimate.

$$SoH_C = (Capacity\ reduction) = \frac{C_n - C_{act}}{C_n}\ 100 \qquad SoH_R = (Internal\ Resistance\ increase) = \frac{R_t - R_0}{R_0}\ 100$$

Embedded/real-time SoH is hard: limited compute, variable conditions, cross-chemistry behavior.

Existing approaches fall into three families with trade-offs:

- Circuit-model based – simple to implement, but approximate;
- Electrochemical models – accurate, but hard for MCUs;
- Data-driven – mathematically simple at run-time, but data-hungry and sensitive to training domain.



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PhD thesis overview

Objective of PhD research activity

Develop and compare two complementary SoH pipelines suitable for embedded use.
Validate across chemistries (e.g., LFP/NMC/LCO) using controlled lab datasets.
Provide deployment guidance by contrasting accuracy, preprocessing needs, computational cost, and interpretability.

Methodology

- **Model-based pipeline:** IR/ARMAX identification and models organized in **LUTs** indexed by state & aging conditions.
- **Data-driven pipeline:** Neural Networks trained for mapping pre-processed signals to SoH.
- **Evaluation:** cross-chemistry training and test, complexity discussion for MCU feasibility and data process effort evaluation; comparative analysis of the two pipelines.

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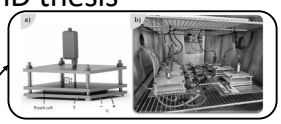
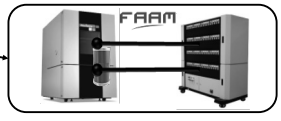
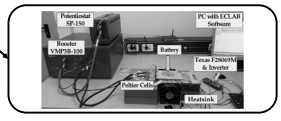
PhD thesis

Dataset collection

- Data of 21 aged NMC cells (source from *University of Michigan*)
- Data of 2 aged LFP cells (source from *FAAM company*)
- Data of LCO cell (source from *Politecnico di Milano*)







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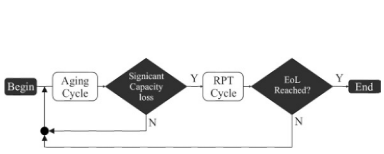
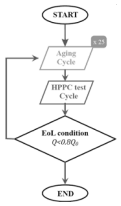
PhD thesis

Experimental setups (cycle aging & characterization protocol)

- ***Ageing protocols:*** repeated charge–discharge cycles under predefined C-rates, DoD and Temperatures;
- ***Thermal control:*** Climate chamber or Peltier's modules;
- ***Common characterization cycle:*** periodic characterization cycles (HPPC cycles) used to perform OCV measure and parameter identification for equivalent-circuit and electrochemical models.
- ***Measurements***: synchronized V–I–T acquisition and periodic residual capacity evaluation to monitor the capacity fade trends and derive label SoH.



NMC Aging protocol



LFP Aging protocol

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PhD thesis

Data processing & modelling workflow

- **Pre-processing of raw logs**: removal of faulty cycles/system trips and resampling operation.
- **Derived features:** evaluate moved charge (Coulomb counting) and residual capacity.
- **Structured datasets:** ordering by cycle/state to be MATLAB-ready structures for model-based & ANN algorithms.

- **Automate multiple evaluation:** scripted routines for parameter identification (*ECM/ARMAX*) and neural networks operations (data windows, normalization, training & testing).
- **Quality metrics:** automatic computation of fit (*RMSE, MAE and* R^2), and model selection logs.
- **Defined validation protocol**: hold-out split with disjoint acquisitions (training vs testing).

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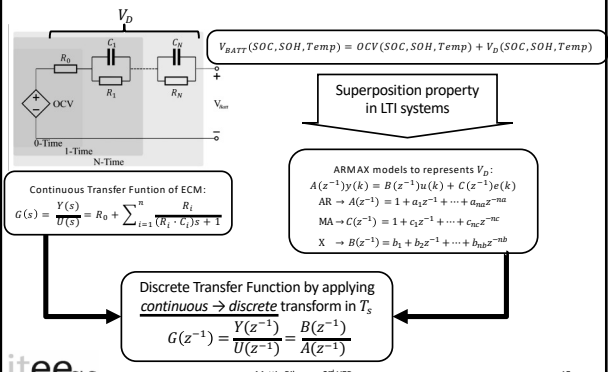
PhD thesis: Model based approach

ARMAX identification and classifier SoH estimator



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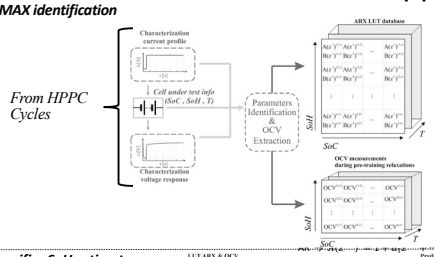
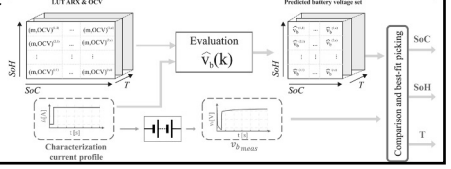
PhD thesis: Model based approach

ARMAX identification



Classifier SoH estimator



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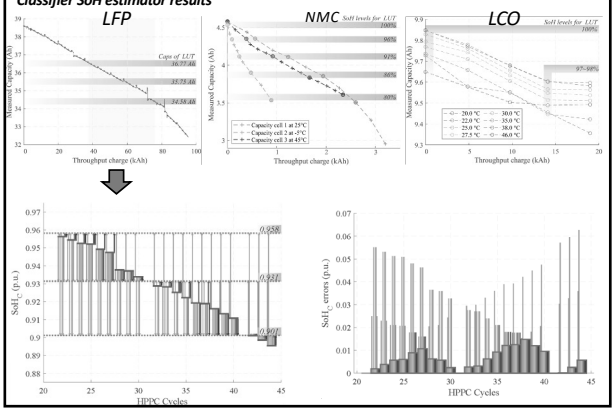
PhD thesis: Model based approach

Classifier SoH estimator results



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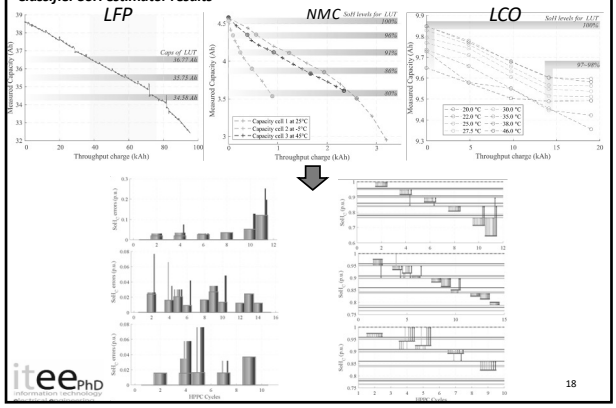
PhD thesis: Model based approach

Classifier SoH estimator results



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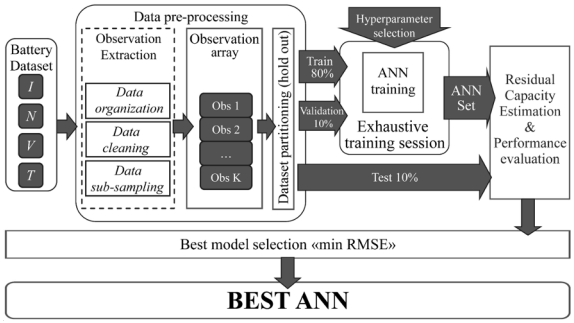
PhD thesis: Data driven approach

Data driven pipeline



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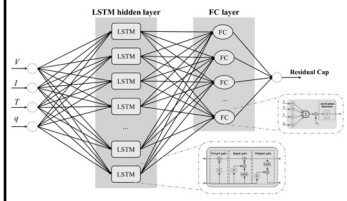
PhD thesis: Data driven approach

Tested ANN architecture



- ***LSTM layer:*** captures extended temporal dependencies in sequences.
- ***Stable training:*** gating mitigates vanishing gradients on long sequences

Dataset used for training and test

For this activity, LFP and NMC datasets were used. The ANNs were trained on 80% of all aging campaign data of a single cell. For testing process was considered remaining data of the same cell (test-set) and, to assess the robustness of the approach, acquisition of unkown cell

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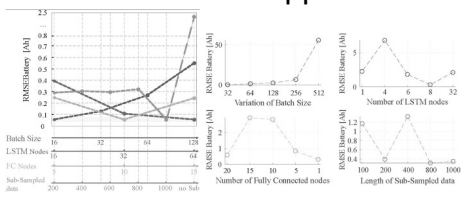
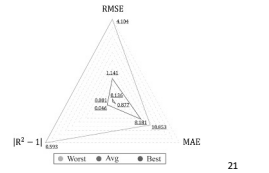
PhD thesis: Data driven approach

Hyperparameter sensitivity test



Evaluation of model

Metric Name	Mathematical Definition
Root Mean Square Error (RMSE)	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$
Maximum Absolute Error (MAE)	$MAE = \max(\lvert y_i - \hat{y}_i \rvert)$
Coefficient of Determination (R^2)	$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$ where $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$



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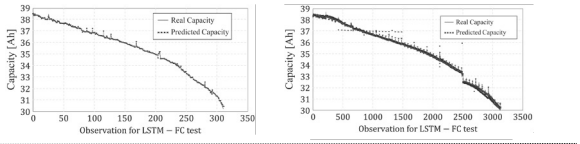
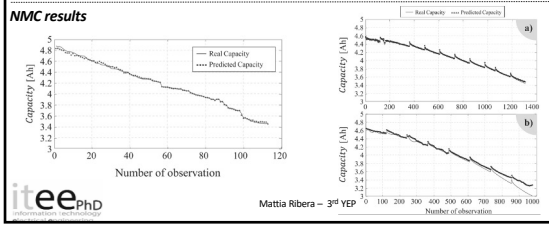
PhD thesis: Data driven approach

LFP results



NMC results



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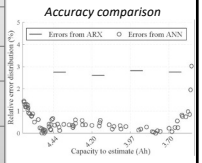
PhD thesis: Conclusion

ARMAX/ECM vs ANN SoH estimators

Aspect	*ARMAX / ECM*	*ANN (LSTM/FC)*
Pre-processing & data needs	Works with **HPPC/characterization** protocol with high sample rate	Uses full aging cycles; needs **large datasets**, stricter curation.
Implementation complexity	Classical system ID and few hyperparameters. Fast to fit models.	Model selection + hyperparameter search. Training pipeline required.
Interpretability	**High** — RC/IR parameters map to physical behavior.	**Low–medium** — latent features; needs post-hoc explainability.
Accuracy	Solid but limited; plateaus around **~2.5–3% mean error** in representative cases.	Higher overall accuracy across the fade trajectory.
Generalization	Best within the same cell/protocol; cross-chemistry requires new Identifications.	Cross-cell generalization possible with sufficient different data.
Computation footprint	Tiny (LUTs/low-order models); MCU-friendly out of the box.	Heavier at inference; can be MCU-feasible
Maintenance	Re-tune or re-identify parameters as conditions change	**Retraining** needed for new domains or shifts (Reinforcement Learning)

Accuracy comparison



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Thanks for the attention

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