Contents of Work Package 3-WP03 – Batteries: Solutions for Testing and Modeling

3-WP03: Batteries: Solutions for Testing and Modeling

Coordinator of the WP

Czech Technical University in Prague, Faculty of Electrical Engineering, MSc. Václav Knap, PhD.

Participants of the WP

Czech Technical University in Prague, Faculty of Transportation Sciences, Ing. Jindřich Sadil, PhD.

Czech Technical University in Prague, Faculty of Mechanical Engineering, Ing. Rastislav Toman

ŠKODA AUTO a.s., Ing. et Ing. Nikola Klusoňová

Garrett Motion Inc., Ing. Jaroslav Pekař, PhD.

Main Goal of the WP

Advancement of battery technology aspects to provide additional value to battery-based automotive vehicles, to improve their design processes, to reduce the development cost, and to provide diagnostic capabilities. Selected tools for achieving these goals are a battery modeling platform and a quick battery diagnostic technique.

Partial Goals for the Current Period

Partial goals for the current period were to develop battery cell models and to initiate degradation tests. Moreover, to create an HW setup and progress in its SW development part that will be used for electrochemical impedance spectroscopy-based battery diagnostics.

Contents of Work Package 3-WP03 – Batteries: Solutions for Testing and Modeling

3-WP03: Batteries: Solutions for Testing and Modeling

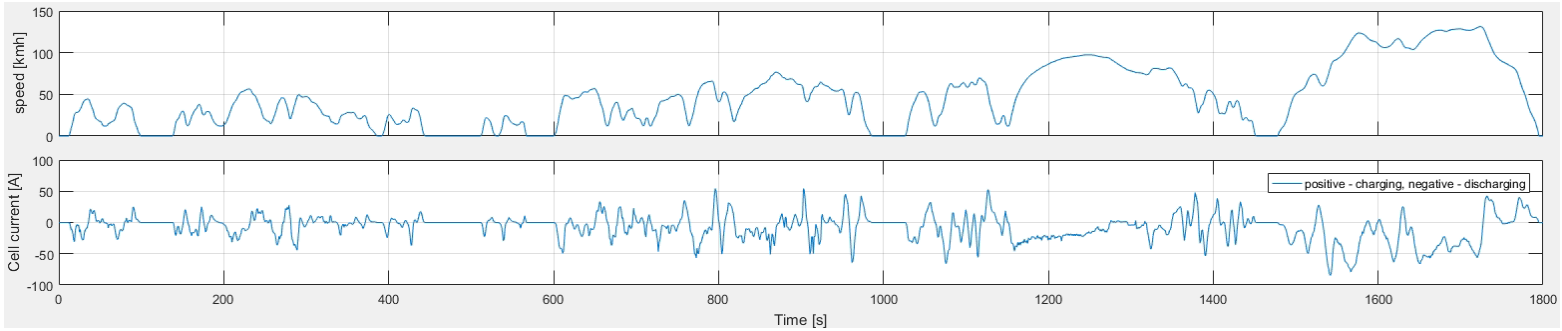
Official 3-WP03 Deliverables:

- 3-WP03-001 | **Complex traction battery model**, R, XII./2025, CTU 0.9; GM 0.1
- 3-WP03-002 | **Device and setup for quick diagnostic of automotive batteries**, G-funk, XII./2025, CTU 0.9; GM 0.1
- 3-WP03-003 | **Report on Milestones - Battery electric vehicle optimizer using complex traction battery model – results description**, O, XII./2025, CTU 0.9; GM 0.1
- 3-WP03-004 | **Report on Milestones - Quick diagnostic for automotive batteries via impedance measurements – results description**, O, XII./2025, CTU 0.9; GM 0.1

Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

3-WP03-001: Complex traction battery model

- **Battery characterization tests** for a battery cell model parametrizations
  - 18650 cylindrical Panasonic 3.25 Ah, NCA/Gr – completed
  - 18650 cylindrical Huahui Energy 1.3 Ah, LCO-LMO/LTO – ongoing
- **Battery degradation campaign**
  - 21700 cylindrical LG M50LT 5 Ah, NMC/Gr-Si – ongoing
- **Electrical modeling for a battery cell**
  - Improved 2RC electrical circuit model (ECM) combined with kinetic battery model (Kibam) → enhanced model (EM)
- **Electric vehicle modeling**
  - Model implementation for generating driving profiles for battery testing

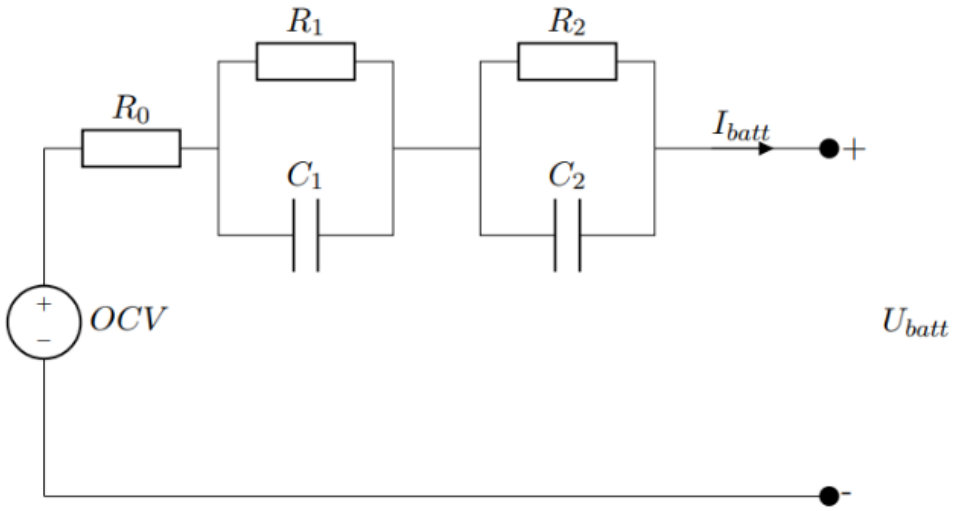


Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

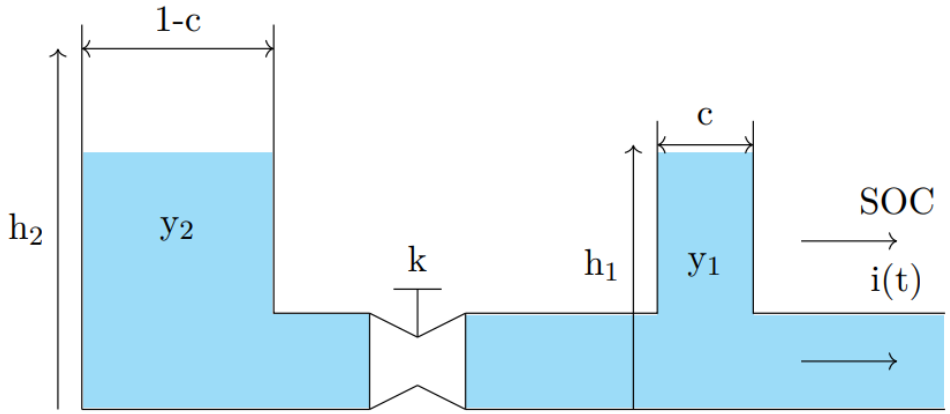
3-WP03-001: Complex traction battery model

Electrical modeling for a battery cell:

ECM



Kibam



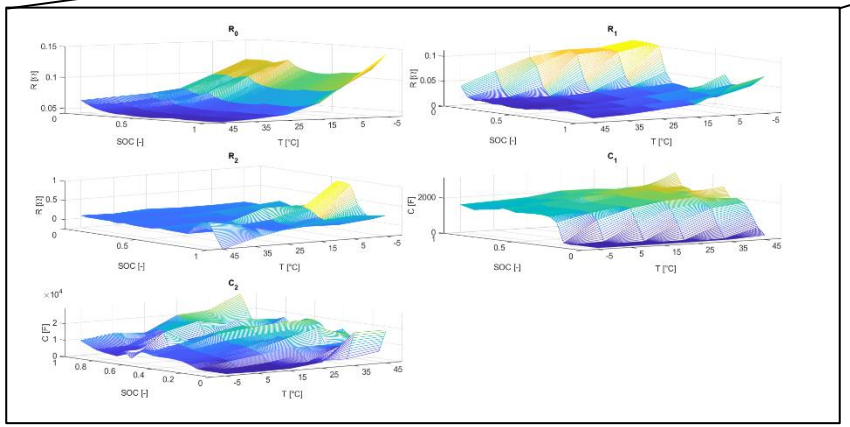
Models combination resulting into an enhanced model (EM)

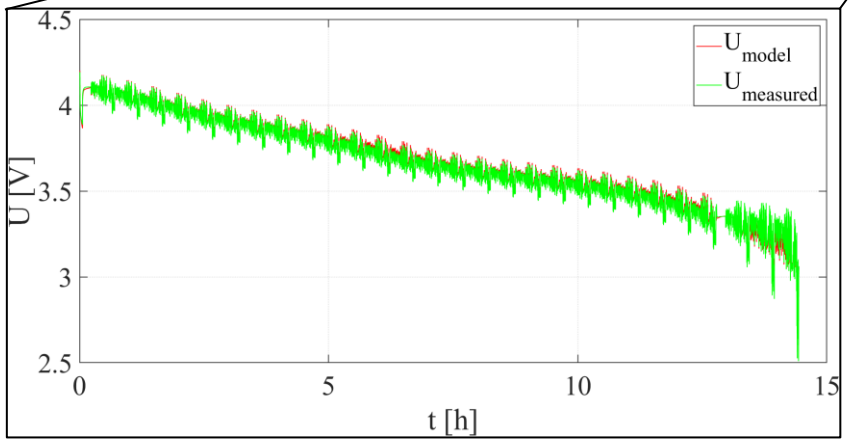
Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

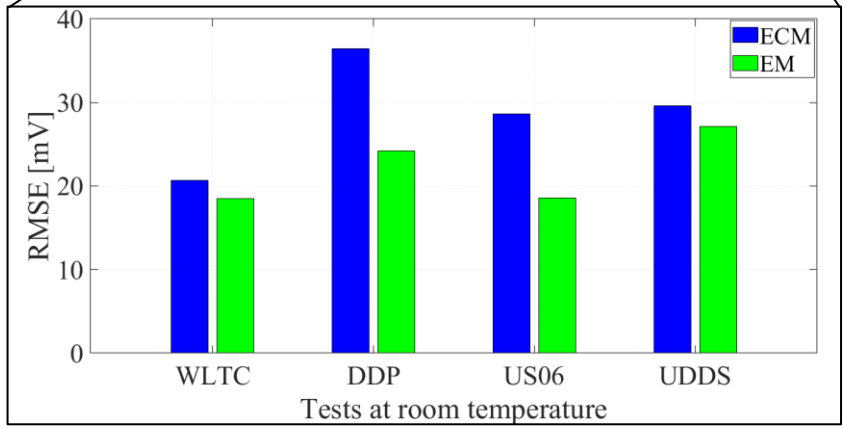
3-WP03-001: Complex traction battery model

Electrical modeling for a battery cell:

Battery characterization → *Battery model parametrization* → *EV driving profile generation & testing* → *Model validation*







Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

3-WP03-001: Complex traction battery model

Dissemination:

- Presented a poster "Kinetic Model for Improved Dynamic Current Response in Lithium-ion Battery Electrical Circuit Models" at ABAF 2024 conference
- Submitted a manuscript "Kinetic Model for Improved Dynamic Current Response in Lithium-ion Battery Electrical Circuit Models" to Monatshefte für Chemie - Chemical Monthly journal

Next steps:

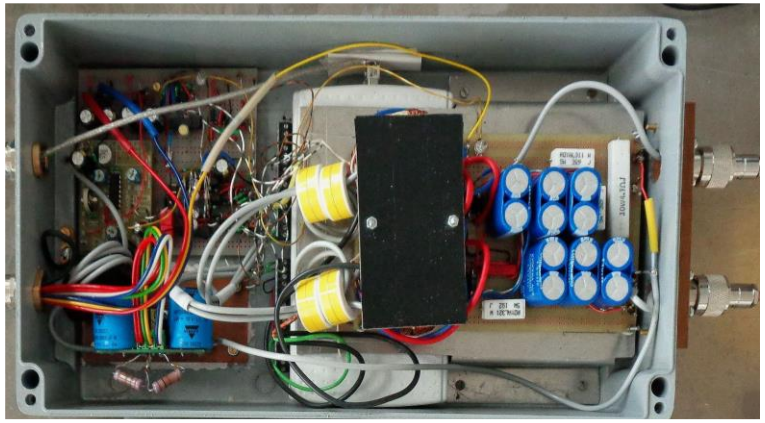
- Battery module/pack modeling
  - Integration of the developed single-cell model into various series/parallel architectures
  - Defining, characterization, and modeling of battery management system functionalities
  - Design and build-up of a battery module to validate the developed model
- Battery characterization tests
  - Continuing to add further cell types and chemistries
- Battery degradation tests
  - Continuation and starting up new tests to provide a lifetime dimension to the model

Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

3-WP03-002: Device and setup for quick diagnostic of automotive batteries

HW design:

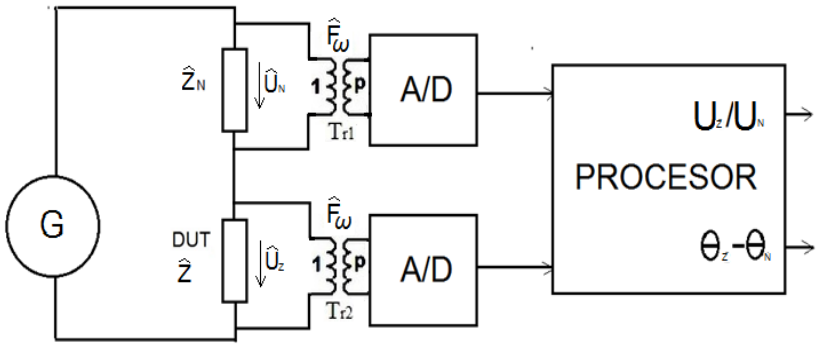
Ver. 1



- To measure impedances in a range of mΩ in frequency ranges 10^{-2} – 10^{4} Hz
- Noise adjustment to increase measurement accuracy

- Generator of the signal G: ICL 8038, voltage controlled
- Power amplifier ZES: TDA7294, total harmonic distortion 0.01 %, Signal to noise ratio 75 dB
- A/D converter: NI USB-6211
- Analogue power supply for low noise (in-house)

Principal scheme:

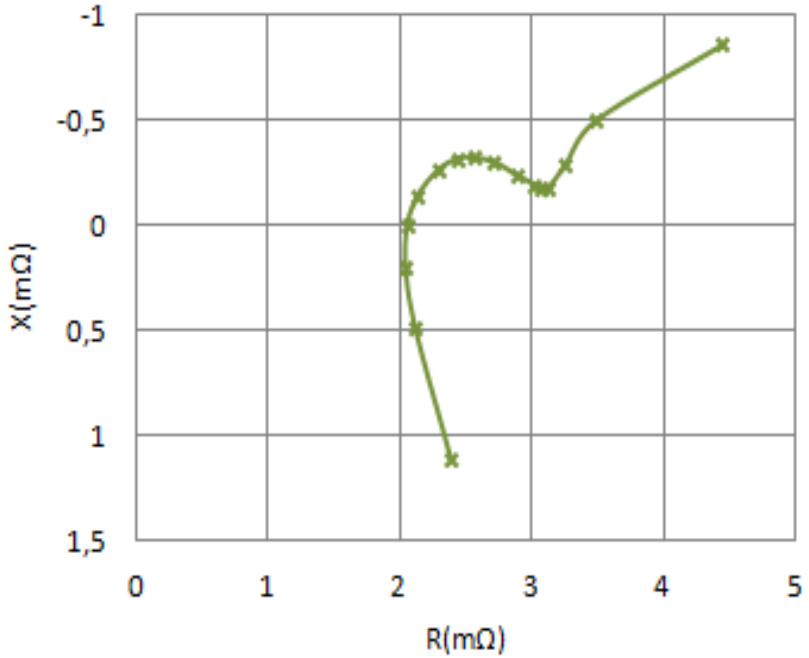


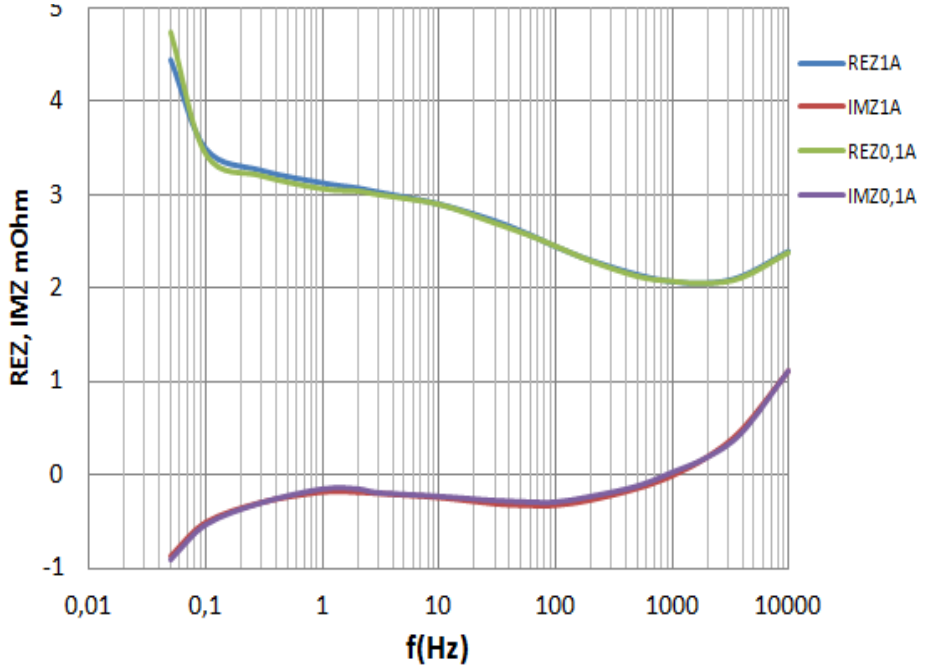
Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

3-WP03-002: Device and setup for quick diagnostic of automotive batteries

Measurements for the device version 1:

- Measurements performed on a prismatic cell Winston 40 Ah, LFP/Gr



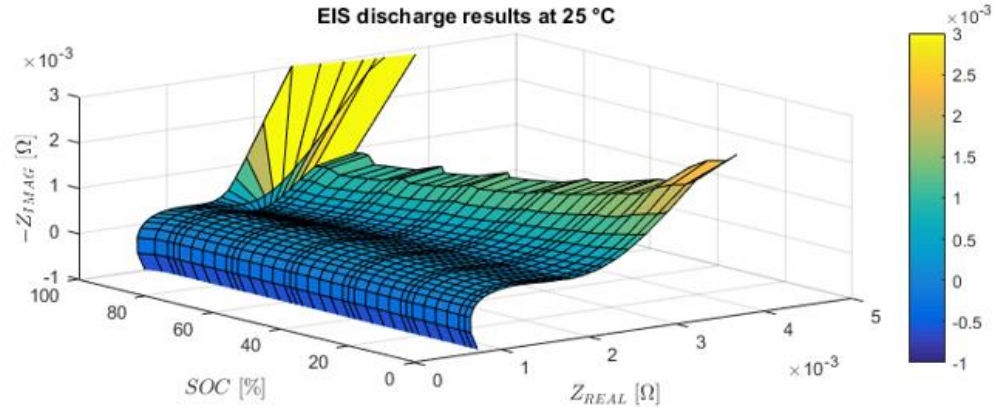


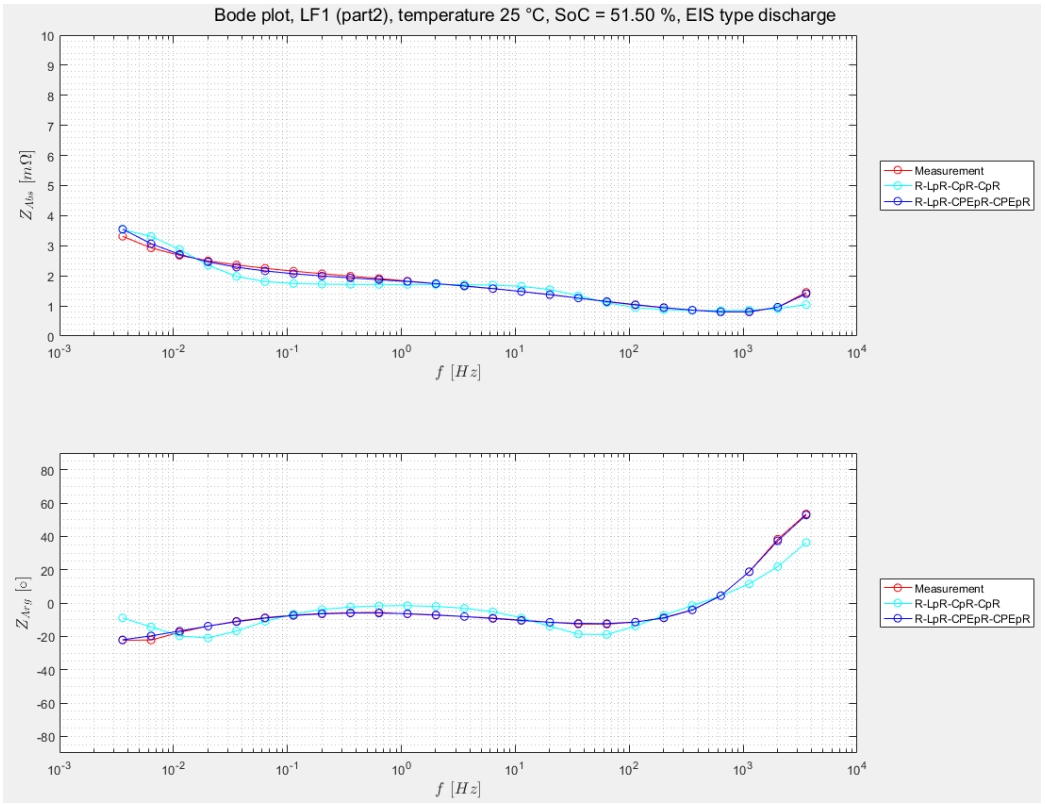
Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

3-WP03-002: Device and setup for quick diagnostic of automotive batteries

Measurements at CTU FTS:

- Validation device measurements performed on a prismatic cell Winston 90 Ah, LFP/Gr





Using CPE decreases fit error significantly

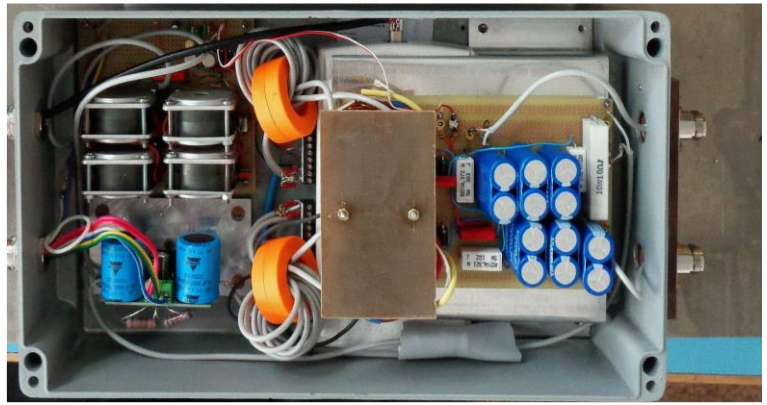
- R-L||R-C||R-C||R model ……. MAE = 0.180 mΩ
- R-L||R-CPE||R-CPE||R model …. MAE = 0.039 mΩ
- (numbers corresponding to the right figure)

Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

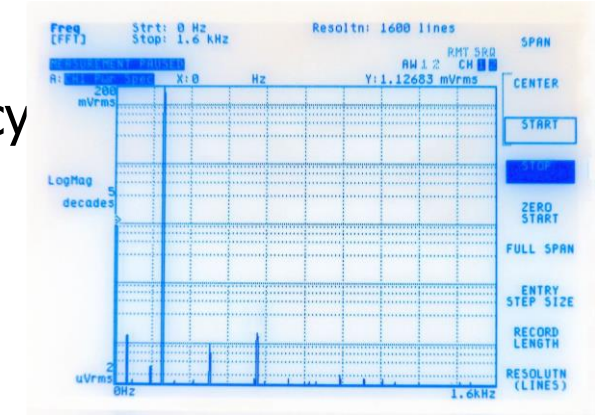
3-WP03-002: Device and setup for quick diagnostic of automotive batteries

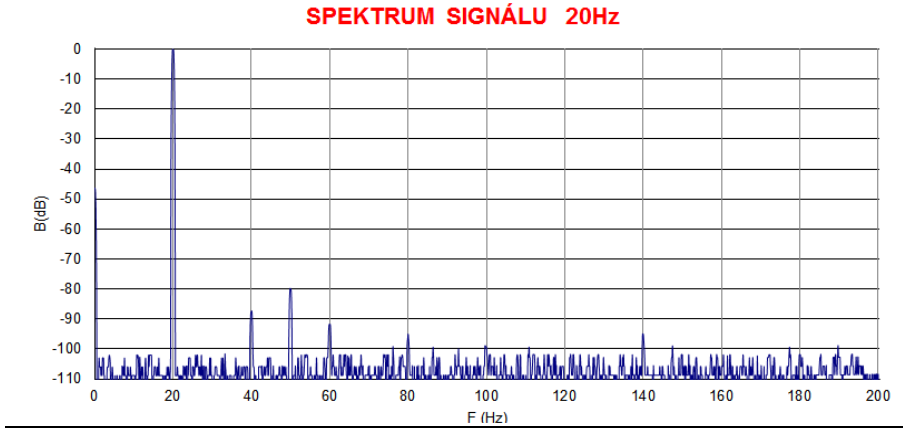
HW design:

Ver. 2

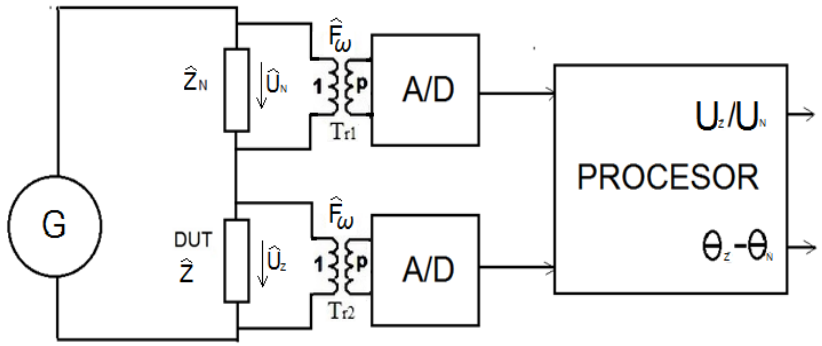


- Improved frequency control (digital)
- Filtration of generated signal
- Clearly generated carry frequency





Principal scheme:

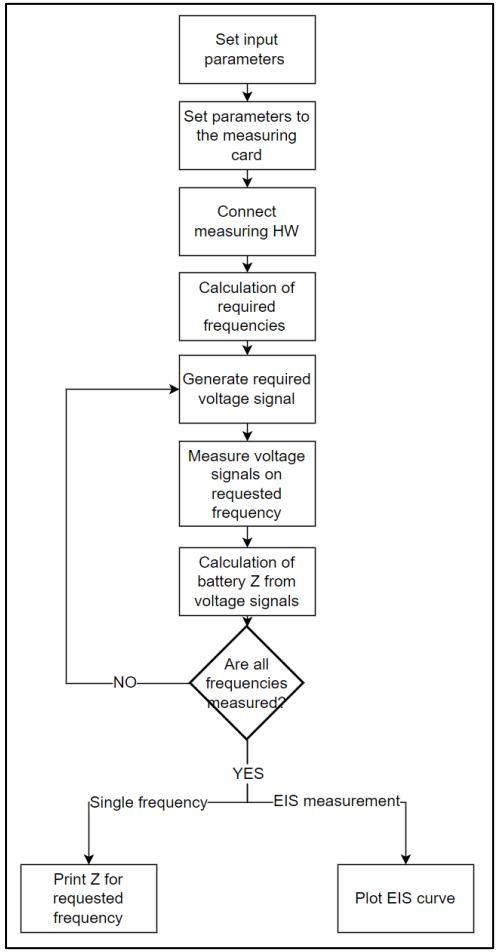


Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

3-WP03-002: Device and setup for quick diagnostic of automotive batteries

SW design

- For the overall control of the hardware system of the device, sensing, processing, and displaying the measured data, a software is developed in MATLAB
- Communication with NI USB 6211 via the Data Aquisition Toolbox
- MATLAB App Designer used to create a GUI
- Performing a frequency sweep from the highest frequency to the lowest, while handling transient phenomena
- Processing data

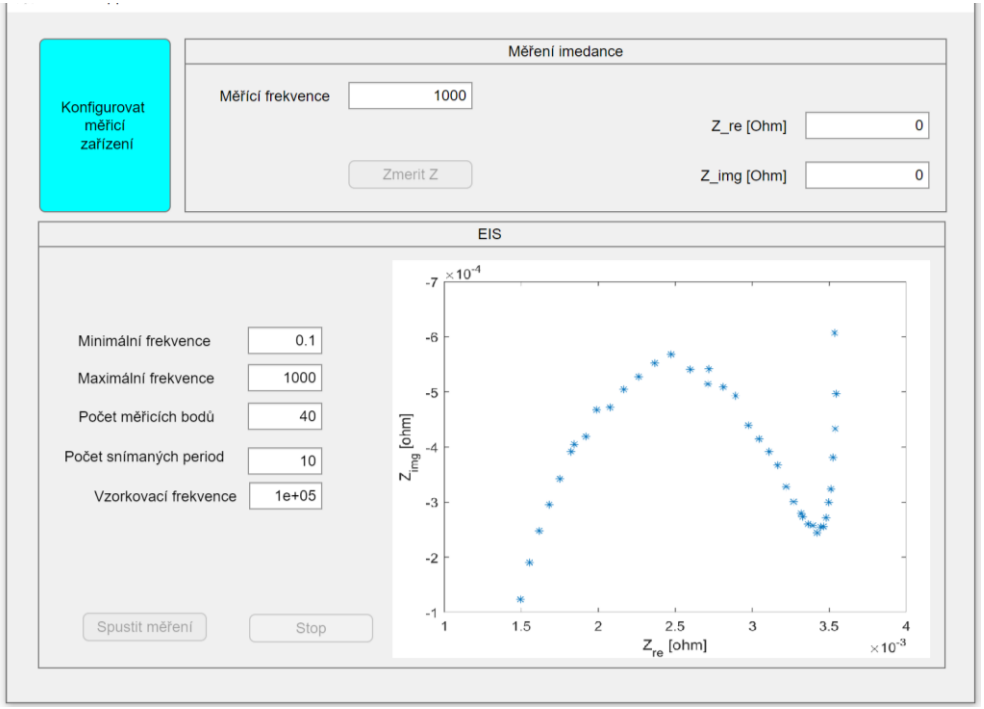


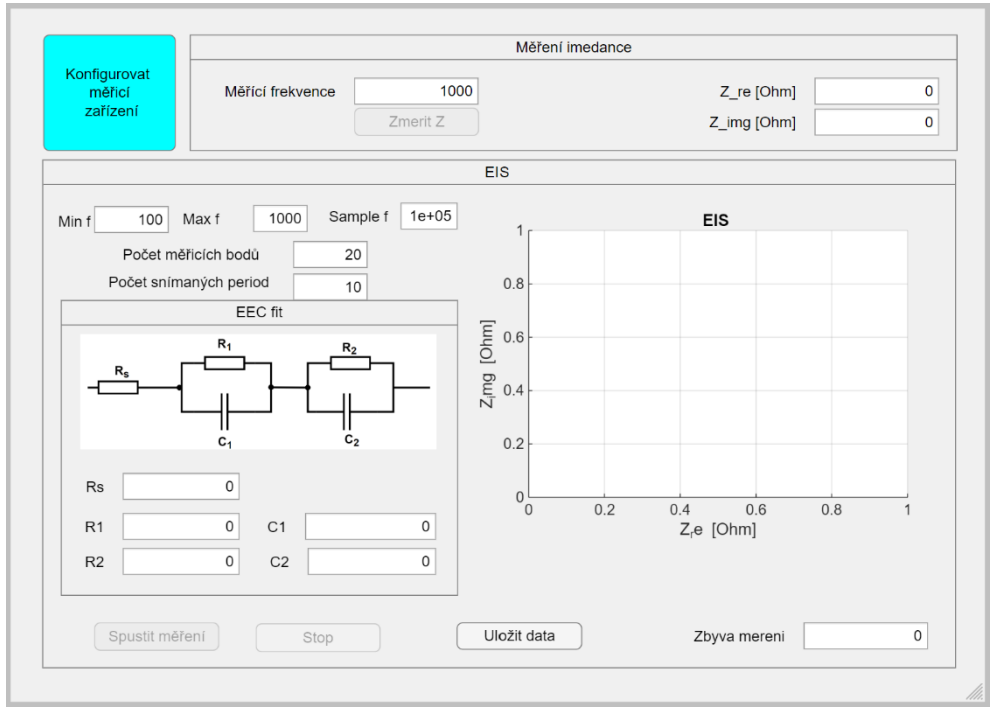
Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

3-WP03-002: Device and setup for quick diagnostic of automotive batteries

SW design

- Demonstrated signal-to-noise ratio: 60 – 75 dB – competitive with commercial devices
- Functionality to fit measured data to an electrical circuit model (currently implemented one)





Activities in 3-WP03 – Batteries: Solutions for Testing and Modeling

3-WP03-002: Device and setup for quick diagnostic of automotive batteries

Dissemination:

- Nováková, K., Papež, V., Sadil, J. et al. Review of electrochemical impedance spectroscopy methods for lithium-ion battery diagnostics and their limitations. *Monatsh Chem* **155**, 227–232 (2024). https://doi.org/10.1007/s00706-023-03165-1

Next steps:

- Complete HW device version 2
- Finalize SW
- Expand diagnostic interpretation
- Testing and validation to map its capability in detail, identify limitations and need for improvements

Fulfillment of goals and deliverables of 3-WP03 – Batteries: Solutions for Testing and Modeling

Current State of Deliverables and Fulfillment of Goals

- 3-WP03-001 | Complex traction battery model, R, XII./2025, CTU 0.9; GM 0.1– **in progress & no major delays:**
  - Experimental tests completed for one type of battery cell.
  - Single cell electrical battery model was developed.

- 3-WP03-002 | Device and setup for quick diagnostic of automotive batteries, G-funk, XII./2025, CTU 0.9; GM 0.1 – **in progress & no major delays**:
  - Hardware of the measurement device was developed.
  - Developed software so far enables a limit functionality.

- 3-WP03-003 | Report on Milestones - Battery electric vehicle optimizer using complex traction battery model – results description, O, XII./2025, CTU 0.9; GM 0.1 – **in progress & no major delays**

- 3-WP03-004 | Report on Milestones - Quick diagnostic for automotive batteries via impedance measurements – results description, O, XII./2025, CTU 0.9; GM 0.1 – **in progress & no major delays**

Fulfillment of goals and deliverables of 3-WP03 – Batteries: Solutions for Testing and Modeling

List of Due Deliverables and Their Added Value

- **3-WP03-001** – aims for a modeling platform of an automotive battery module/pack, which can be used for vehicle optimization, test bench of state estimation algorithms, and an effective range prediction. It is expected to decrease the cost of the development process and to further add value to the end product.
- **3-WP03-002** – quick diagnostic method for lithium-ion battery cells, which will assess their current electrochemical state. It is expected to be used for battery evaluation, quality control, and cell sorting. It is expected to open the path for battery module diagnostics and to on-board diagnostics.
- **3-WP03-003** – reporting and dissemination of 3-WP03-001.
- **3-WP03-004** – reporting and dissemination of 3-WP03-002.

Current contribution of 3-WP03 – Batteries: Solutions for Testing and Modeling

Assessment of the Contribution of Deliverables

- Complex traction battery model, its integration or used in optimization – 4-WP06, 3-WP04, 4-WP07, 3-WP12, 3-WP13, 4-WP09, 4-WP04 and potential NCK2 (BOVENAC) project. It will be further utilized in future research projects and contractual research.
- Diagnostics of automotive batteries and its application within the related activities – 3-WP11, 4-WP04 and potential NCK2 (BOVENAC) project. It will be further utilized in future research projects and contractual research.

Assessment of the Formal/Administrative Goals of the Work Package

- Currently the finances (reporting/spending), commercialization, and deliverables activities are carried and fulfilled primary by CTU. ŠKODA AUTO a.s. and Garrett Motion Inc. participate mainly in a consultancy manner.

Current contribution of 3-WP03 – Batteries: Solutions for Testing and Modeling

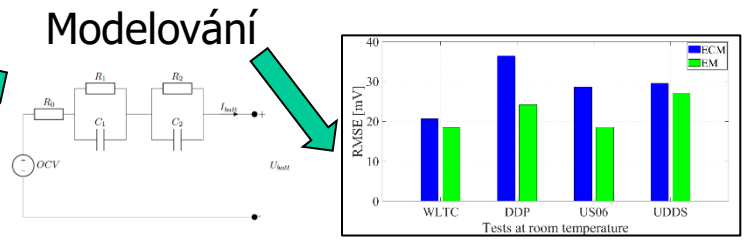
Acknowledgment

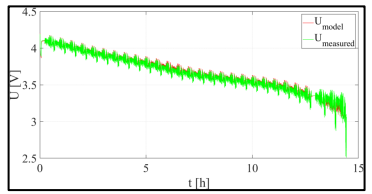
This research has been realized using the support of Technological Agency, Czech Republic, programme National Competence Centres II, project # TN02000054 Božek Vehicle Engineering National Center of Competence (BOVENAC).

Výtah z prací 2023-2025 na 3-WP03 Baterie: Řešení pro testování a modelování

Václav Knap, vaclav.knap@cvut.cz

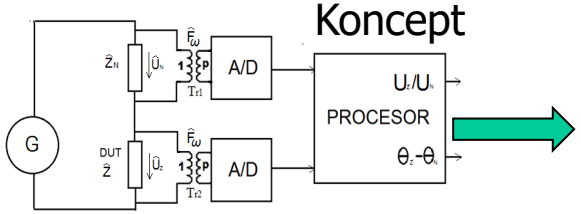
Pracovní balíček se zaměřuje na dva klíčové výstupy v oblasti bateriových technologií. Výstup 3-WP03-001, komplexní model trakční baterie, má sloužit k integraci s modely dalších částí vozu a umožnit optimalizaci designu i provozu vozidla. Od počátku projektu byly provedeny laboratorní charakterizační testy bateriových článků, jejichž výsledky byly využity pro vytvoření elektrického modelu. Tento model, postavený na náhradním obvodovém schématu, byl dále rozšířen o kinetický model pro dosažení vyšší přesnosti. Diagnostika baterií je klíčová pro třídění, zajištění kvality a aplikace ve druhém životě. Výstup 3-WP03-002, zařízení pro rychlou diagnostiku automobilových baterií, se zaměřuje na vývoj rychlé, dostupné a přesné diagnostické metody, která podpoří kvalitu a bezpečnost bateriových aplikací. Během projektu byla vyvinuta první stabilní verze měřicího zařízení pro elektrochemickou impedanční spektroskopii a aktuálně se dokončuje druhá verze, která dále zlepšuje vlastnosti zařízení a umožňuje rychlejší experimentální režimy. Vyvinutý řídicí software již podporuje základní testování a obsluhu zařízení. Na výstupech spolupracovalo ČVUT v Praze jako hlavní původce, přičemž ŠA a GM přispívali formou konzultací během pravidelných schůzek.

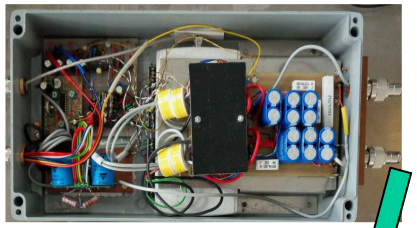


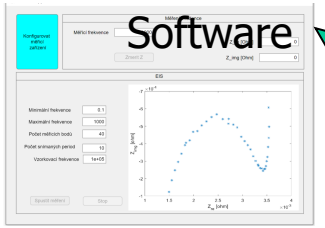


Validace

Diagnostické zařízení pro baterie



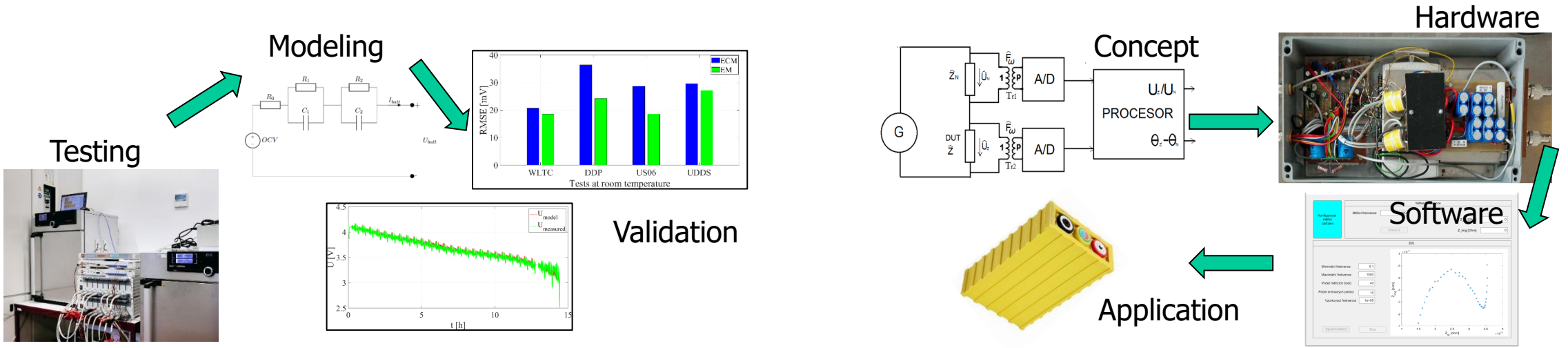




Results of 3-WP03 – Batteries: Solutions for Testing and Modeling – Achieved 2023-2025

Václav Knap, vaclav.knap@cvut.cz

The work package focuses on two key outputs in the field of battery technology. Output 3-WP03-001, a Complex traction battery model, is intended to integrate with models of other parts of the vehicle and enable optimisation of vehicle design and operation. Since the beginning of the project, laboratory characterisation tests of the battery cells have been carried out and the results have been used to create the electrical model. This model, based on a surrogate circuit diagram, was further extended with a kinetic model to achieve higher accuracy. Battery diagnostics are key to sorting, quality assurance and second life applications. Output 3-WP03-002, device and setup for quick diagnostic of automotive batteries, focuses on developing a fast, affordable and accurate diagnostic method to support quality and safety in battery applications. During the project, the first stable version of the measurement device for electrochemical impedance spectroscopy has been developed and a second version is currently being completed to further improve the device's features and enable faster experimental modes. The developed control software already supports basic testing and operation of the device. CTU in Prague has been the main contributor to the outputs, with SA and GM contributing through consultation during regular meetings.



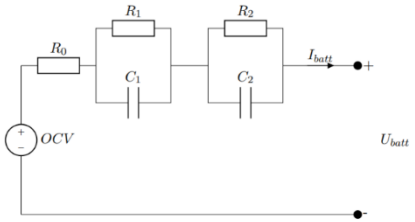
Výtah z prací 2024 na 3-WP03 Baterie: Řešení pro testování a modelování

Václav Knap, vaclav.knap@cvut.cz

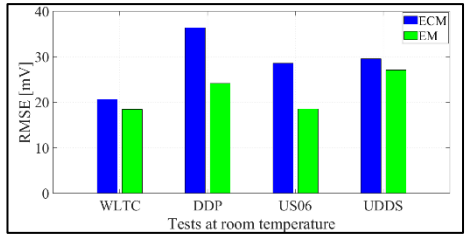
Během řešení v roce 2024 byla dokončena laboratorní charakterizace jednoho typu bateriového článku a další započaty. Na základě testů byl vyvinut elektrický model formou náhradního obvodového schématu a ten dále vylepšen o zahrnutí kinetického modelu, dosahující tak zvýšenou přesnost. V rámci diagnostiky byl dokončen hardware první verze měřícího zařízení pro elektrochemickou impedanční spektroskopii a započata práce na druhé vylepšené verzi. Rozběhly se práce na řídicím a diagnostickém software, který dosáhl stupně, kdy umožňuje prvotní omezené testy.

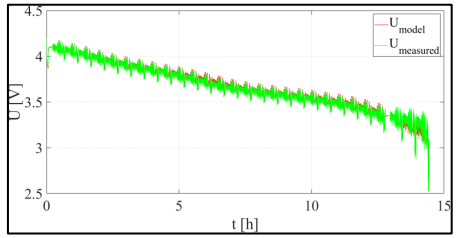
Testování

Modelování



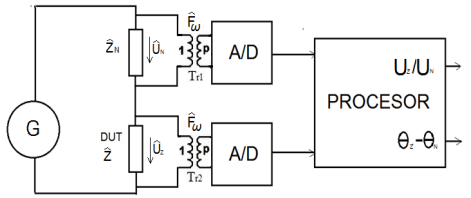
Validace



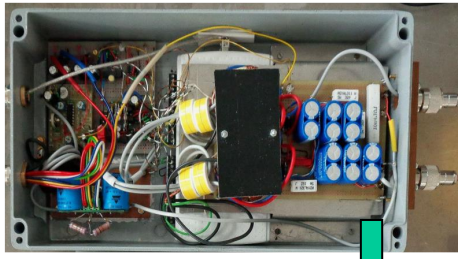


Diagnostické zařízení pro baterie

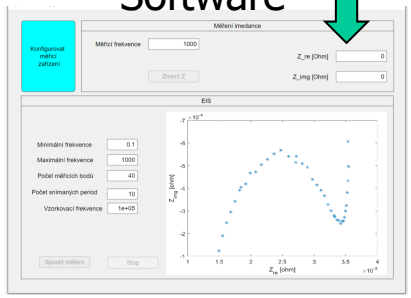
Koncept měření



Hardware



Software



Užití

Results of 3-WP03 – Batteries: Solutions for Testing and Modeling – Achieved 2024

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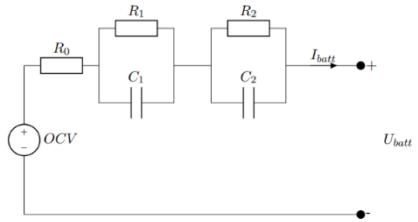
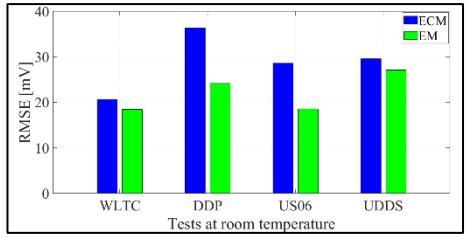
During the 2024, laboratory characterisation of one type of battery cell has been completed and others started. Based on the tests, an electrical model in the form of a surrogate circuit diagram was developed and this was further improved by the inclusion of a kinetic model, achieving increased accuracy. As part of the diagnostics, the hardware of the first version of the electrochemical impedance spectroscopy measuring device was completed and work on a second improved version has begun. Work on the control and diagnostic software is underway and has reached the stage where initial limited tests are possible.

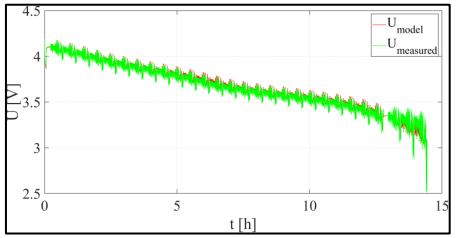
Testing

Modeling



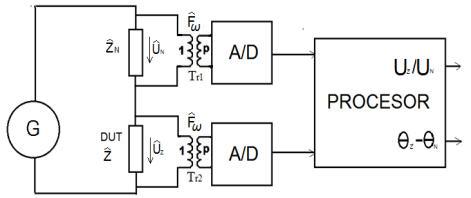
Validation



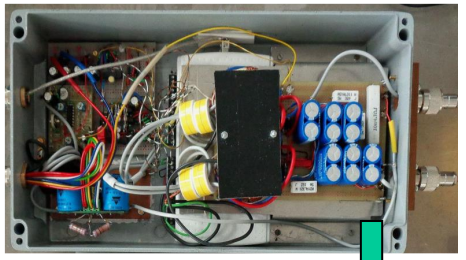


Diagnostické zařízení pro baterie

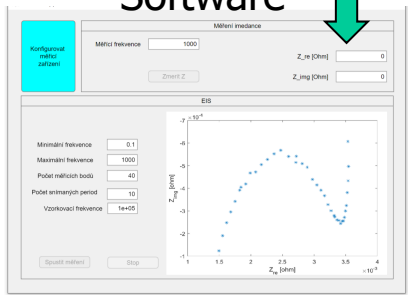
Concept of Measurement



Hardware



Software



Application