TAL TECH | **TALLINNA TEHNIKAÜLIKOOL**
TALLINN UNIVERSITY OF TECHNOLOGY

AI and impedance spectroscopy: from healthcare to health of batteries

Olev Märtens, PhD, TalTech, research group of measurement electronics

Abstract: *Electrical impedance spectroscopy (EIS) is often an efficient method to characterize the tissues, materials, electrochemical objects and processes and much more, statically or dynamically directly or through inductive, capacitive, electroacoustical or other coupling. Adding machine learning (ML) can significantly enhance the possibilities of this technology. Use cases so far and challenges are described*

About presenter – Olev Märtens

TalTech, sr researcher, PhD, …inventor & engineer , IEEE IMS member 20+ years

Olev Märtens (SM, IEEE) was born in Tallinn, Estonia, in 1960. He received the Diploma degree in engineer of electronics (cum laude) and the Ph.D. degree from the Tallinn University of Technology (TUT), Tallinn, in 1983 and 2000, respectively. He has experience from Industrial R&D at the Design Office of the Tallinn Radio Factory RET in 1980's, and the SMEs, in 1990's. In academy, since 2000, has been a Professor and Senior Researcher of measurement electronics with the Thomas Johann Seebeck Department of Electronics, TUT. He is the author of tens of technical papers and inventions from the field of instrumentation and has been and is the Principal Investigator of several R&D projects. Dr. Martens was a recipient of the IEEE I2MTC2020 International Instrumentation and Measurement Technology Conference Best Paper Award in 2020 and the IEEE IMS Faculty Course Award in 2018. He is also a Outstanding Reviewer of 2022 of IEEE Transactions on Instrumentation and Measurement journal. He has supervised 5 PhD Thesis works

Outline of the presentation

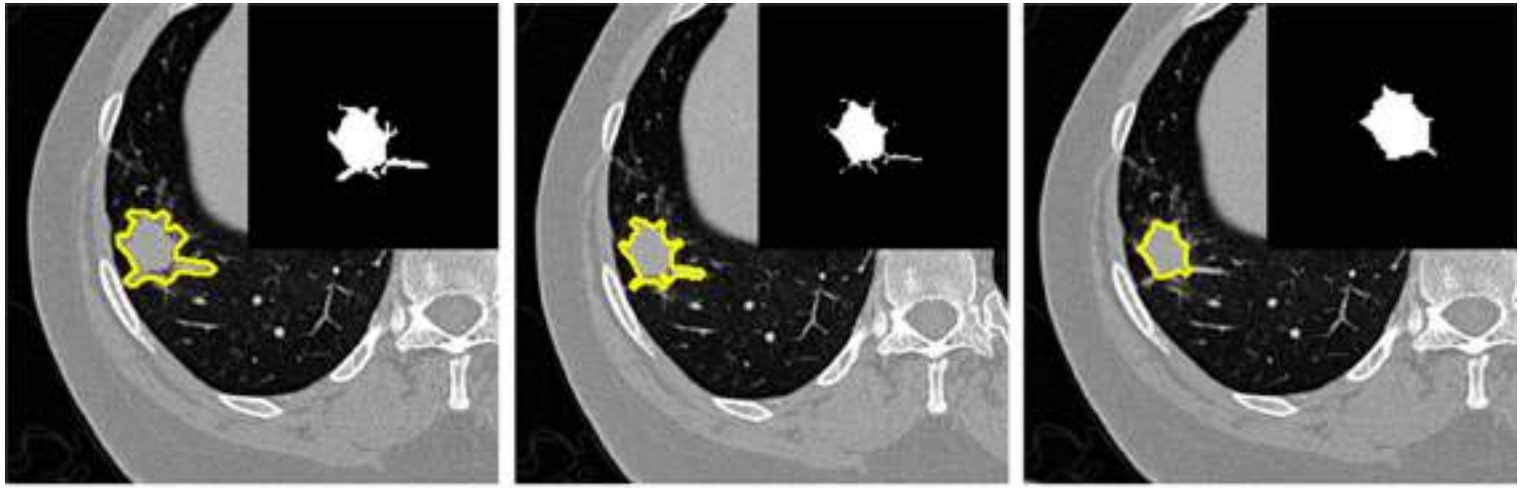
1. Background of the presenter and the research group;

2. Electrical Impedance and applications;

3. Estimating of the Battery health and condition (with and without AI).

Done! ANINDYA GUPTA , PhD Thesis 2018 *(sup O.Märtens, Y.L.Moulles, T.Saar)*

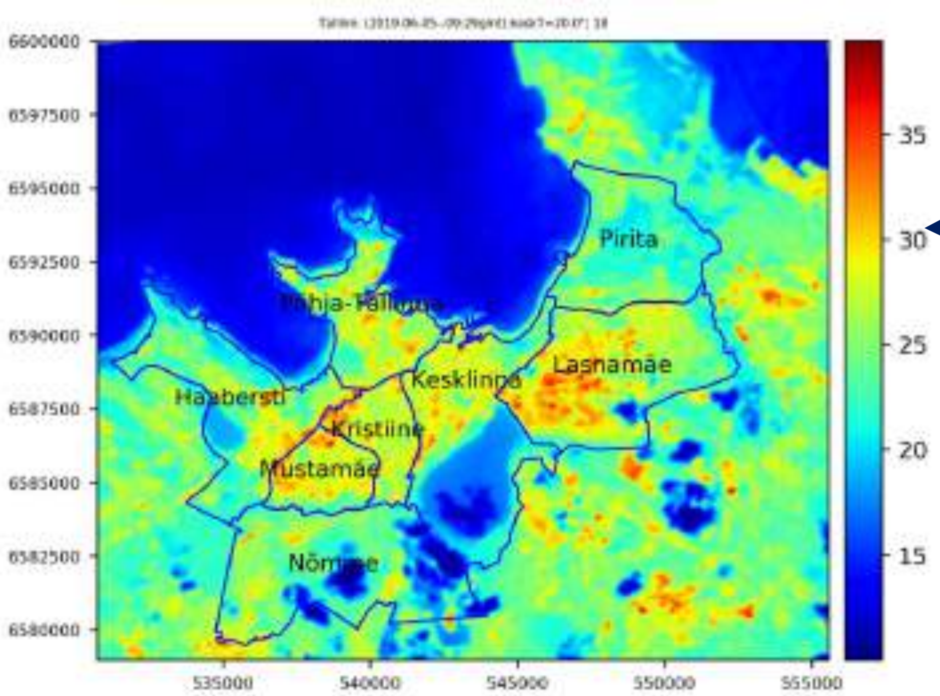
Classification and Denoising of Objects in TEM and CT Images Using Deep Neural Networks



(a) (b) (c)

LIDC database: *7 academic centers + 8 medical imaging companies -> data set of* ***<u>1018 cases</u>*** *– clinical thoracic CT scan and an associated XML annotation by 4 radiologists*

Olev: Idea to promote environmental (**incl climate-related**) hybrid measurement solutions

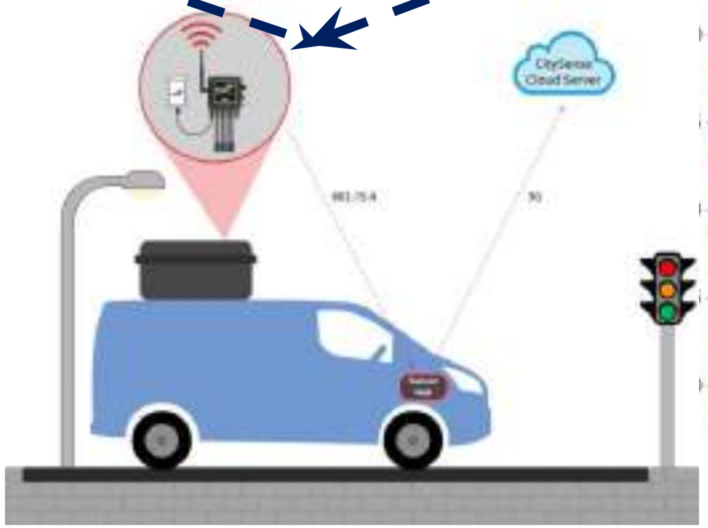


Land surface temperature measured from Landsat-8 satelliite data,

O.M. et al, 2019/2020;

Also air quality can be esimated from remote data!

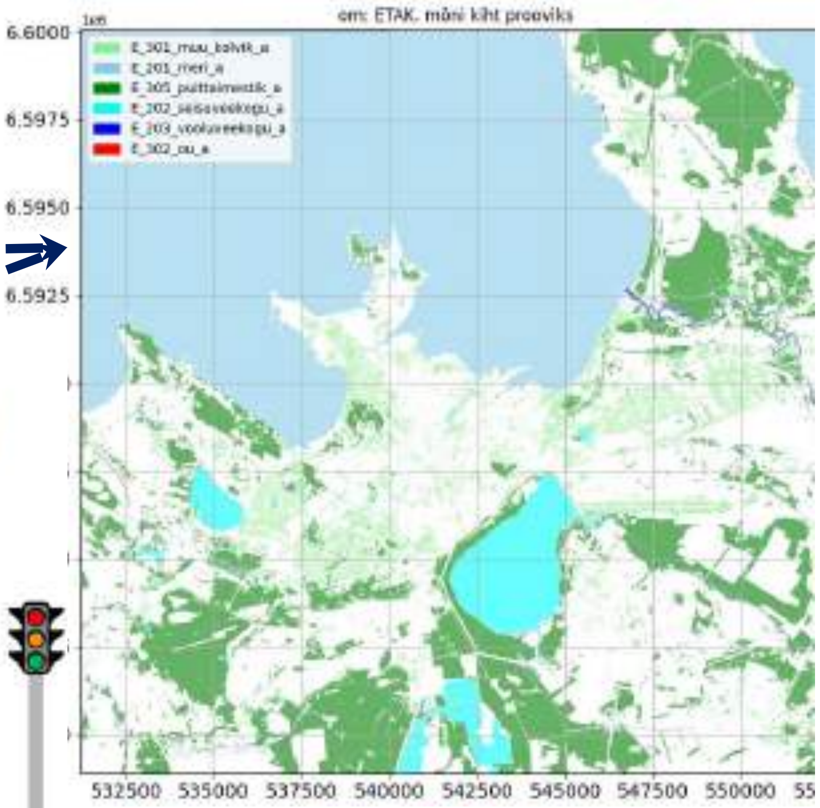
„remote sensing“ +
„Ground truth“ +
ML-based *object models*



Green utility/public vehicles acquiring sensordata © https://www.libelium.com/

Possible project 2025+

TalTech Smart City-Sense *(U.R. et al)*



O.M. Estonian base map (Maa-amet, geoportaal, usable for ML)

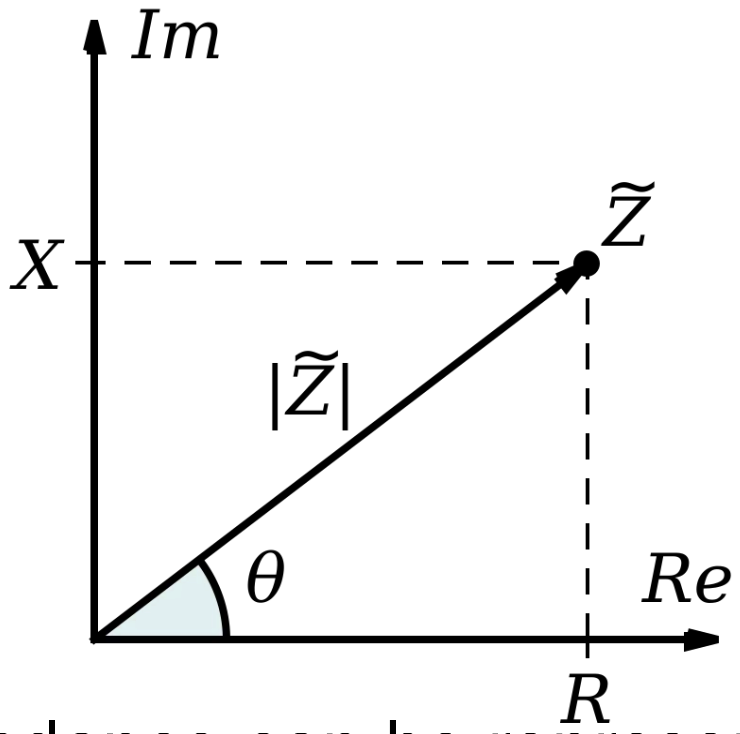
Electrical impedance (from wiki)

In electrical engineering, **impedance** is the opposition to alternating current presented by the combined effect of resistance and reactance in a circuit.[1]

Quantitatively, the impedance of a two-terminal circuit element is the ratio of the complex representation of the sinusoidal voltage between its terminals, to the complex representation of the current flowing through it. In general, it depends upon the frequency of the sinusoidal voltage.

Impedance extends the concept of resistance to alternating current (AC) circuits, and possesses both magnitude and phase, unlike resistance, which has only magnitude.

Electrical impedance …



Cartesian form:

$$Z_{cmpl} = R + j\,X \;, \qquad (1)$$

or Polar form

$$Z_{cmpl} = Z_m * \exp\,(j*\theta), \quad (2)$$

j is the imaginary unit, and is used instead of i in this context to avoid confusion with the symbol for electric current

Impedance can be represented as a complex number, with the same units as resistance, for which the SI unit is the ohm (Ω). Its symbol is usually *Z*, and it may be represented by writing its magnitude and phase in the polar form $|Z|\angle\theta$. However, Cartesian complex number representation is often more powerful for circuit analysis purposes.

- The introduction of the concept of impedance in AC circuit is justified by the fact that there are two additional impeding mechanisms to be taken into account besides the normal resistance of DC circuits: the induction of voltages in conductors self-induced by the magnetic fields of currents **(inductance),** and the electrostatic storage of charge induced by voltages between conductors **(capacitance).** The impedance caused by these two effects is collectively referred to **as reactance** and forms the imaginary part of complex impedance whereas resistance forms the real part

For DC

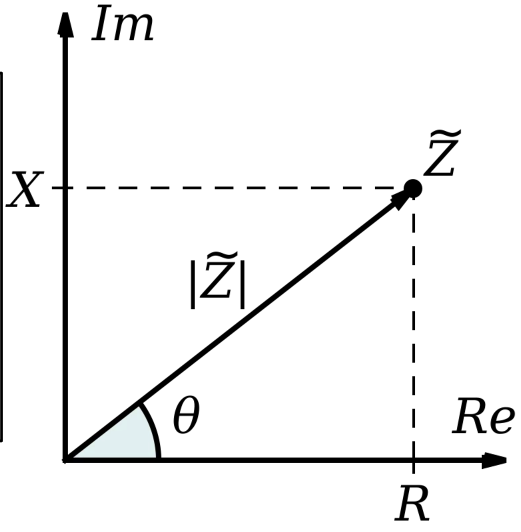
(Ohm's Law):

$R = U / I$

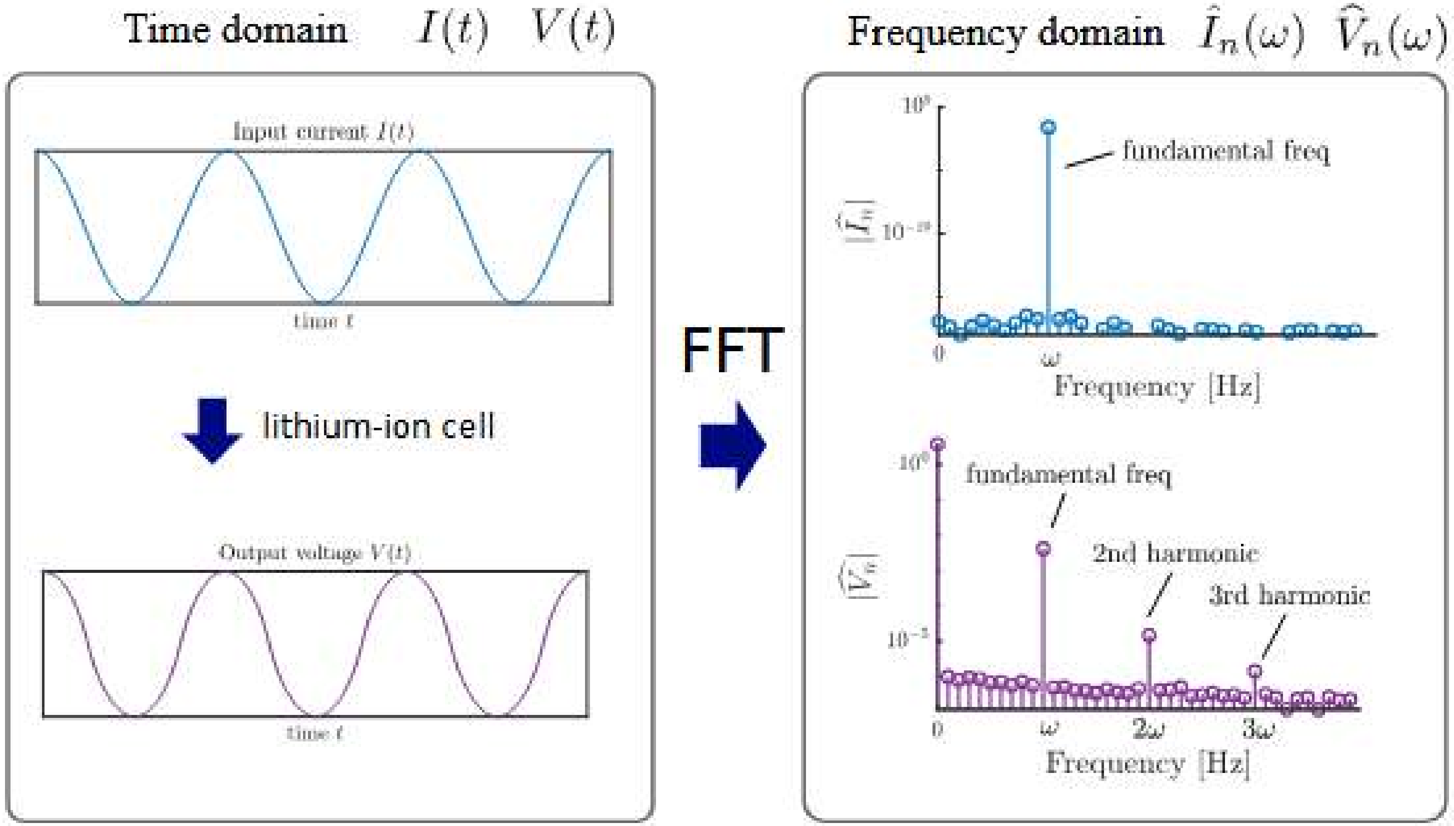
For AC

(Ohm's Law):

$Z_{cmpl} = U_{cmpl} / I_{cmpl}$

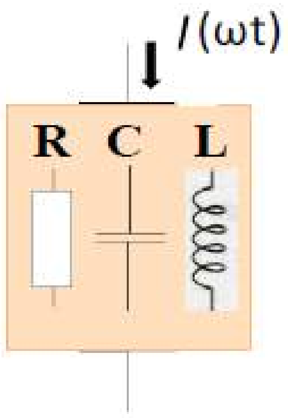


Impedance extends the concept of resistance to AC circuits, and possesses both magnitude and phase, unlike resistance, which has only magnitude. When a circuit is driven with direct current (DC), there is no distinction between impedance and resistance; the latter can be thought of as impedance with zero phase angle.

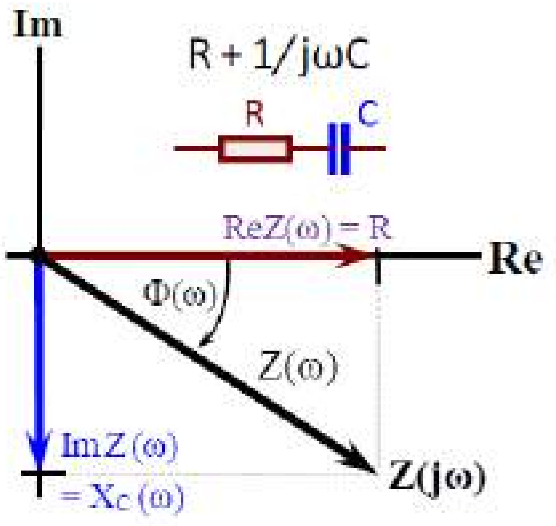


NB! Ohm's law if for LINEAR objects (R or Z is constant!). This is not the case for electrochemistry, including the batteries!

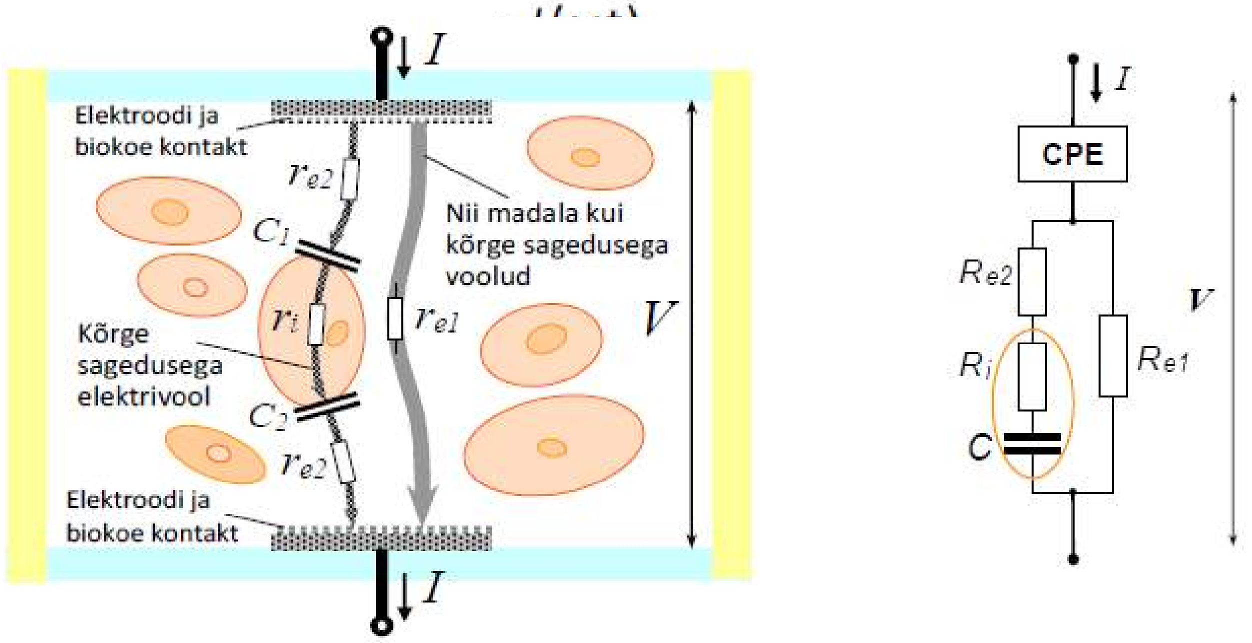
From the paper Kirk, Toby L., et al. "Nonlinear electrochemical impedance spectroscopy for lithium-ion battery model parameterization." Journal of The Electrochemical Society 170.1 (2023): 010514.



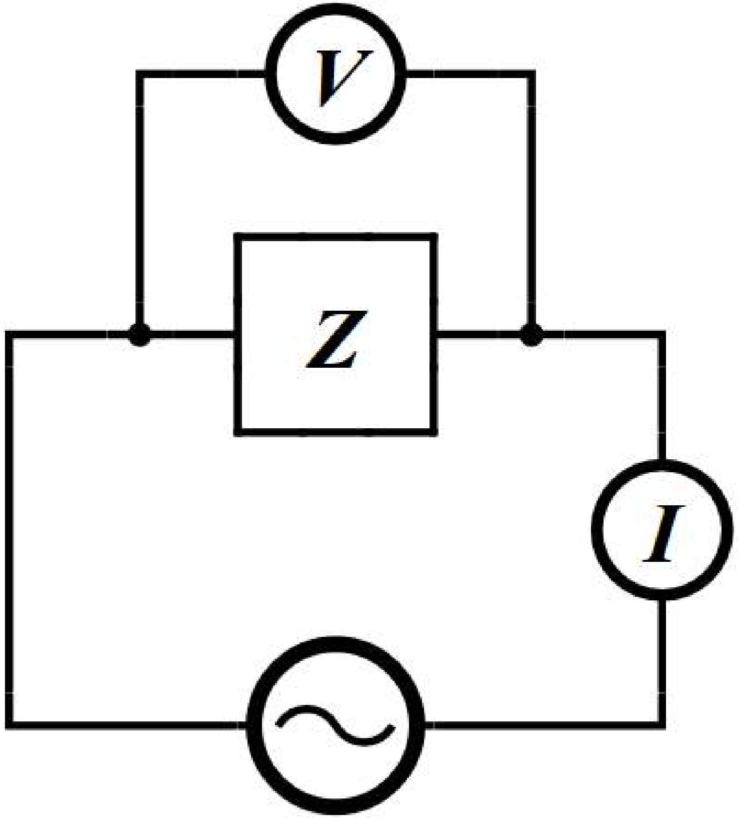
Joon. 1. Impedantsi Z komponendid R, C, L.



Joon. 3. Järjestikimpedantsi Z(jω) = R + 1/(jωC) esitus vektordiagrammina komplekstasandil.



Bio-impedance (by Mart Min)

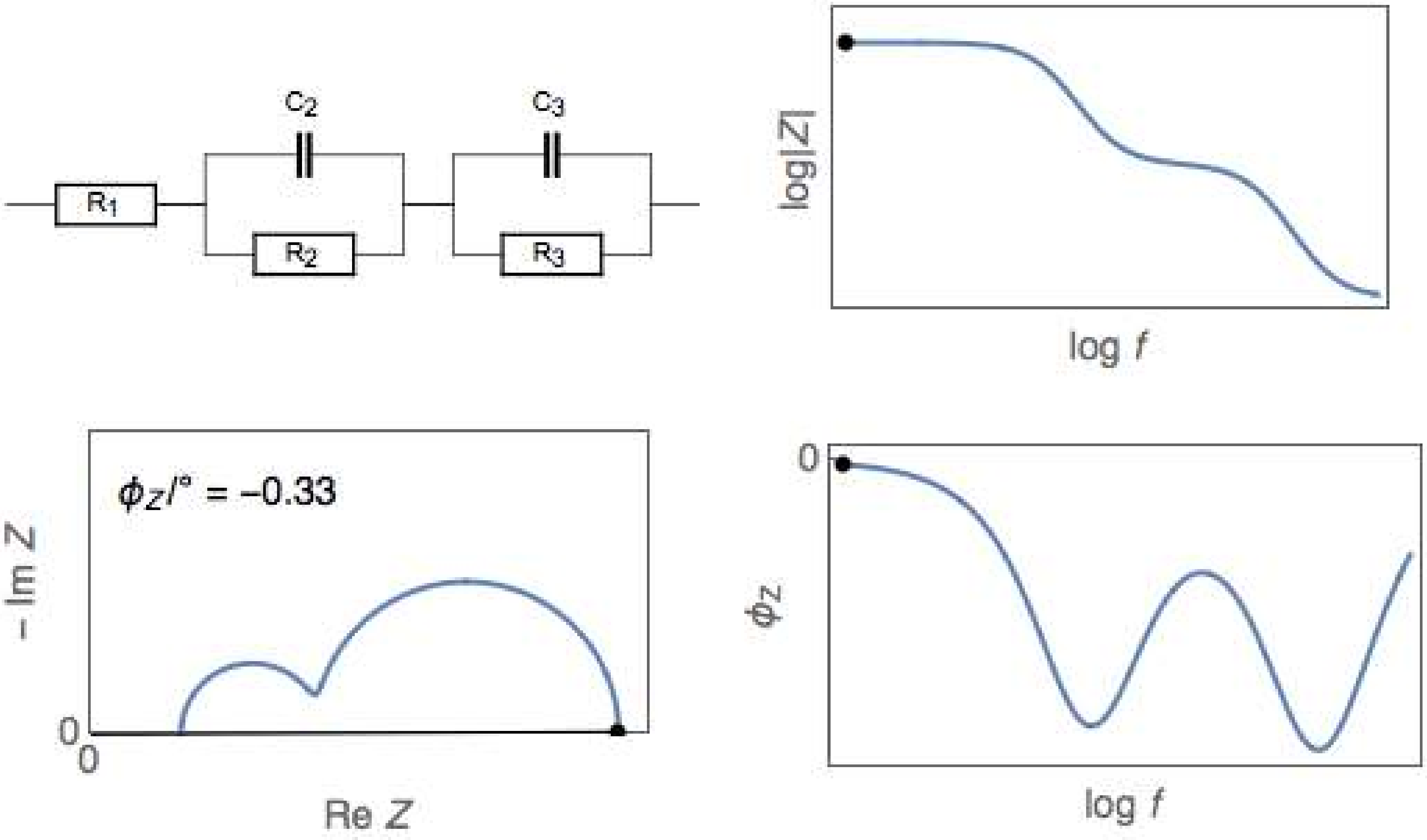


$$V = IZ = I|Z|e^{j\arg(Z)}$$

An AC supply applying a voltage V , across a load Z, driving a current I

„Excitation“ Source (generator) can be voltage or current source,
response to be measured is respectively current or voltage (drop)

Bode' *(left)*and Nyquist *(right)* diagrams for impedance spectra



https://www.biologic.net/topics/what-is-eis/

Done!

TMS320F28069-based impedance spectroscopy

Education and Research Conference (EDERC), 2012 5th European DSP

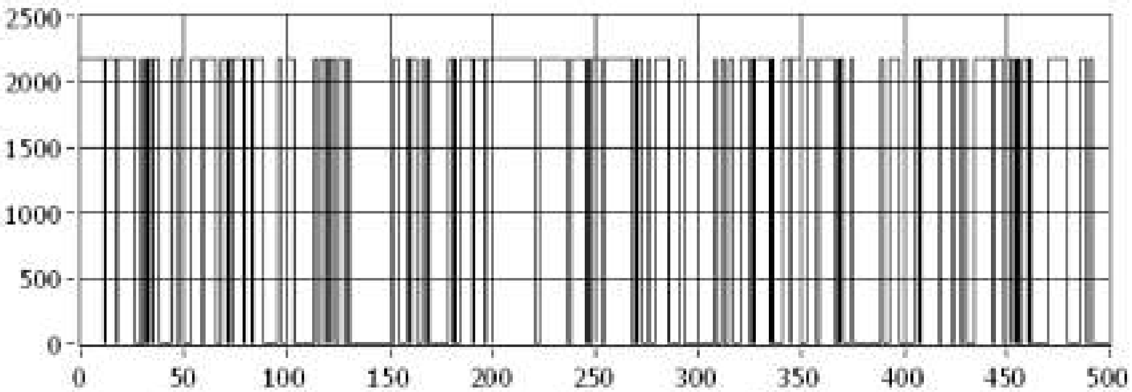
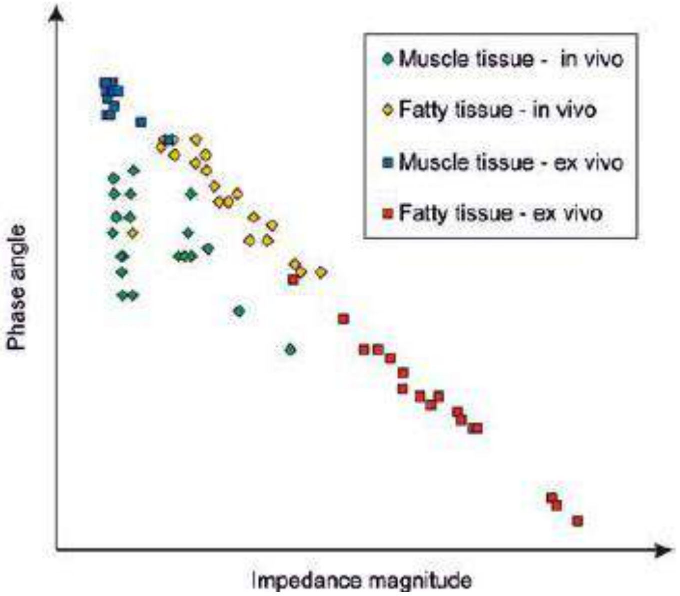


Figure 1 – Binary signal with required frequency content

Impedance based „smart needle"- in co-operation with ***Injeq ltd*** (Finland); ***ML-based classification of soft tissues***



Patents: EE05668, EP2565654, US10698023; ***Raul Land,*** et al, Method and device for broadband analysis of systems and substances

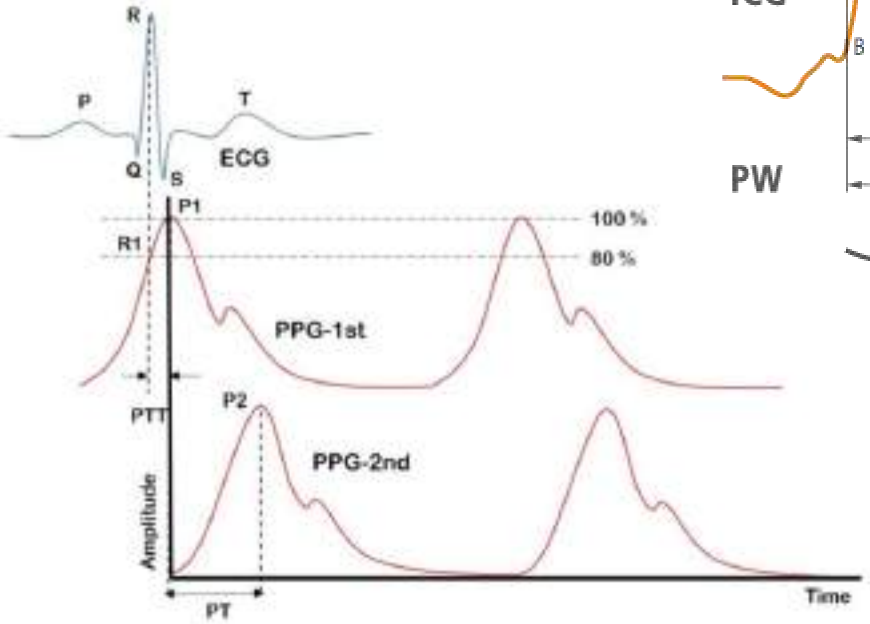
Possible ML applications?

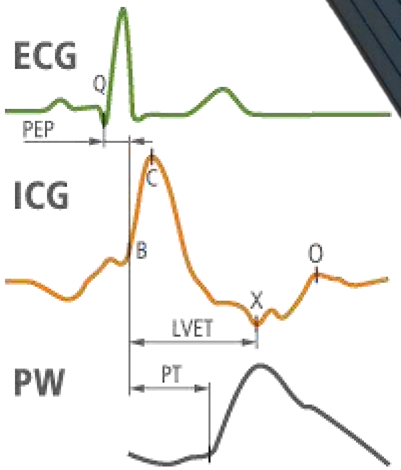
Data acquisition HW available!

Cuffless blood pressure (BP) estimation by Pulse Tarnisition Time or Pulse Arrival Time or raw signal to ML-toolbox,

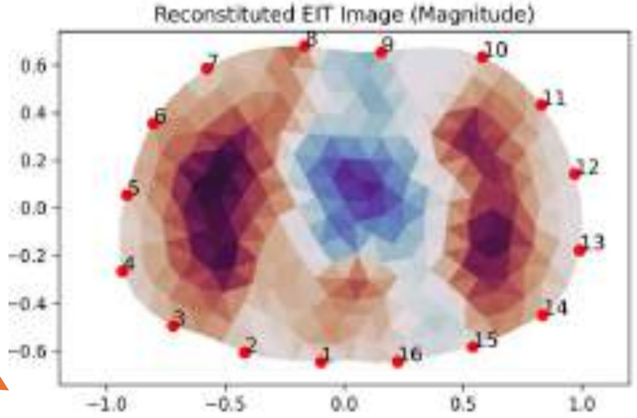
by using PPG , ECG or ICG *(impedance cardiography).*

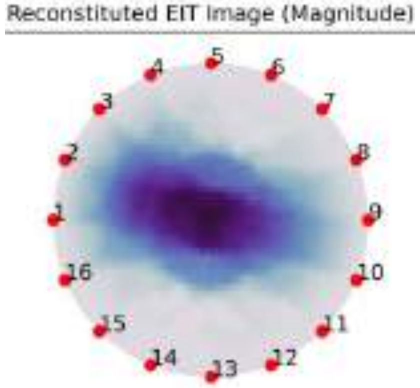
S. C. Kim et al, Blood Pressure Estimation Algorithm Based on Photoplethysmography Pulse Analyses. Appl. Sci. ***2020****, 10, 4068.*





Electrical impedance tomography (EIT) – *ML could be used for image reconstruction alternatively to strict math methods?*



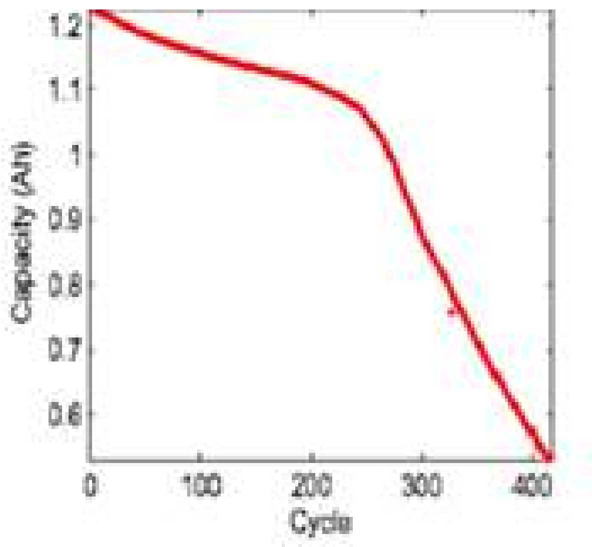


Batteries

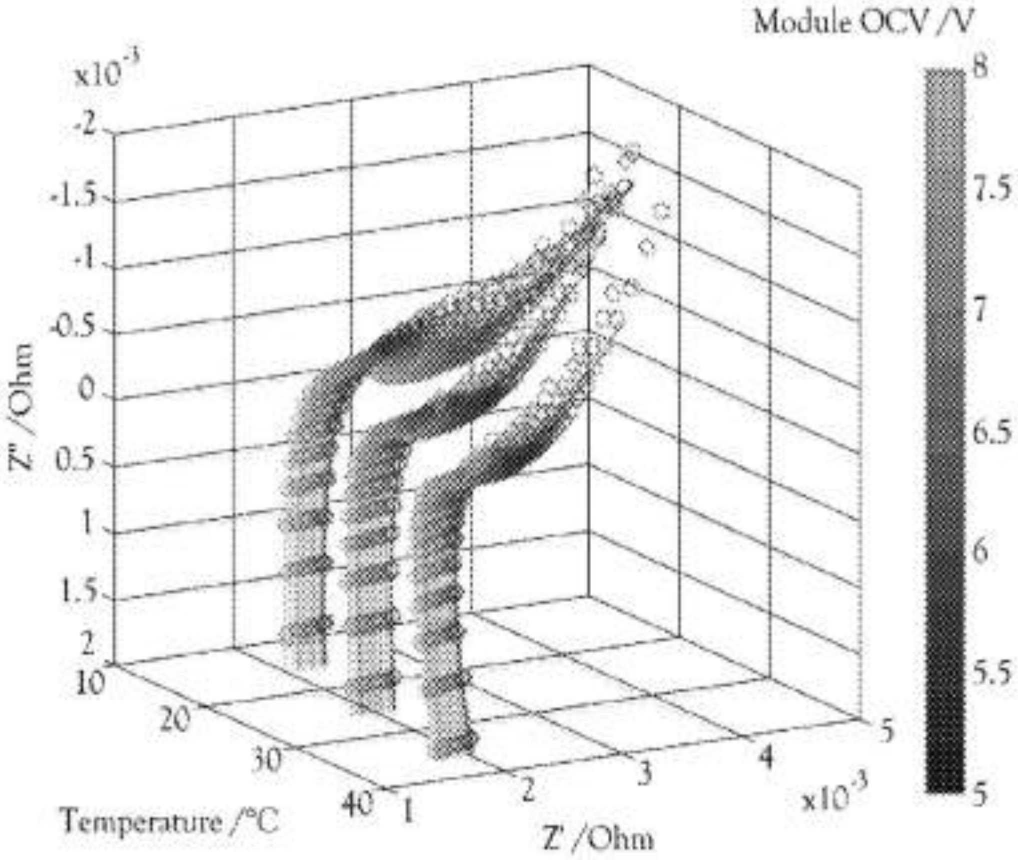
Table 1. Overview of the main characteristics of the most important rechargeable battery systems [1].

Battery system	NiCd	NiMH	Li-ion
Average operating voltage (V)	1.2	1.2	3.6
Energy density ($W\,h\,l^{-1}$)	90–150	160–310	200–280
Specific energy ($W\,h\,kg^{-1}$)	30–60	50–90	90–115
Self-discharge rate (%/month) at 20 °C	10–20	20–30	5–10
Cycle life	300–700	300–600	500–1000
Temperature range (°C)	−20–50	−20–50	−20–50

Some curves



Capacity loss of one type of battery), *from V. Pop, H. Bergveld, P. Notten, and P. Regtien, "State-of-the-art of battery state-of-charge determination," Meas. Sci. Technol. Prof. Holstlaan, vol. 16, 12 2005*



US patent 11262412 (using OCV and EIS, granted 2022)

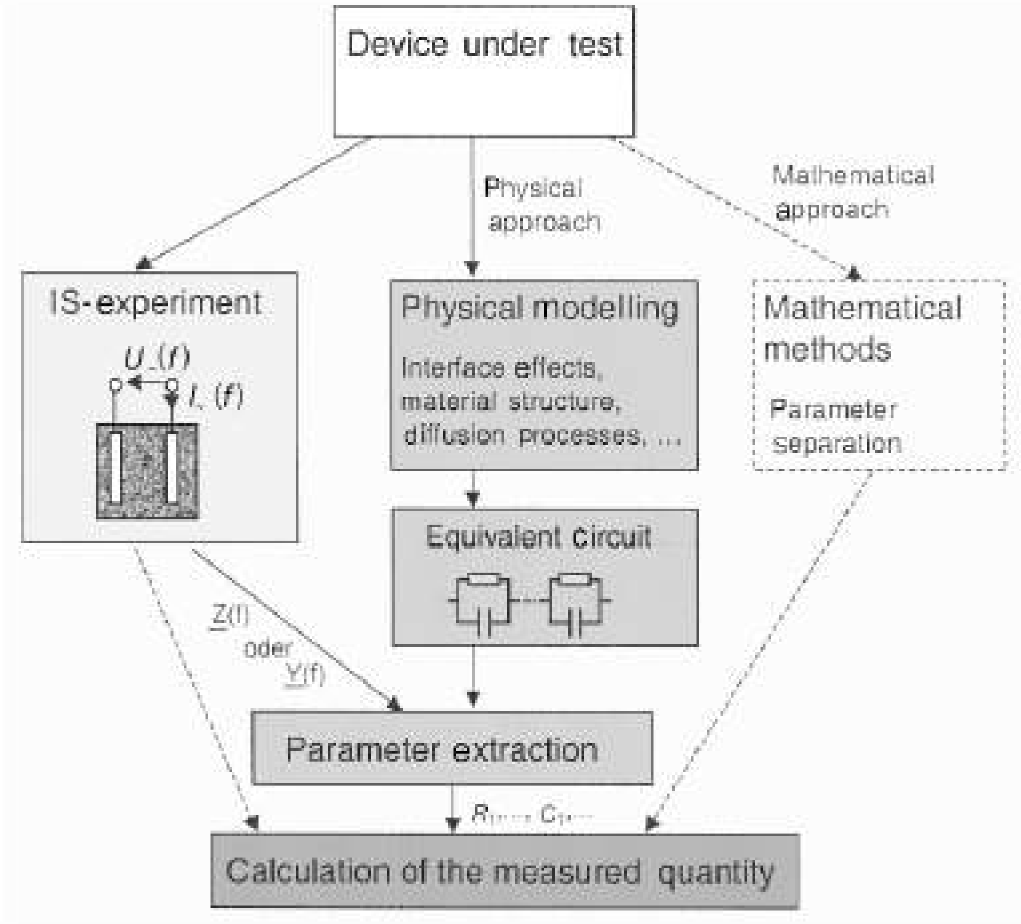
Table 2. History of SoC development.

Year	Researcher/ company	Method
1963	Curtis	Voltage measurements
1970	Lerner	Comparison between two batteries (one has a known SoC)
1974	York	Threshold in voltage levels
1974	Brandwein	Voltage, temperature and current measurements
1975	Christianson	OCV
1975	Dowgiallo	Impedance measurements
1975	Finger	Coulomb counting
1978	Eby	OCV and voltage under load
1980	Kikuoka	Book-keeping
1981	Finger	Voltage relaxation
1984	Peled	Look-up tables based on OCV and T measurements
1985	Muramatsu	Impedance spectroscopy
1986	Kopmann	Look-up tables based on V, I and T measurements
1988	Seyfang	Book-keeping and adaptive system
1992	Aylor	OCV, OCV prediction and coulometric measurements
1997	Gerard	Voltage and current measurements, artificial neural networks
1999	Salkind	Coulomb counting, impedance spectroscopy, fuzzy logic
2000	Garche	Voltage and current measurements, Kalman filters
2000	Bergveld	Book-keeping, overpotential, EMF, maximum capacity learning algorithm

State-of-Charge estimation, over years,

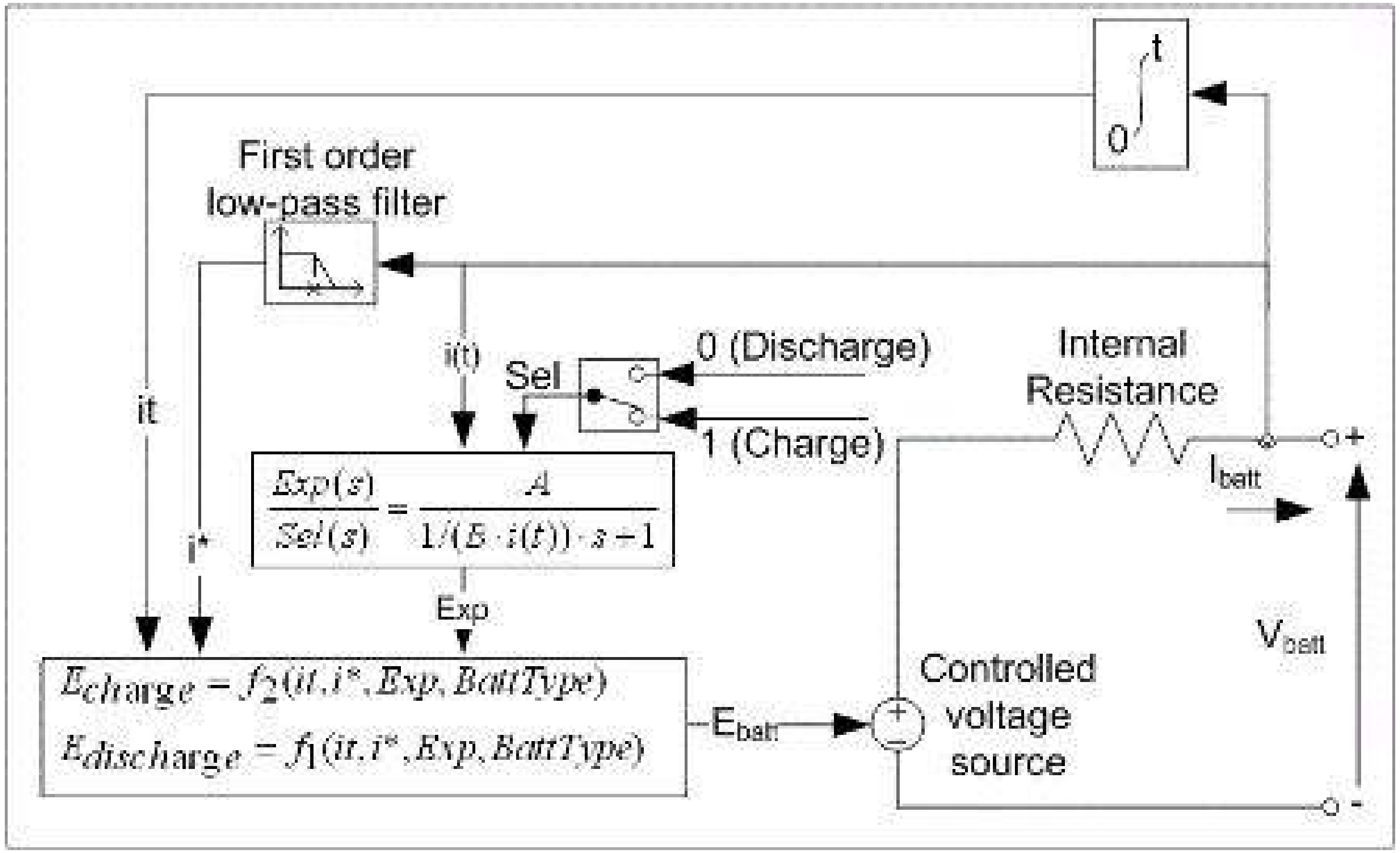
from V. Pop, H. Bergveld, P. Notten, and P. Regtien, "State-of-the-art of battery state-of-charge determination," Meas. Sci. Technol. Prof. Holstlaan, vol. 16, 12 2005

Possible framework for the battery model



Tränkler, H.-R.; Kanoun, O.; Min, M.; Rist, M. (2007). Smart sensor systems using impedance spectroscopy. Proceedings of the Estonian Academy of Sciences. Engineering, 13 (4), 455–478.

Equivalent electrical circuit - framework for the battery model



MATLAB / Simulink (equivalent electrical circuit approach). Battery block implements a generic dynamic model that represents most popular types of rechargeable batteries. This figure shows the equivalent circuit that the block models.

https://se.mathworks.com/help/physmod/sps/powersys/ref/battery.html

Example paper : battery SOH and AI

Jingyuan Zhao et al, ***Battery state of health estimation under fast charging via deep transfer learning***, iScience, Volume 28, Issue 5, 2025,112235, ISSN 2589-0042, https://doi.org/10.1016/j.isci.2025.112235.

(https://www.sciencedirect.com/science/article/pii/S2589004225004961

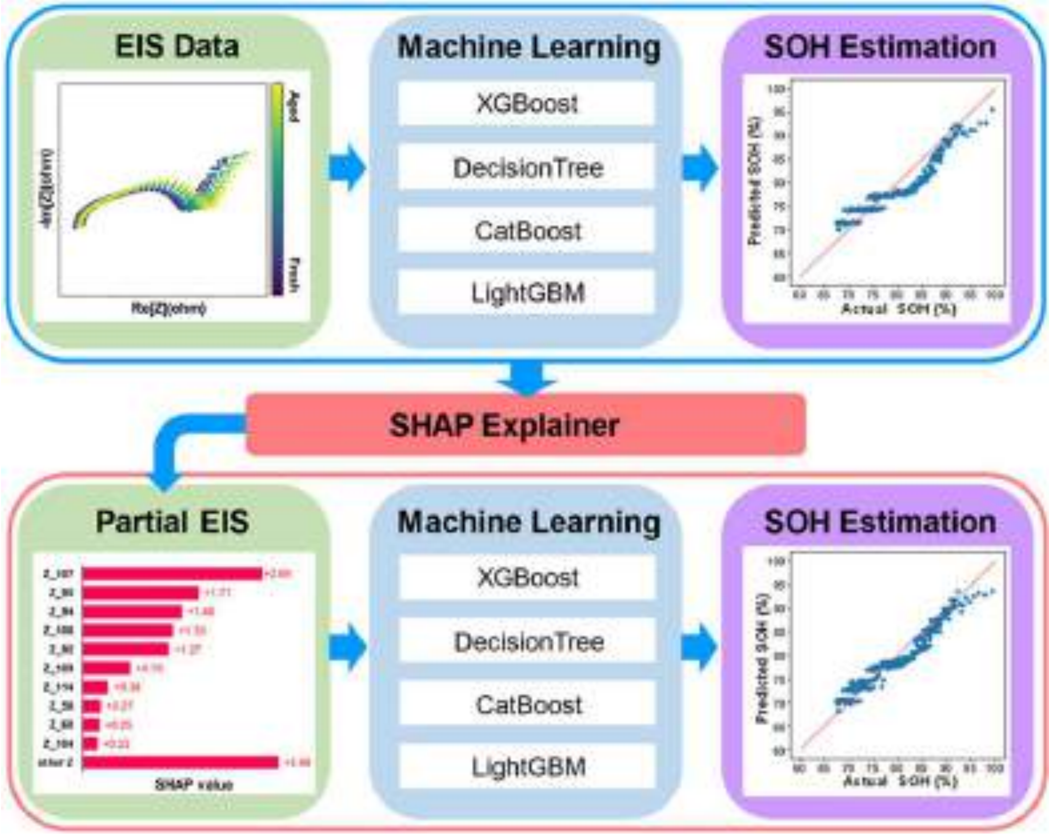
- Proposed a CNN and self-attention-based multi-fusion model for battery SOH estimation
- Two datasets of 222 LFP batteries are used for training, validation, and testing
- Achieves high accuracy using partial voltage and capacity in an end-to-end approach
- Transfer learning enhances generalization to capture cell-to-cell variations

Possible ML applications?

Evaluation of the Battery status and health

Bizhong Xia et al, ***Rapid estimation of battery state of health using partial electrochemical impedance spectra and interpretable machine learning,*** Journal of Power Sources, Volume 603, **2024**

Electrochemical impedance spectroscopy (EIS) has proven effective in rapidly accessing internal data of lithium-ion batteries, as evidenced by numerous studies



Incorporating the ***SHAP (SHapley Additive exPlanations)*** method, which originates from the Shapley value in game theory, could y enhance the interpretability of machine learning,… **including life and health sciences** Applying SHAP to electrochemical impedance spectroscopy in a machine learning framework for predicting battery health could elucidate the importance of each impedance frequency point. This would facilitate a more focused approach in selecting specific frequencies in the impedance spectrum that are most indicative of battery aging.

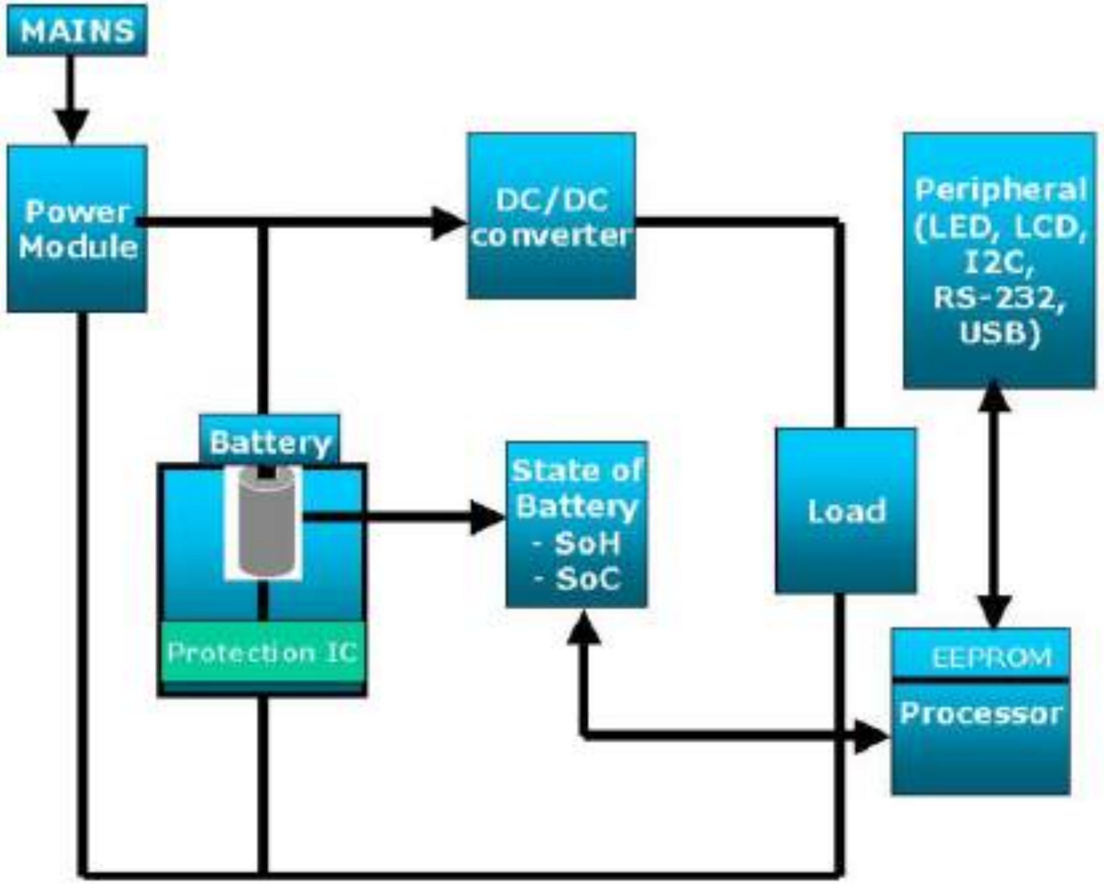
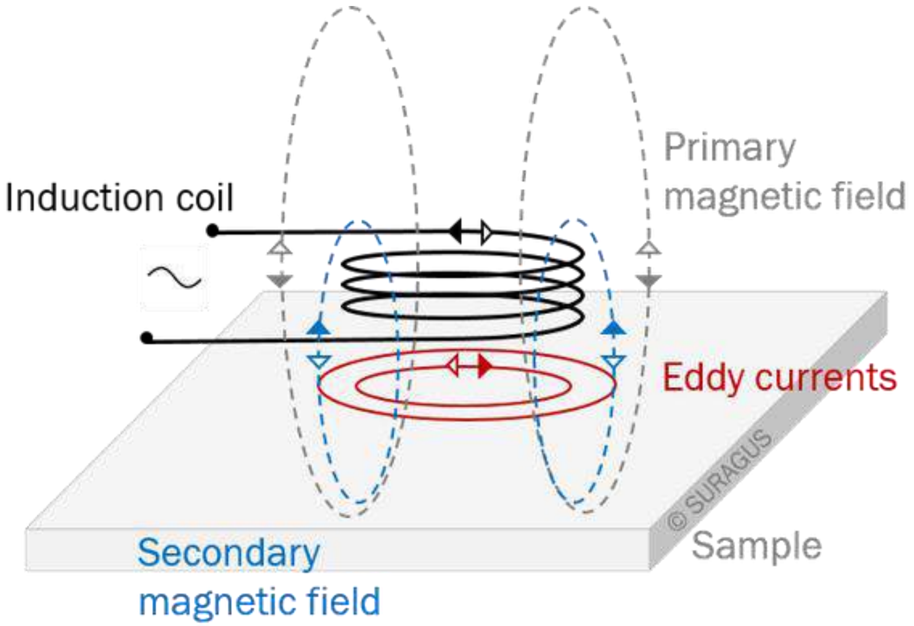


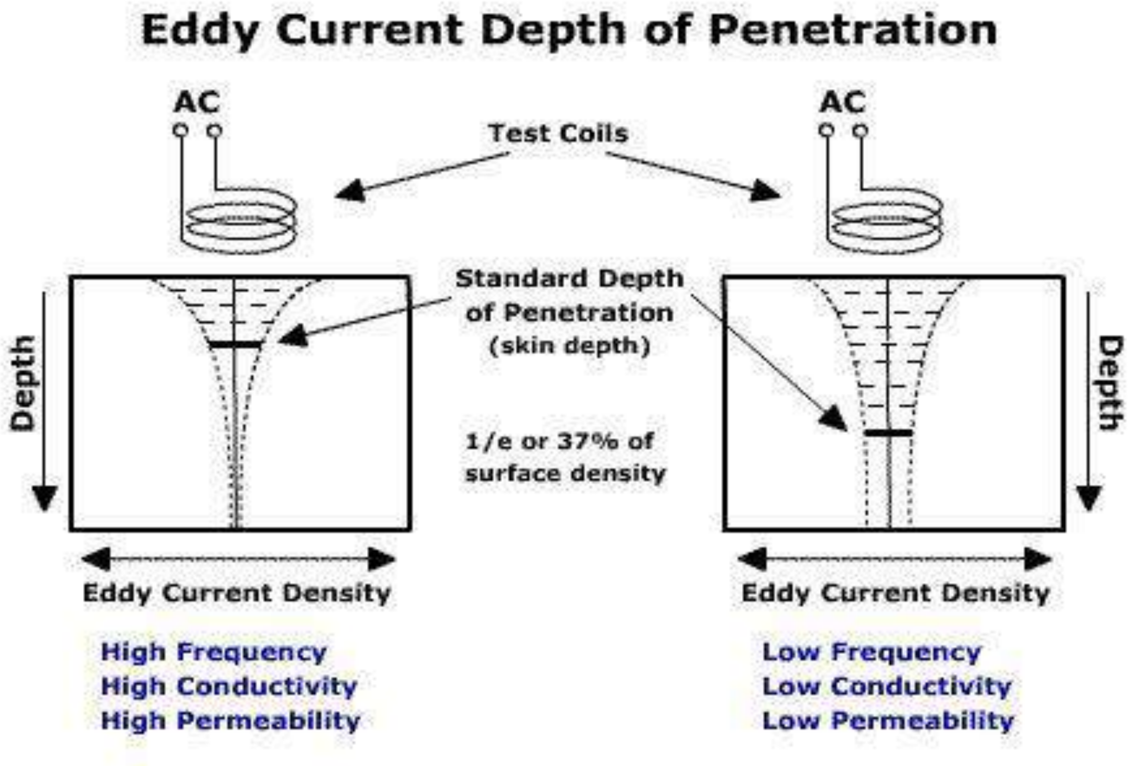
Figure 1. General architecture of a battery-management system [1].

- V. Pop, H. Bergveld, P. Notten, and P. Regtien, “State-of-the-art of battery state-of-charge deter-
- mination,” Meas. Sci. Technol. Prof. Holstlaan, vol. 16, 12 2005

Eddy current testing can be useful. Also for batteries!



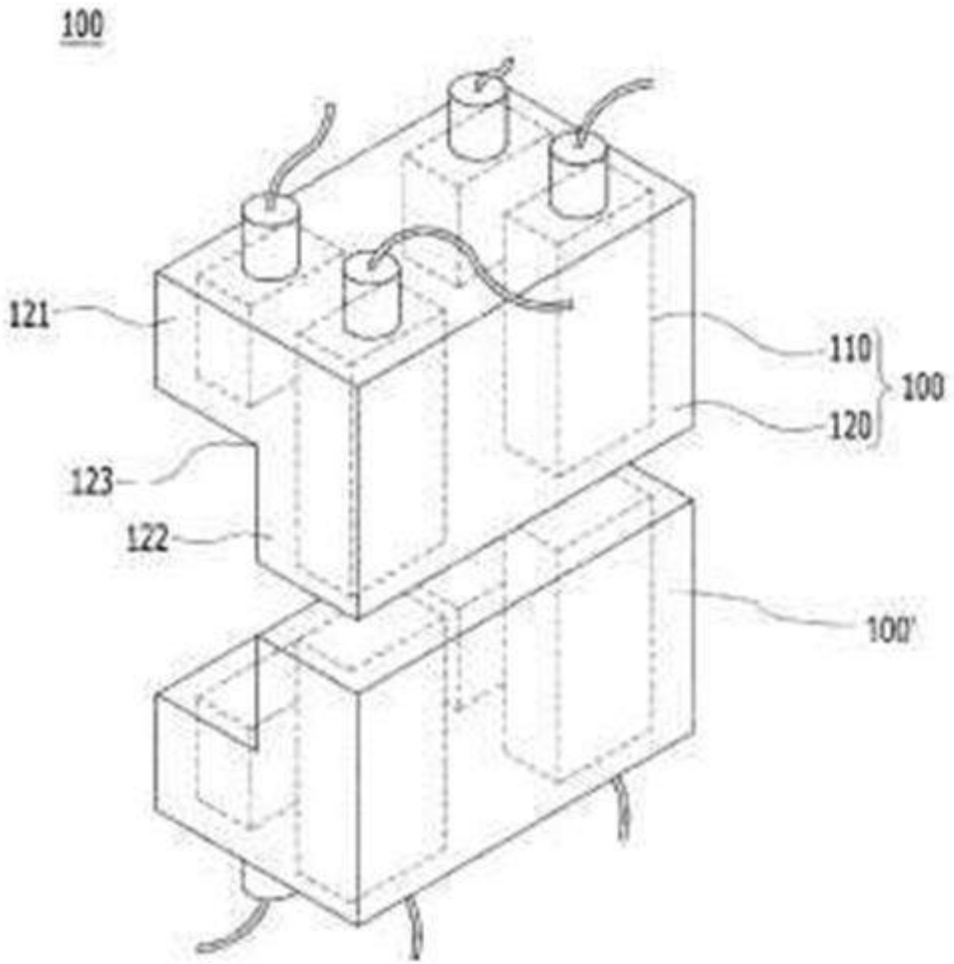
https://www.suragus.com/en/technology/eddy-current/



NDT Resource Center

https : / / www .nde - ed . org / EducationResources /CommunityCollege / EddyCurrents /Physics / depthcurrentdensity. htm.
Accessed: 2010-07-01

Eddy current testing can be useful!



- KR20220094571 patent for detecting crack by Eddy current

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Eesti Teadusagentuur

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Thank You!

Questions?

Interest to EIS methods is welcome!

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