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Electrochemical Low-Frequency Impedance Spectroscopy for Diagnostics of Fuel Cells

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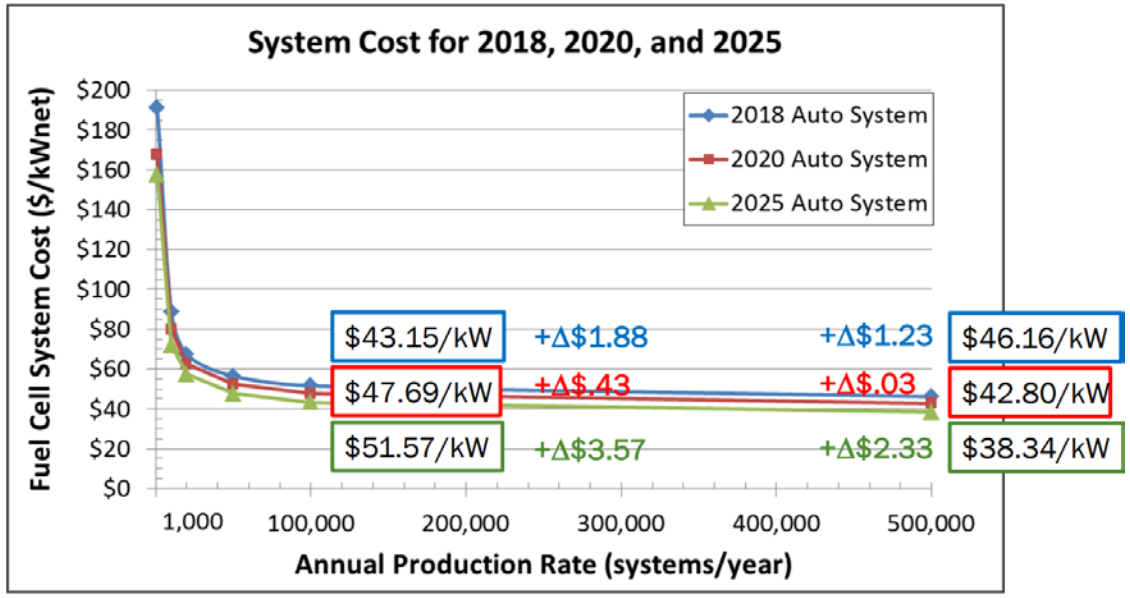
Outline

- Motivation
- Diagnostics of fuel cells by EIS
- Relay feedback applied to EIS: ELFIS
- Simulation results
- Practical implementation
- Testing on full-size stack

Fuel cell research focus

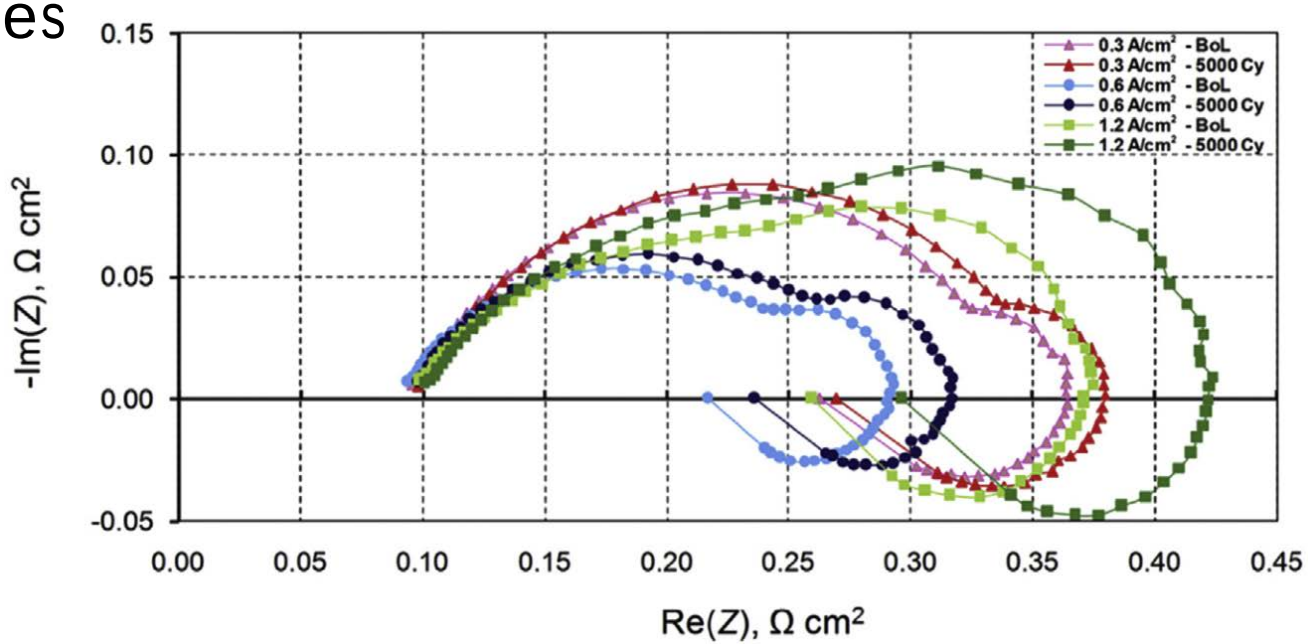
- Fuel cells still over 1000 €/kW
- Breakthrough needs < 300 €/kW
- Mass production would help
- Recent focus on:
  - Lower costs
  - Longer lifetimes
- Total Cost of Ownership
  - OPEX, CAPEX, lifetime
- Lifetime is the most uncertain!



*Cost results shown for both 100,000 & 500,000 systems/year

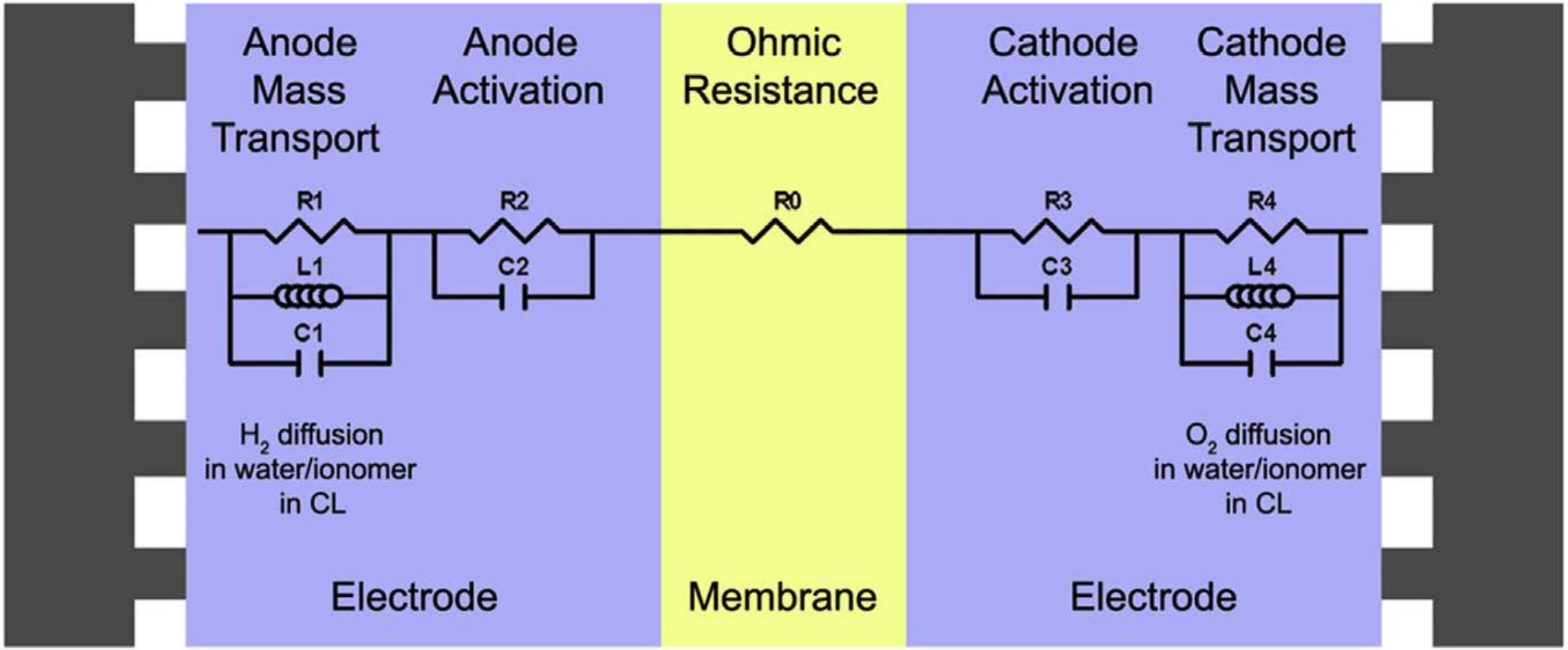
Electrochemical Impedance Spectroscopy

- Measure impedance of fuel cells
  1. Set a given voltage (or current)
  2. Induce small oscillations in voltage (or current)
  3. Read oscillations in other variable
  4. Calculate magnitude & phase
  5. Repeat for many frequencies
- Difficult to have on-board
  - Requires large equipment
  - Produces much information
- Slower sampling at low *f*
  - "Tail" appears



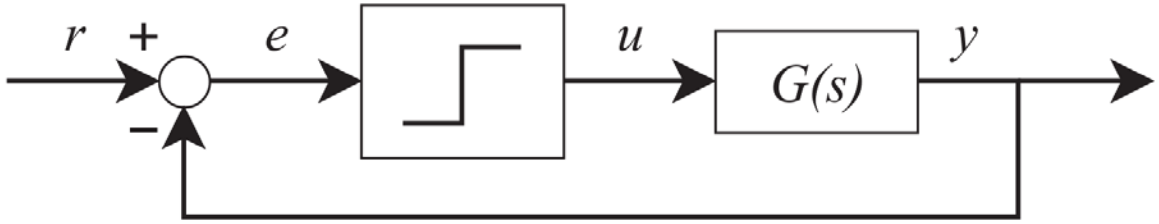
EIS Modelling of Fuel Cells

- Equivalent circuit with RLC elements to model "tail"
- Prognostic variable R_4: tracks degradation state

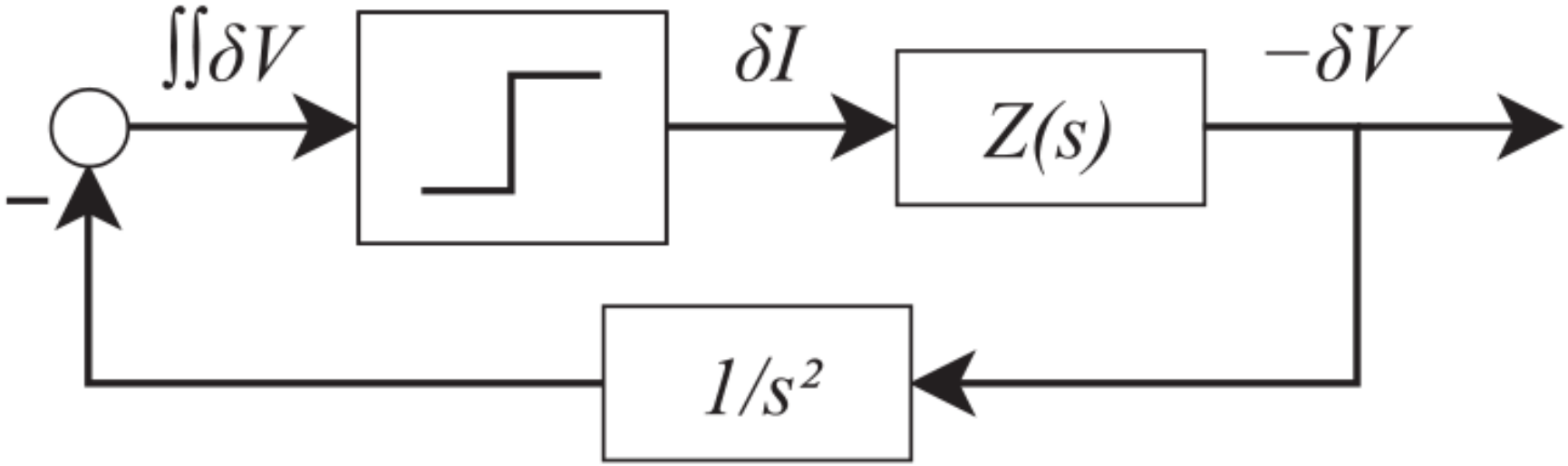


Relay Feedback

- Classical
  - Find properties of $G(s)$
  - Converges to $\angle G = 180°$
  - Magnitude, frequency are inputs to PID tuning

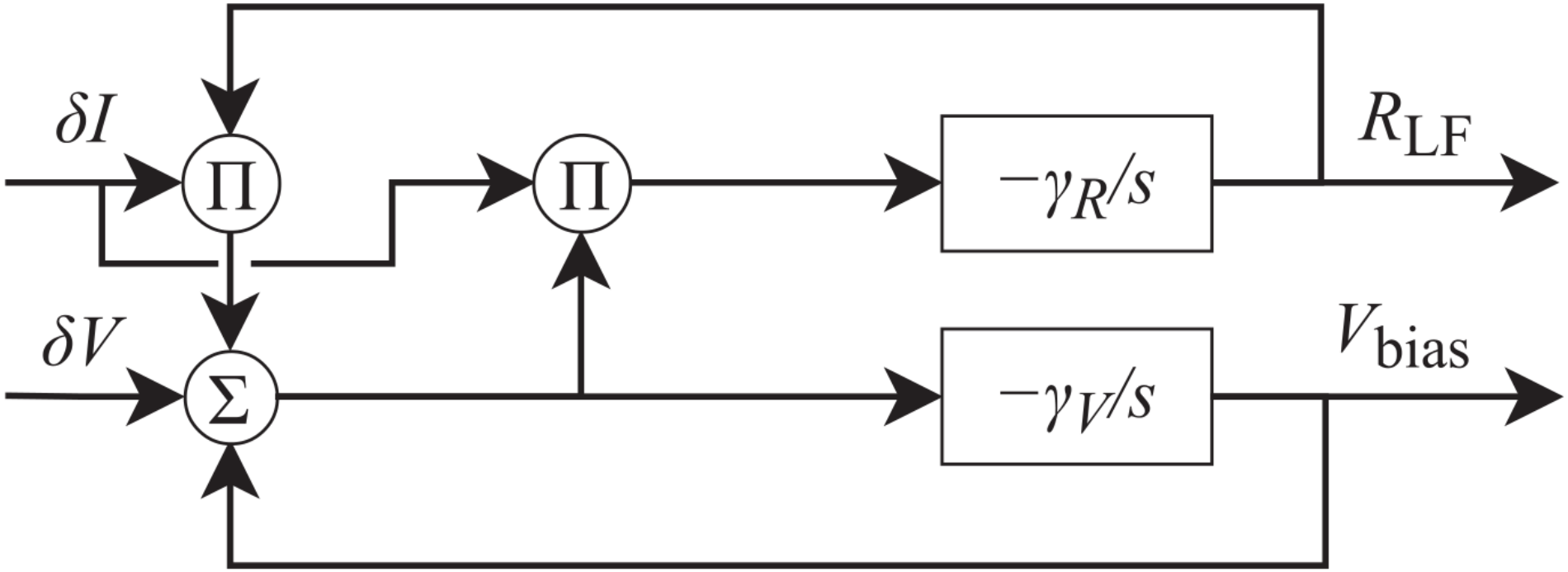


- Low-Frequency Resistance (LFR) tracking in fuel cells:
  - We look for 0°: shift phase by 180° including 2 integrators ($1/s$)



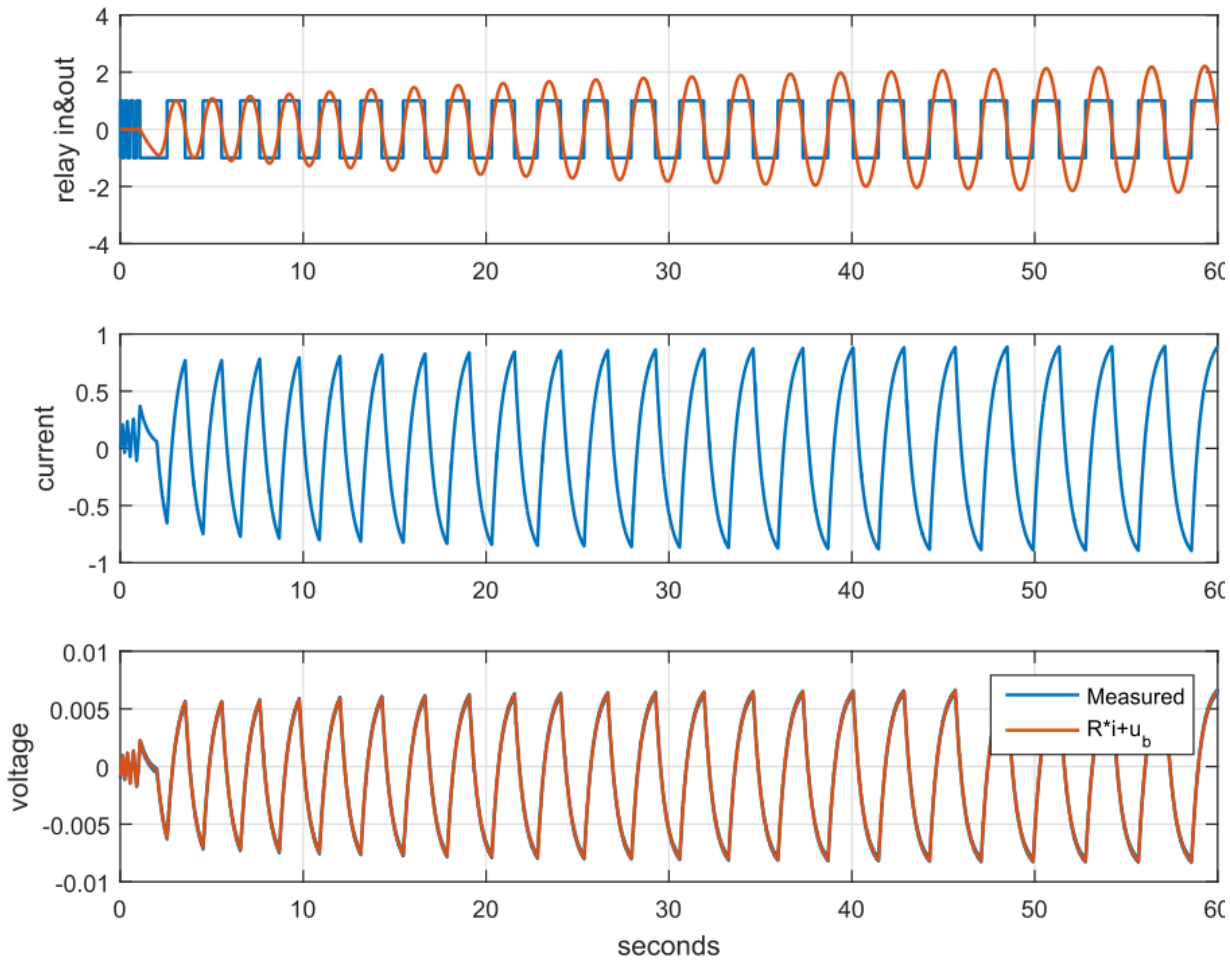
Estimator for Voltage Bias

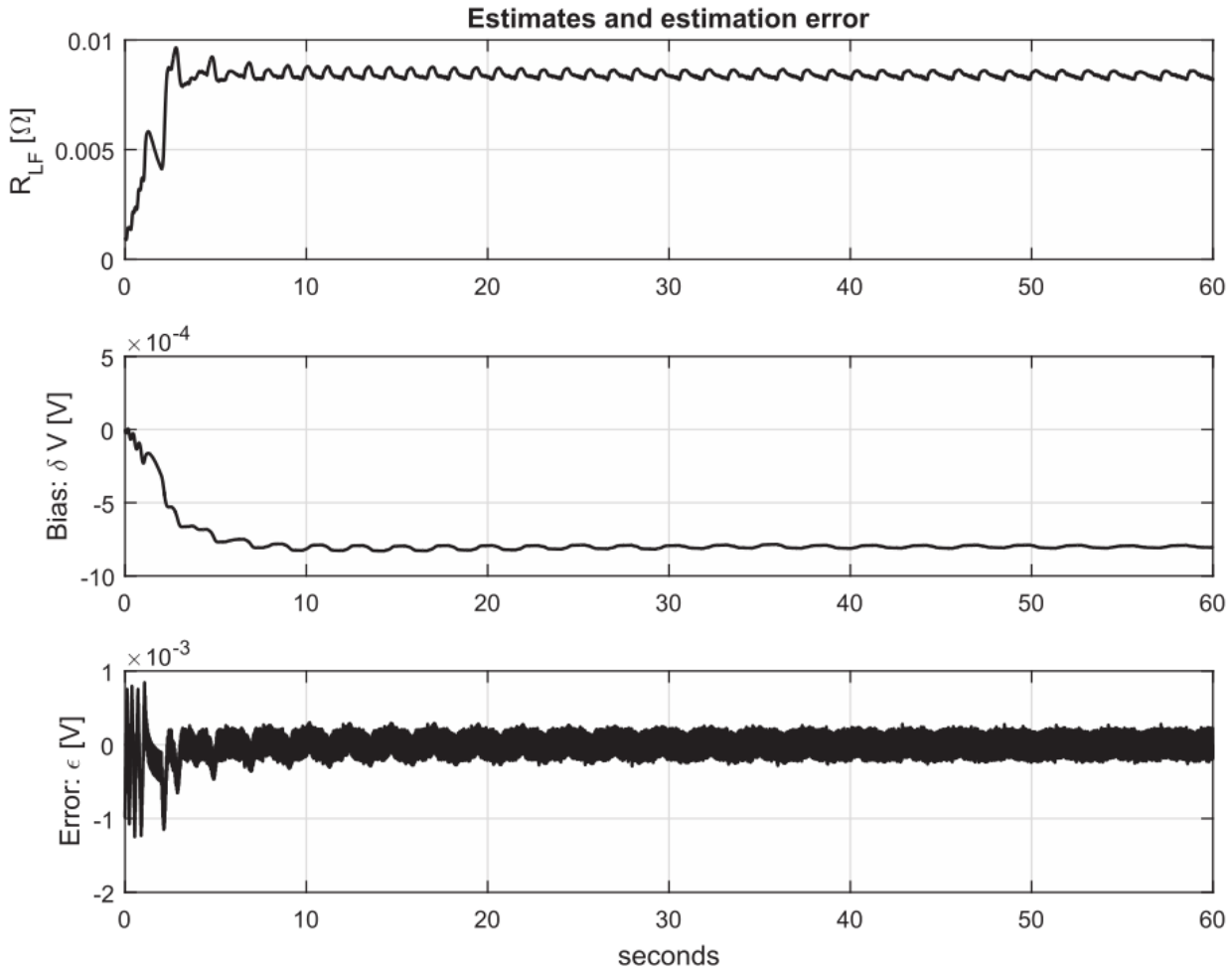
- Voltage can drift from steady state over time
- Find an estimator by gradient method
- Free R_{LF} estimate, but nonlinear estimator



Simulations in MatLab

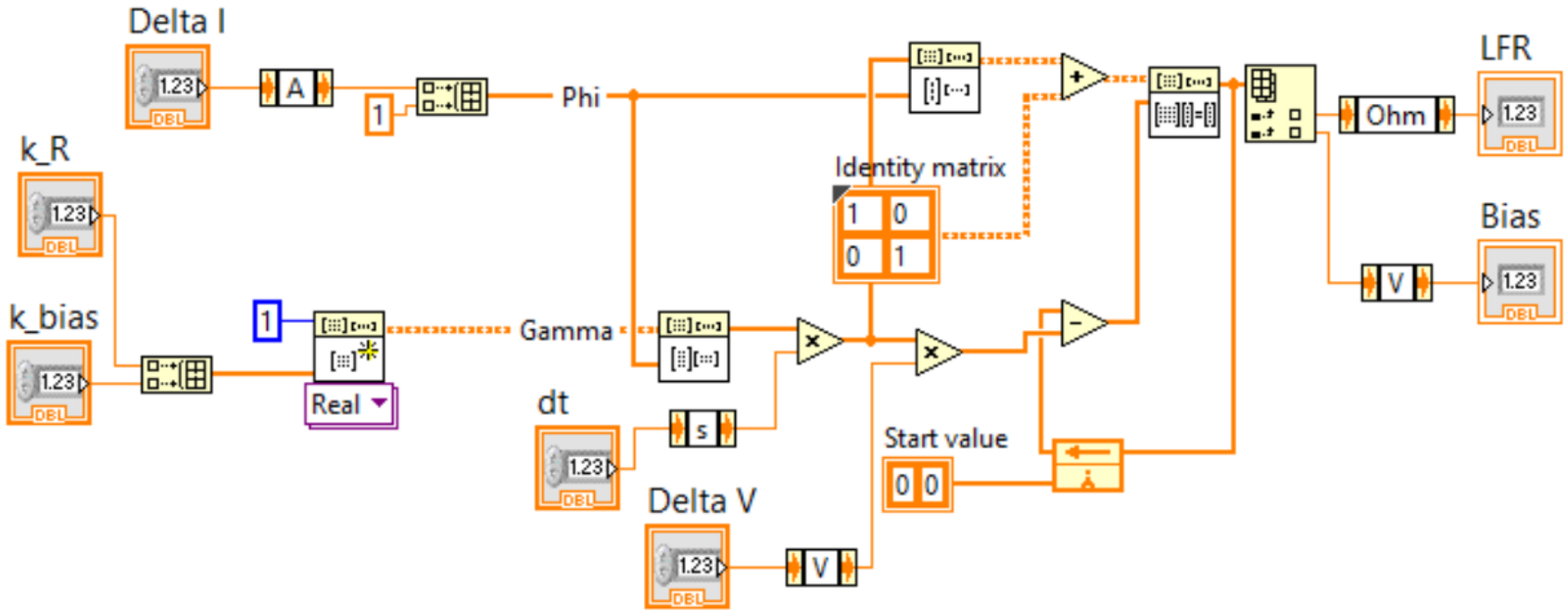
- Convergence in 7 seconds!





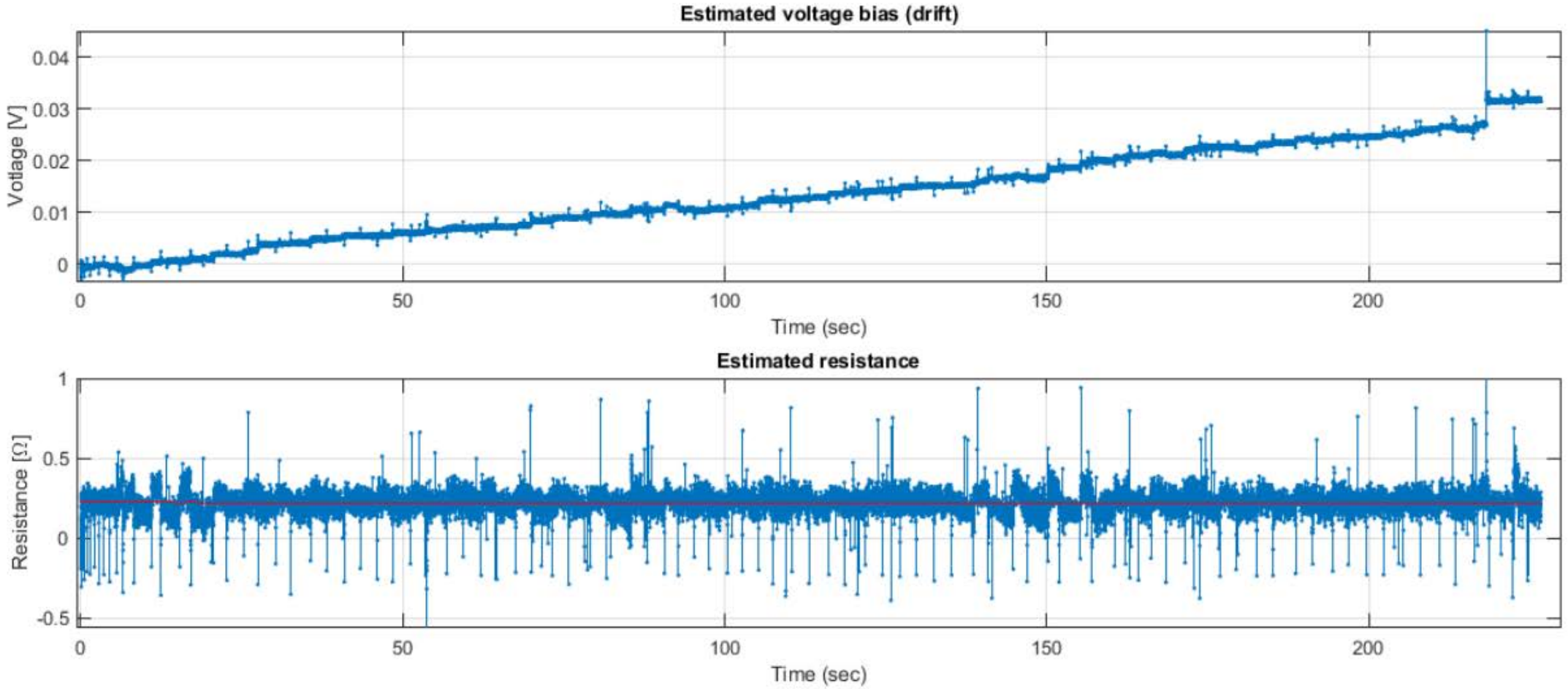
Implementation

- Estimator is numerically unstable
  - Works in MatLab, crashes in LabVIEW
- Need to employ backward (implicit) Euler method
- Difficult to read, but it works!



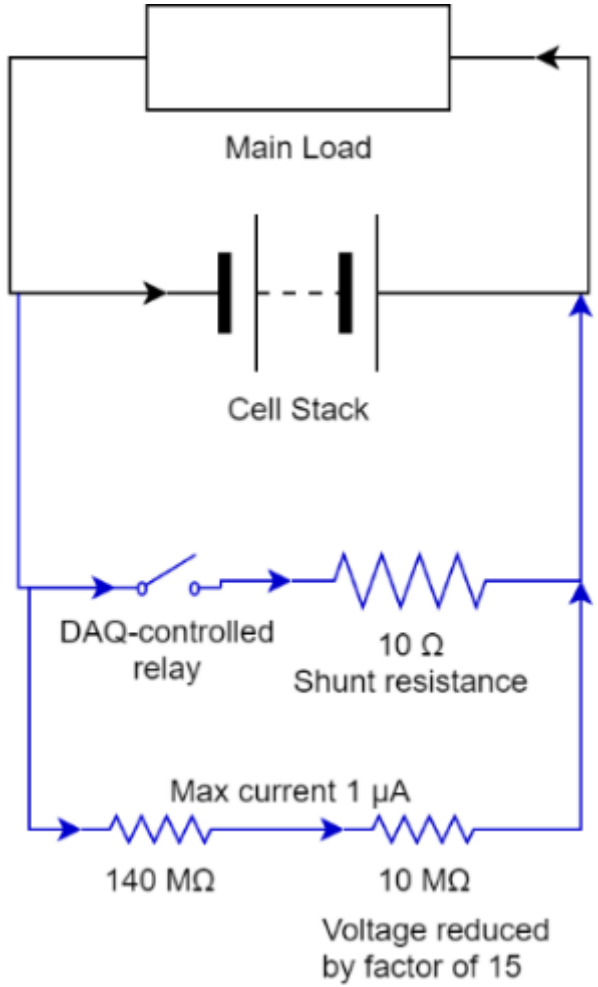
Laboratory test on 20 kW stack

- LFR measured at 230 mΩ, even as voltage kept drifting



Further work

- Method currently under extensive cell testing at NTNU Trondheim
  - Improving current resistance-based setup to power electronics
- Giantleap bus demonstration in the Netherlands uses the method
  - Data will be released



Conclusion

- LFR is a good measure of cell degradation
- Full on-board EIS is problematic
- ELFIS can run with available hardware
- Numerical instability has been addressed
- ELFIS has been demonstrated on full-size stacks

Thank you for your attention!

Giantleap Improves Automation of Non-polluting Transportation with Lifetime Extension of Automotive PEM fuel cells

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