Federico Zenith

Increasing Reliability of Fuel-Cell Buses

The Giantleap Project

April 2, 2019
Hannover Messe
Technical Forum

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Outline

Introduction

Hydrogen Range Extender

Low-Frequency Online EIS

Voltage Rejuvenation

Balance-of-Plant Degradation

Prognostics for Fuel-Cell Systems

Outline

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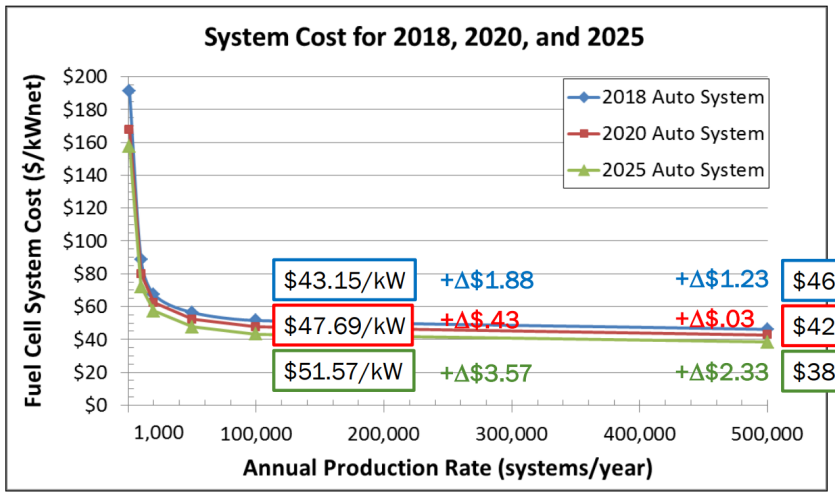
Motivation

- Fuel cell cost still >1000 €/kW
- Breakthrough needs <300 €/kW
- Awaiting mass manufacturing…

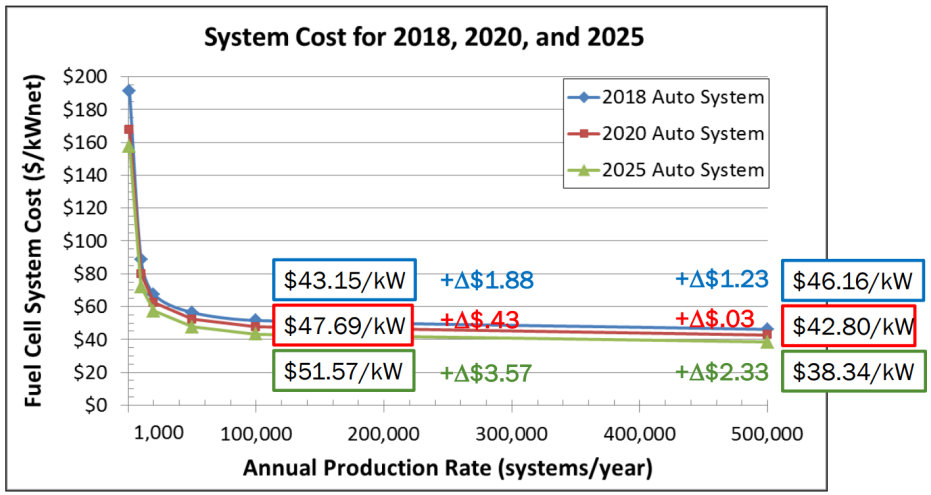


*Cost results shown for both 100,000 & 500,000 systems/year

Source: James, B., US DoE, 2018

Motivation

- Fuel cell cost still >1000 €/kW
- Breakthrough needs <300 €/kW
- Awaiting mass manufacturing…
- Shift to heavy-duty & industry
- Focus: Total Cost of Ownership
- TCO: OPEX, CAPEX, lifetime
- **Lifetime** is the most uncertain!



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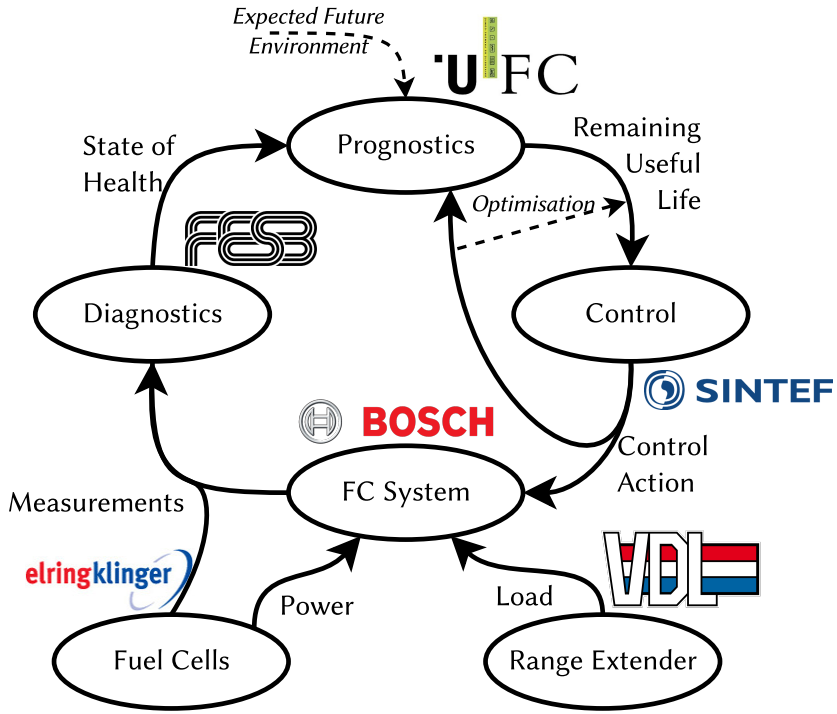
http://giantleap.eu

- Low availability in CHIC project
  - 70 % instead of 98 % for diesel
  - Often problems with BoP
  - Often problems with supply chain
  - Rarely problems with fuel cell
- Giantleap concept:
  - Battery bus range extender
  - On-line diagnostic tools
  - Prognostics for fuel cells and BoP



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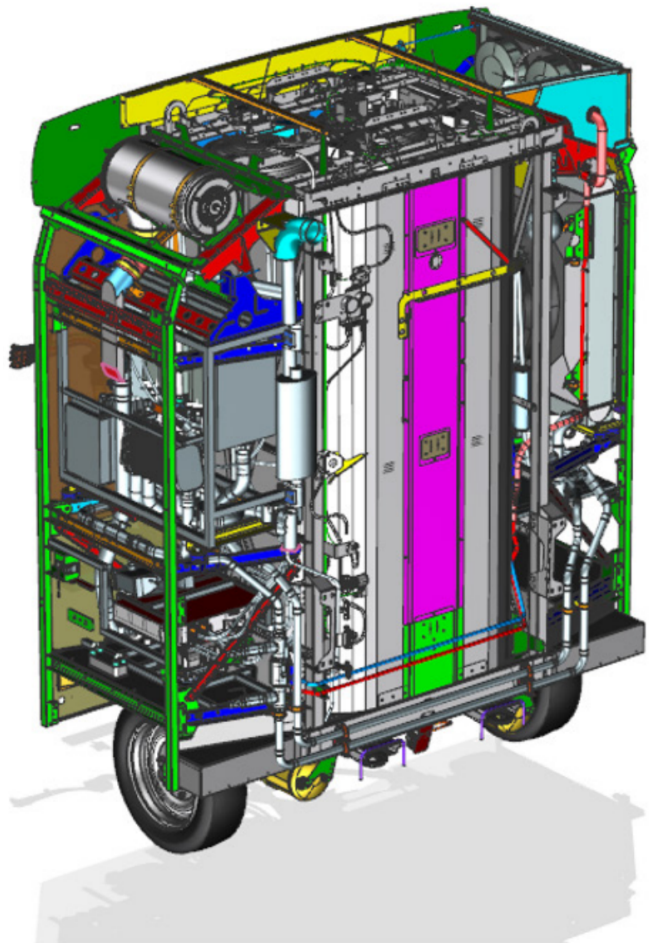
Hydrogen Trailer on Battery Bus

- Easy connection by operators
- Flexible bus fleets
- City bus becomes regional bus
- Standard CCS protocols
- ElringKlinger 76 kW stack modules
- Bosch BoP system
- Interesting bureaucratic implications…



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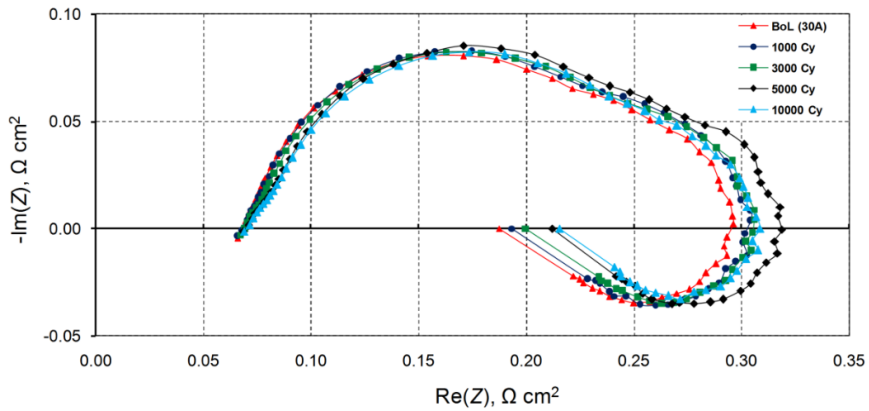
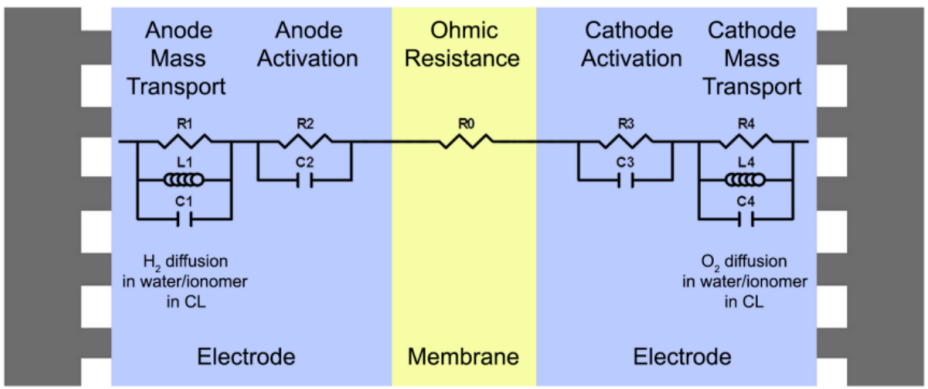
Catalyst Degradation

Tests Performed at FESB, Split

- Accelerated stress tests
- Cycling between 0.6 V to 0.9 V
- EIS down to 10 mHz
- Low-frequency “tail” appears
- Model with resonant loops
- R_4 is a *prognostic variable*
  - can only be measured dynamically
  - … but no EIS in field system





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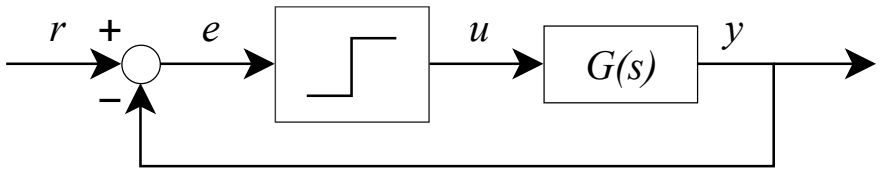
Relay Feedback Applied on Electrochemistry

Concept developed at SINTEF, Trondheim

- Relay feedback
  - PID autotuning technique
  - A relay is essentially sgn()
  - Identifies key properties of dynamic system $G(s)$
- Converges at $\angle G(s) = 180°$



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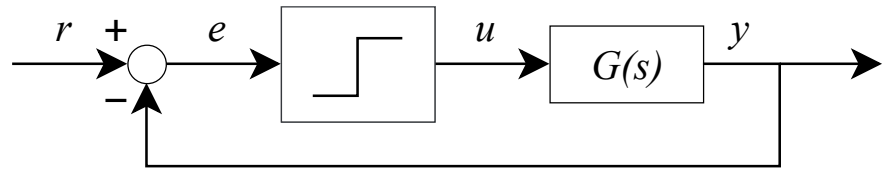
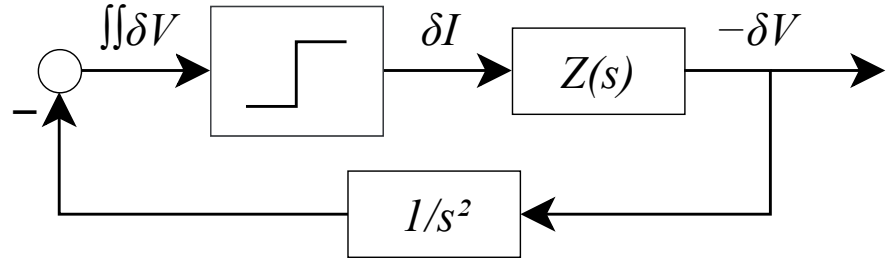
- Converges at $\angle G(s) = 180°$
- Adapt to LFR identification:
  - Add two integrators $(1/s^2)$
  - Now converges to $\angle Z(s) = 0°$
  - Bonus: strong noise filtering
- Cheap to implement; for 40 kW:
  - 80 € solid-state relay
  - 50 € shunt resistor





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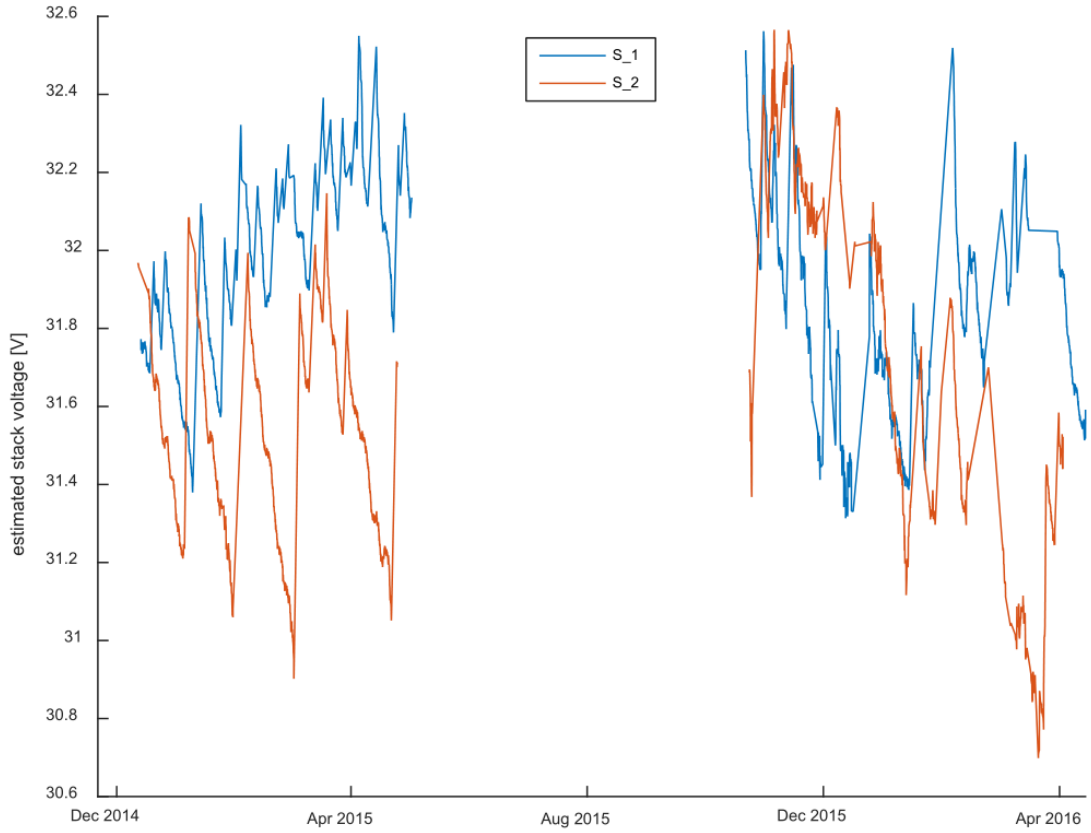
Reduction or Reversal of Voltage Degradation

Initial Indications in Sapphire

- Frequent PC crashes
- Emergency shutdowns
- Voltage improvement
- Effect reproduced in controlled conditions



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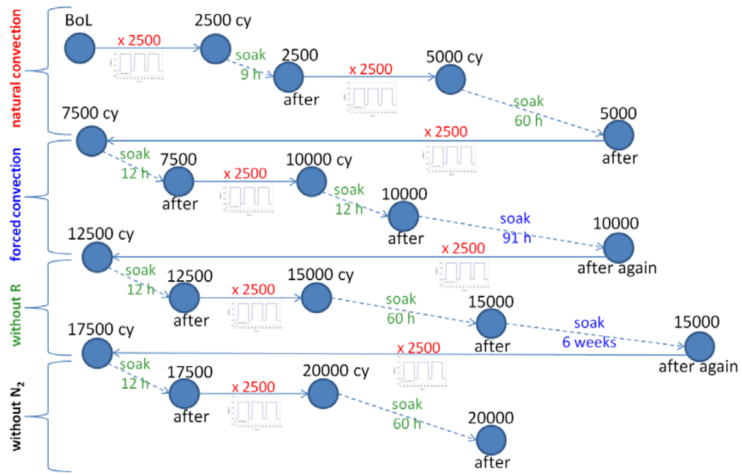
Study of Rejuvenation Phenomena

Report by FESB, Split

- Recent report in Giantleap
  - `http://giantleap.eu/?p=276`
- Systematic testing on EK cells
- Consistent AST and soak times
- Results:
  - Necessary to shut down with resistor
  - Counterproductive to purge with N_2
  - Quenching with ice did not help
  - Long soak times reduce recovery
- Possible explanations:
  - Accumulated water in cell
  - Oxygen in catalyst layer



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Balance-of-Plant Long-Term Testing Data

Extensive Tests Performed by Bosch Engineering, Abstatt

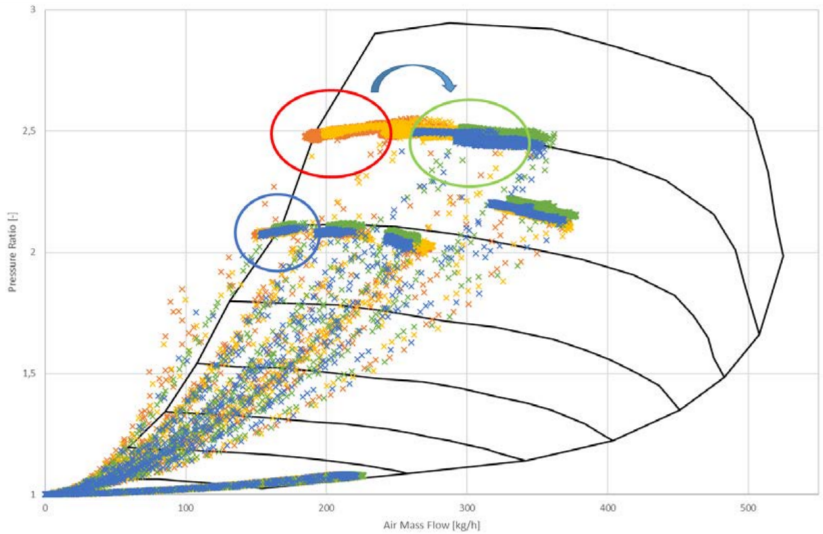
- BoP is a major source of failures
  - Compressors especially
  - Supply chain can be a problem
- No BoP data openly available
- Tested compressor and humidifier
- Hydrogen valve also considered
- Public report on experiments
  - `http://giantleap.eu/p=267`
  - Data will be made available

Compressor failure after 200 h of testing: broken impeller shaft

Compressor Degradation and Failure

Rotrex EC15-20 Electric Supercharger

- Standard automotive part
- Connected to stack cathode inlet
- Transients beyond surge line
- Nominal working area was expected much smaller
- Vibrational sensor: ≈3 h warning
- Workaround: bypass valve
- Real solution: specific FC BoP parts



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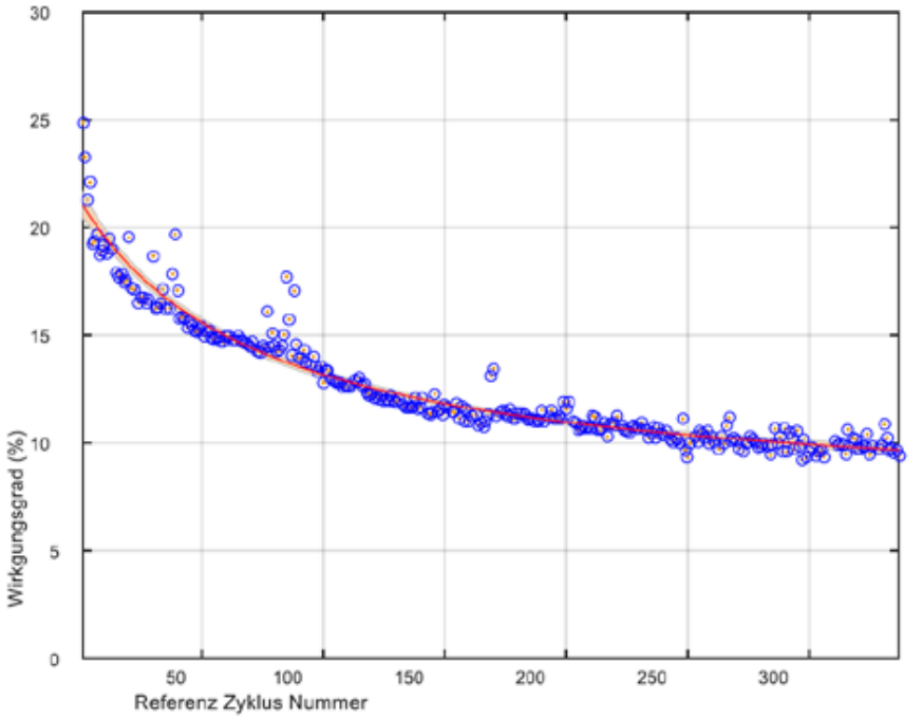
Humidifier Degradation

- Rather fast degradation
- Possible causes:
  - Freezing
  - Fouling
  - Pressure gradients
  - Particles
  - Vibrations
- Good curve fit with model
- Appears to eventually stabilise



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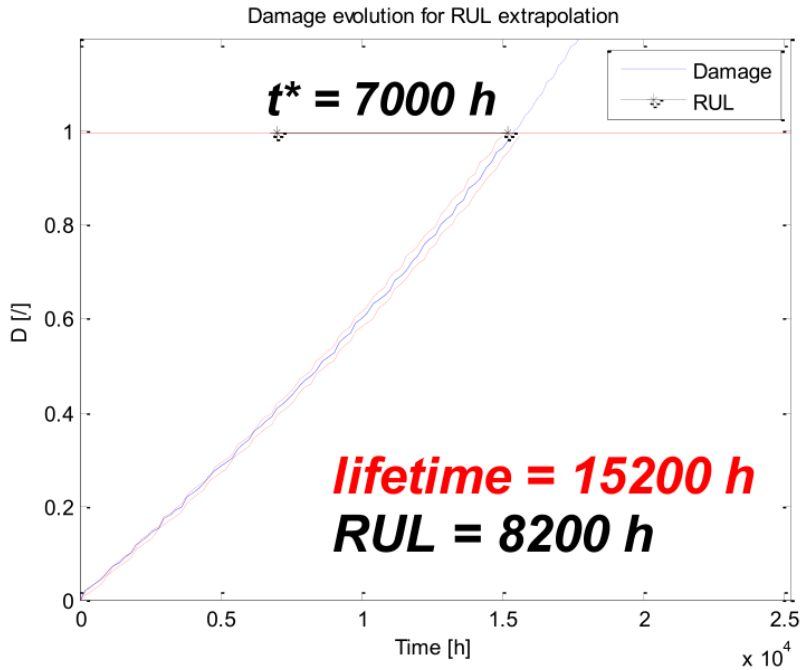
Prognostics of Fuel Cells

Developed at FCLAB/UFC, Belfort

- Meets EK's lifetime target
- Critical issue: definition of EoL
- Prognostics-as-a-service?
  - Little on-board computing power
  - Upload data to cloud
  - Run long-term prognostics
- Currently being extended to BoP



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Conclusions

- Reliability is the key to industry acceptance
- Range extenders give fleet flexibility
- Relay feedback provides cheaply important data
- Some voltage degradation is reversible
- BoP degradation is due more attention
- Prognostics predicts sufficient FC lifetime

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Thank you for your attention!

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Giantleap **I**mproves **A**utomation of **N**on-polluting **T**ransportation with **L**ifetime **E**xtension of **P**EM fuel cells

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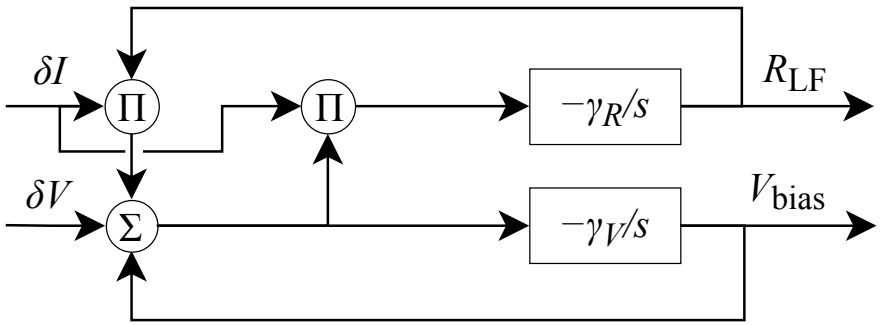
FCH

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

Parameter Estimation with Relay Feedback

- Switching around a steady state
- Steady state may drift
- Estimator with gradient method
- Bonus: on-line R_{LF} estimate



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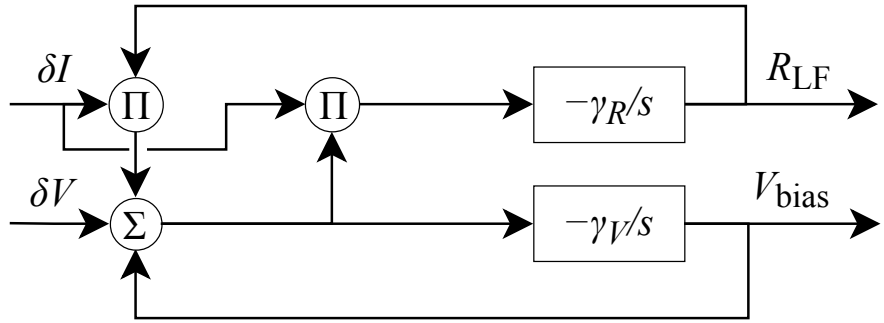
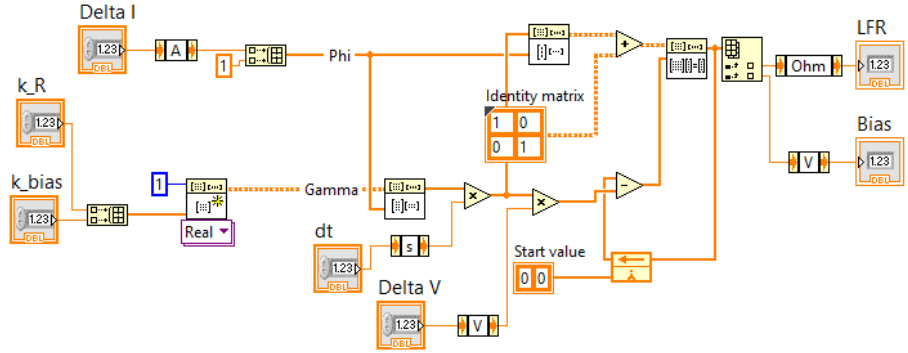
Parameter Estimation with Relay Feedback

- Switching around a steady state
- Steady state may drift
- Estimator with gradient method
- Bonus: on-line R_{LF} estimate
- Malus: numerically unstable
- Use low γ_i, or Backwards Euler
- Method tested, in peer review

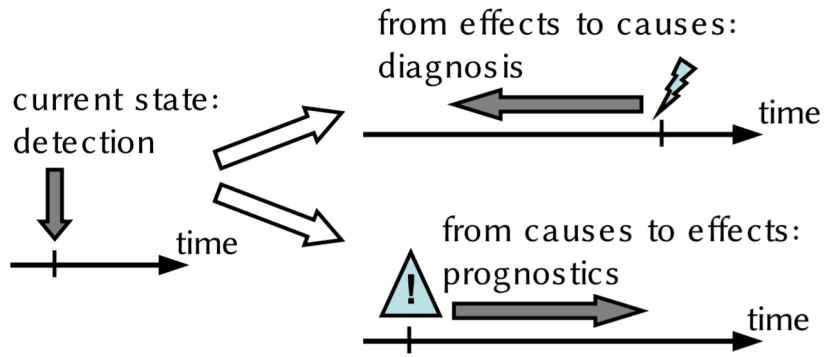




Prognostics, Control and Optimisation

The Importance of Asking the Right Question

- Prognostics' input: current state
- Output: residual useful life (RUL)
- How to optimise RUL?



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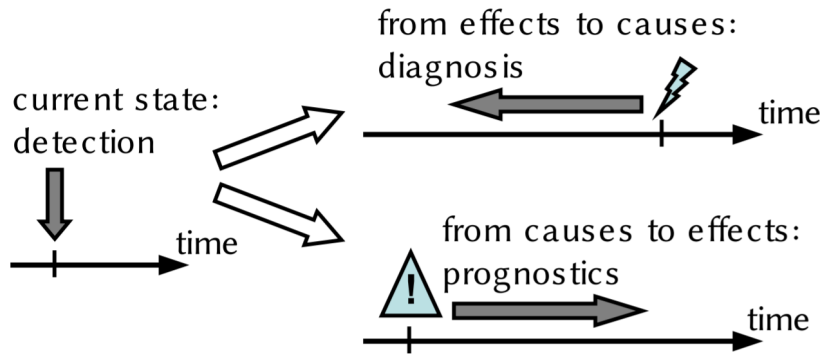
Prognostics, Control and Optimisation

The Importance of Asking the Right Question

- Prognostics' input: current state
- Output: residual useful life (RUL)
- How to optimise RUL?
  - Trivial: *Don't use system!*
- Better: maximise energy
  - Possibly with interest rate r

$$\max \int_0^{\mathrm{RUL}} E\,\mathrm{e}^{-rt}\,\mathrm{d}t$$

- Rejuvenation adds a further layer



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