Vehicle Propulsion Systems
Lecture 8
Fuel Cell Vehicles

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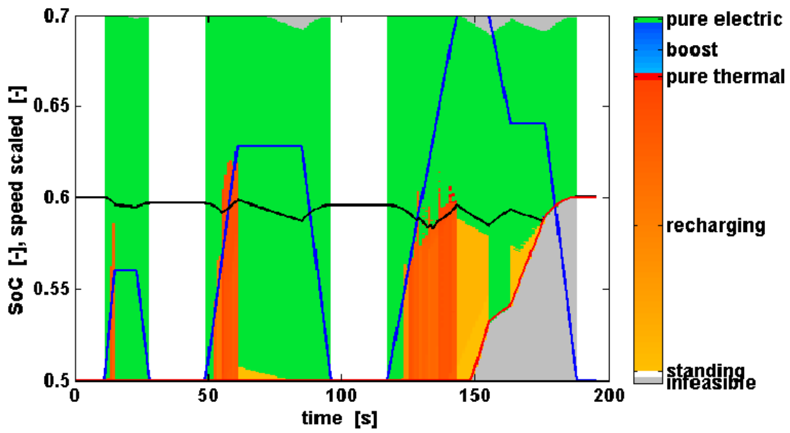
Outline

Deterministic Dynamic Programming – Parallel Hybrid Example

- Fuel-optimal torque split factor $u(SOC, t) = \frac{T_{e-motor}}{T_{gearbox}}$
- ECE cycle
- Constraints $SOC(t = t_f) \geq 0.6$, $SOC \in [0.5, 0.7]$



Global optimum guaranteed within discretization.

Non-causal.

Full knowledge about the mission.

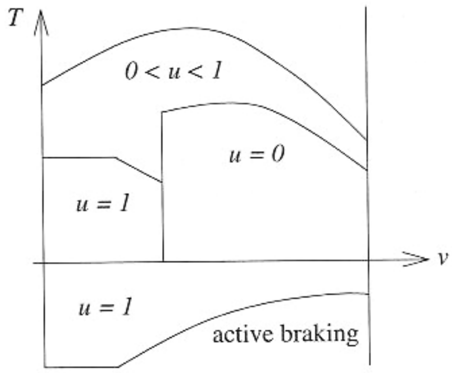
Curse of dimensionality $N_t \, N^{2\,d}$.

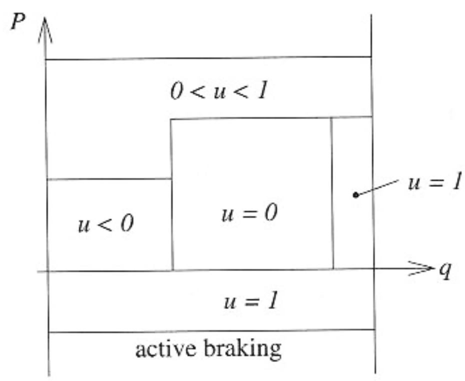
$d \in [1, 3]$

The reference tool used for development and comparisons.

Heuristic Control Approaches

- Parallel hybrid vehicle (electric assist)





- Determine control output as function of some selected state variables:
  vehicle speed, engine speed, state of charge, power demand, motor speed, temperature, vehicle acceleration, torque demand

On-Line Control – ECMS

- Given the optimal λ^* (cycle dependent exchange rate between fuel and electricity) .
- Hamiltonian

$$H(t, q(t), u(t), \lambda^*) = P_f(t, u(t)) + \lambda^* P_{ech}(t, u(t))$$

- Optimal control action

$$u^*(t) = \arg\min_u H(t, q(t), u, \lambda^*)$$

- Guess λ^*, run one cycle see end SOC, update λ^*, and iterate until $SOC(t_f) \approx SOC(0)$.

ECMS – Equivalent Consumption Minimization Strategy

- μ_0 depends on the (soft) constraint

$$\mu_0 = \frac{\partial}{q(t_f)}\phi(q(t_f)) = /\text{special case}/ = -w$$

- Different efficiencies

$$\mu_0 = \frac{\partial}{\partial q(t_f)}\phi(q(t_f)) = \begin{cases} -w_{dis}, & q(t_f) > q(0) \\ -w_{chg}, & q(t_f) < q(0) \end{cases}$$

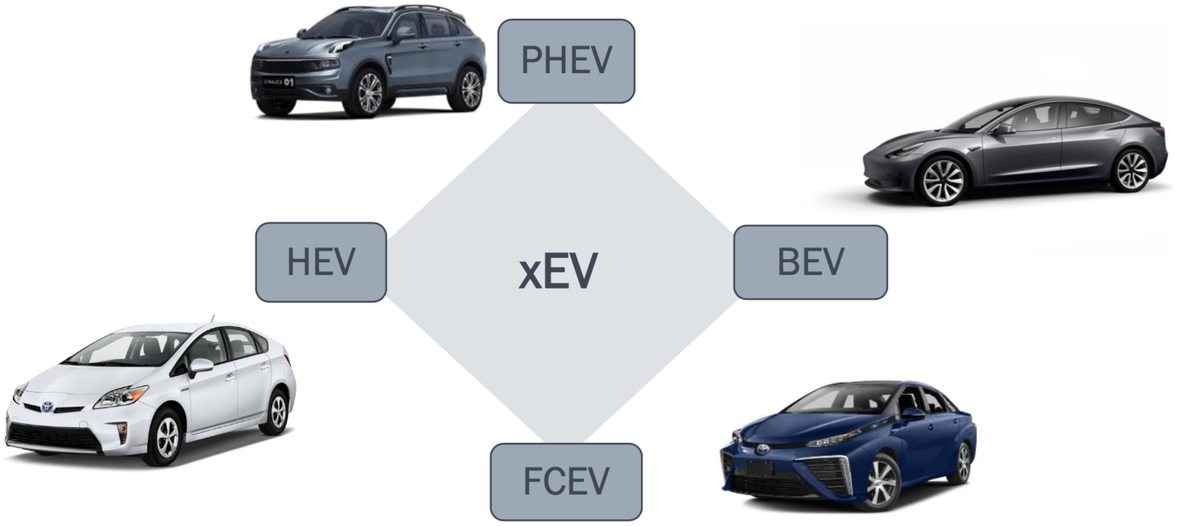
- Introduce equivalence factor (scaling) by studying battery and fuel power

$$s(t) = -\mu(t)\frac{H_{LHV}}{V_b\, Q_{max}}$$

ECMS – Equivalent Consumption Minimization Strategy

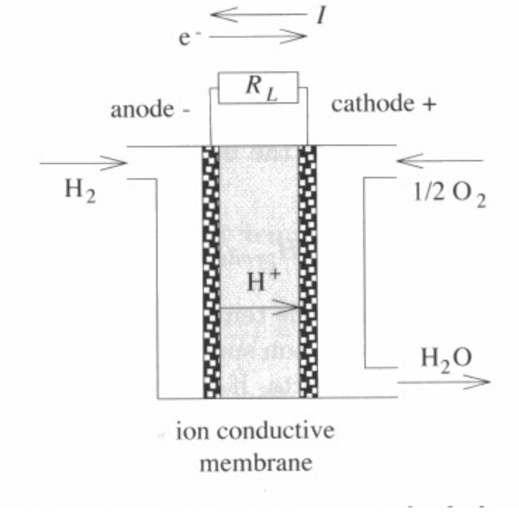
Outline

Introducing xEVs - From Victor Judez @ CEVT



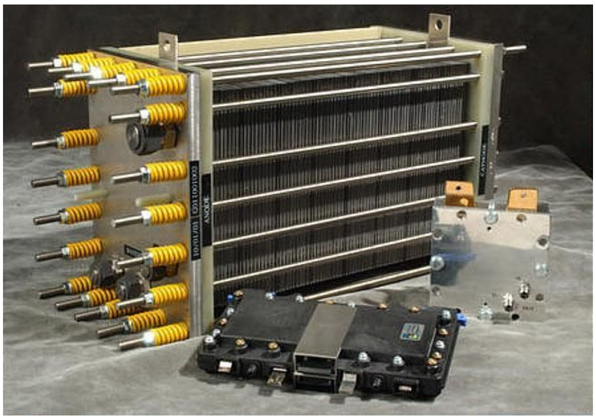
Fuel Cell Basic Principles

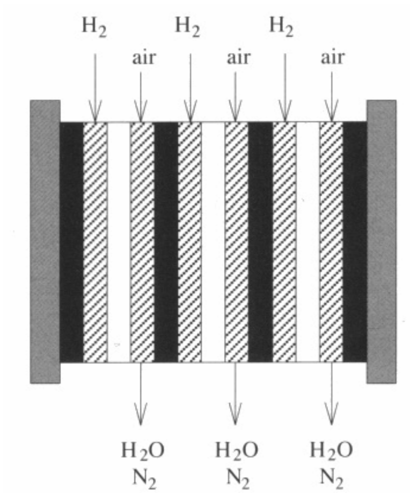
- Convert fuel directly to electrical energy
- Let an ion pass from an anode to a cathode
- Take out electrical work from the electrons



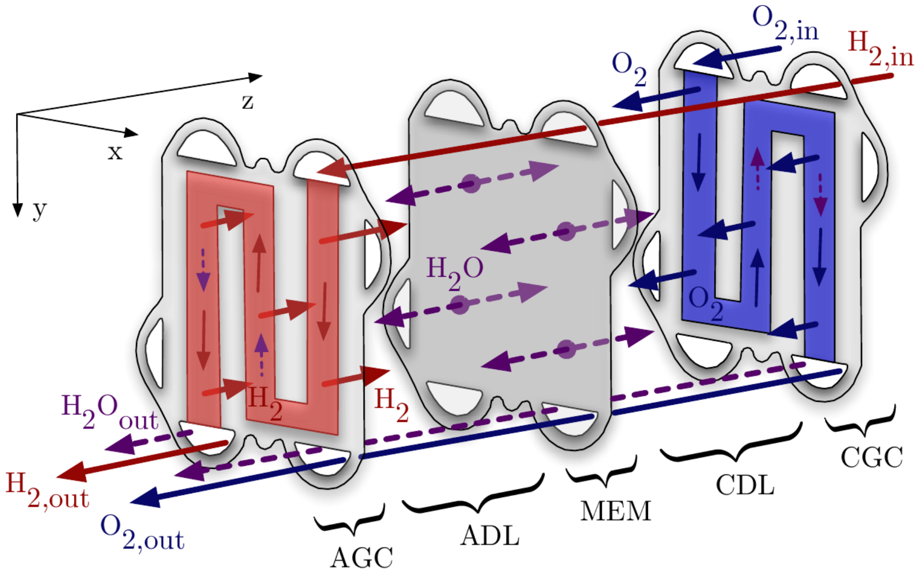
Fuel Cell Stack

- The voltage out from one cell is just below 1 V.
- Fuel cells are stacked, in series.

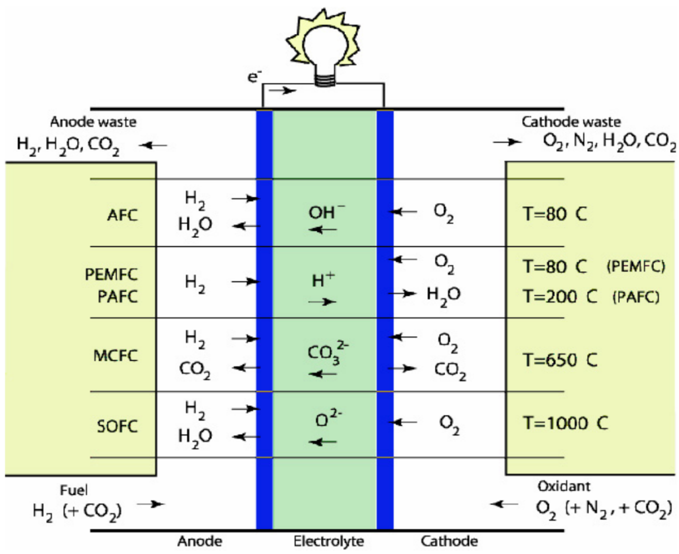




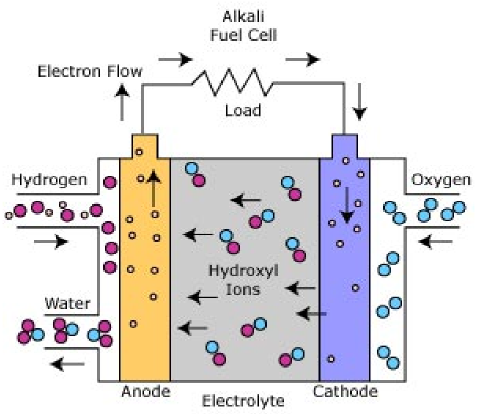
Components in a Fuel Cell Stack



Overview of Different Fuel Cell Technologies



AFC – Alkaline Fuel cell

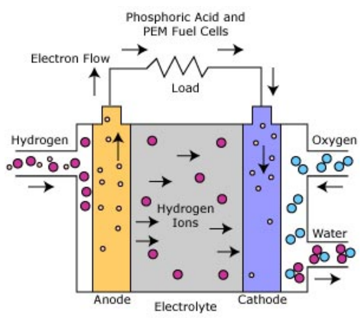


- Among the most efficient fuel cells 70%
- Low temperature 65-220°C
  - Quick start, fast dynamics
  - No co-generation
- Sensitive to poisoning

PEMFC – Proton Exchange Membrane Fuel Cell

Advantages:

- Relatively high power-density characteristic
- Operating temperature, less than 100°C
  –Allows rapid start-up
- Good transient response, i.e. change power
  –Top candidate for automotive applications
- Other advantages relate to the electrolyte being a solid material, compared to a liquid

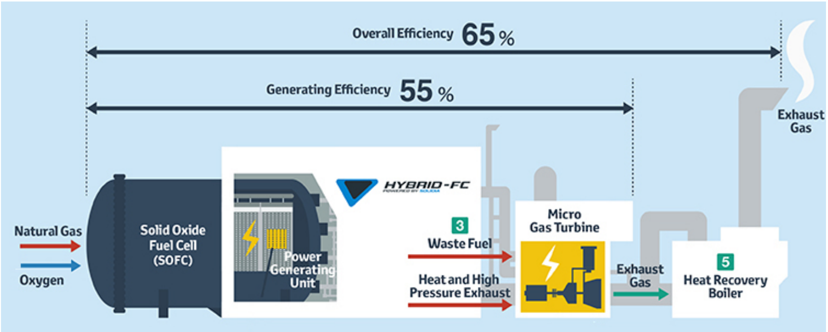


Disadvantages:

- Require expensive catalyst material (Platinum)
- For some applications operating temperature is low
- The electrolyte is required to be saturated with water to operate optimally.
  –Careful control of the moisture of the anode and cathode

The Other Types of H_2 Fuel Cells

- Other fuel cell types are
  - PAFC – Phosphoric Acid Fuel Cell 175°C
  - MCFC – Molten Carbonate Fuel Cell 650°C
  - SOFC – Solid Oxide Fuel Cells 1000°C
- Hotter cells, slower, more difficult to control
- Power generation through co-generation



Hydrogen Fuel Storage

- Hydrogen storage is a challenging task.
- Some examples of different options.
  - Compressed Hydrogen storage
  - Liquid phase – Cryogenic storage, -253°C
  - Metal hydride
  - Sodium borohydride $NaBH_4$

Comparison of H_2 Fuel Cells – US DOE

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	< 1kW–100kW	60% transpor-tation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte re-duces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature cor-rosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabi-lized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature cor-rosion and breakdown of cell components • High temperature opera-tion requires long start up time and limits

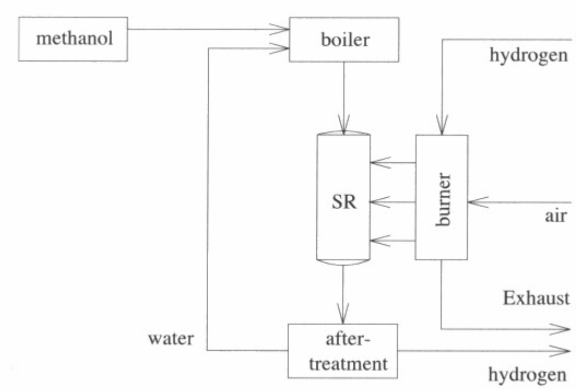
DMFC – Direct Methanol Fuel Cell

- Basic operation
  - Anode Reaction: $CH_3OH + H_2O \Rightarrow CO_2 + 6H^+ + 6e^-$
  - Cathode Reaction: $3/2O_2 + 6H^+ + 6e^- => 3H_2O$
  - Overall Cell Reaction: $CH_3OH + 3/2O_2 => CO_2 + 2H_2O$
- Main advantage, does not need pure Hydrogen.
- Applications outside automotive
  –battery replacements
  –small light weight
- Low temperature
- Methanol toxicity is a problem

Reformers

- Fuel cells need hydrogen – Generate it on-board –Steam reforming of methanol.

$$2\,CH_3OH + O_2 \Rightarrow 2\,CO_2 + 4\,H_2$$

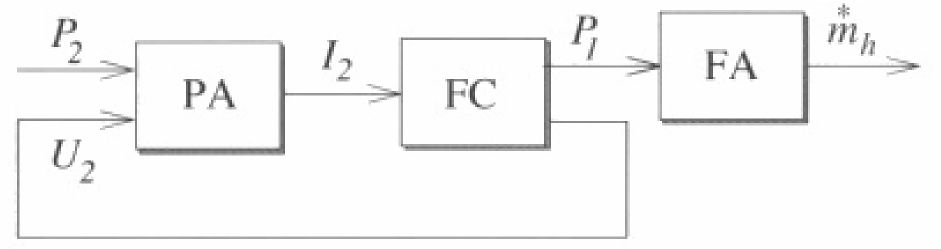


Fuel Cell Applications in USA – US DOE

Outline

Quasistatic Modeling of a Fuel Cell

- Causality diagram



- Power amplifier (Current controller)
- Fuel amplifier (Fuel controller)
- Standard modeling approach
- Keys for understanding:
  - Cell – The polarization curve
  - Operation – The Surrounding System

Fuel Cell Thermodynamics

- Starting point reaction equation

$$H_2 + \frac{1}{2} O_2 \Rightarrow 2\, H_2 0$$

- Open system energy – Enthalpy H

$$H = U + pV$$

- Available (reversible) energy – Gibbs free energy G

$$G = H - TS$$

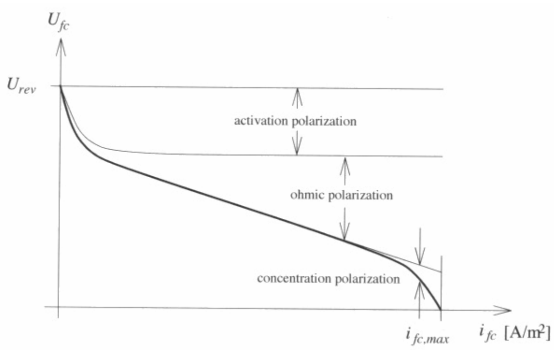
- Open circuit cell voltages

$$U_{rev} = -\frac{\Delta G}{n_e\, F}, \qquad U_{id} = -\frac{\Delta H}{n_e\, F}, \qquad U_{rev} = \eta_{id}\, U_{id}$$

  F – Faradays constant ($F = q\, N_0$)
- Heat losses under load $P_l = I_{fc}(t)\,(U_{id} - U_{fc}(t)) \Rightarrow$ Cooling system

Fuel Cell Performance – Polarization curve

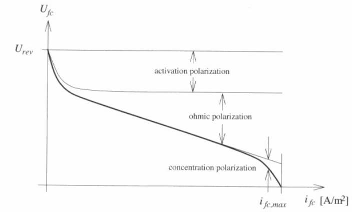
- Polarization curve of a fuel cell
  Relating current density $i_{fc}(t) = I_{fc}(t)/A_{fc}$, and cell voltage $U_{fc}(t)$ Curve for one operating condition
- Fundamentally different compared to combustion engine/electrical motor
- Excellent part load behavior
  –When considering only the cell
  –η_{cell} follows the Voltage



Single Cell Modeling – Describing the Polarization Curve

Fuel cell voltage

$$U_{fc}(t) = U_{rev}(t) - U_{act}(t) - U_{ohm}(t) - U_{conc}(t)$$



- Activation energy – Get the reactions going
  Semi-empirical Tafel equation

$$U_{act}(t) = c_0 + c_1 \ln(i_{fc}(t)), \text{ or } U_{act}(t) = \ldots$$

- Ohmic – Resistance to flow of ions in the cell

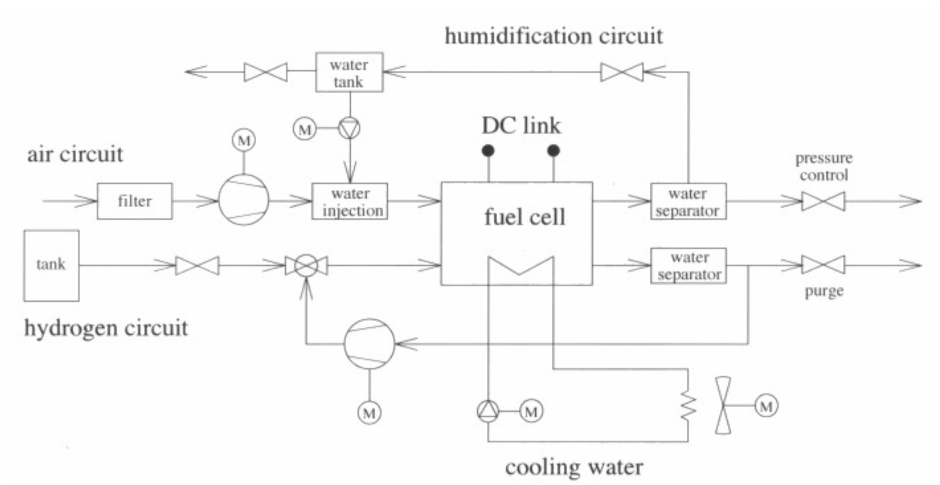
$$U_{ohm}(t) = i_{fc}(t)\,\tilde{R}_{fc}$$

- Concentration, change in concentration of the reactants at the electrodes

$$U_{conc}(t) = c_2 \cdot i_{fc}(t)^{c_3}, \text{ or } U_{conc}(t) = \ldots$$

Fuel Cell System Modeling

- A complete fuel cell system

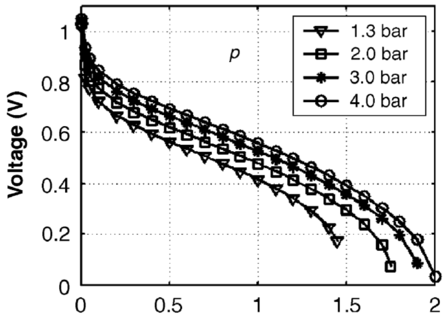


- Power at the stack with N cells

$$P_{st}(t) = I_{fc}(t)\,U_{fc}(t)\,N$$

Important effects for the cell and system

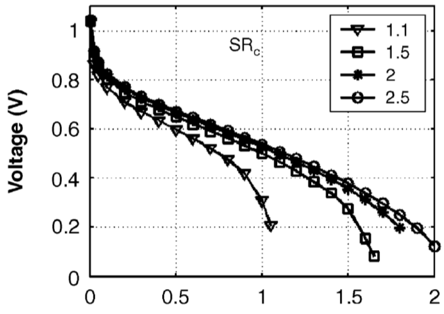
Cell Pressure



(c)

Boosting the performance

Cell excess air λ



(b)

$$2H_2+\lambda O_2 \rightarrow 2\,H_2O+(\lambda-1)O_2, \lambda \geq 1$$

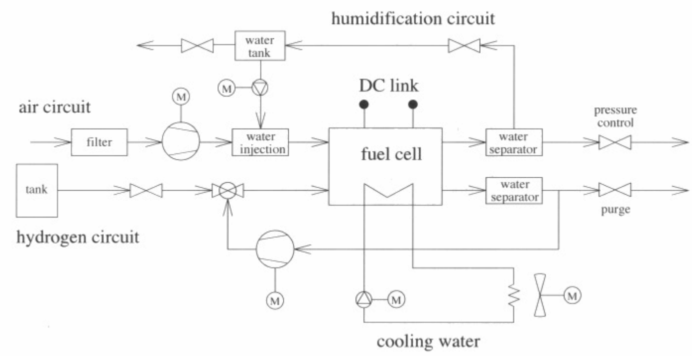
Fuel Cell System Modeling

- Describe all subsystems with models

$$P_2(t) = P_{st}(t) - P_{aux}(t)$$

$$P_{aux} = P_0 + P_{em}(t) + P_{ahp}(t) + p_{hp}(t) + P_{cl}(t) + p_{cf}(t)$$

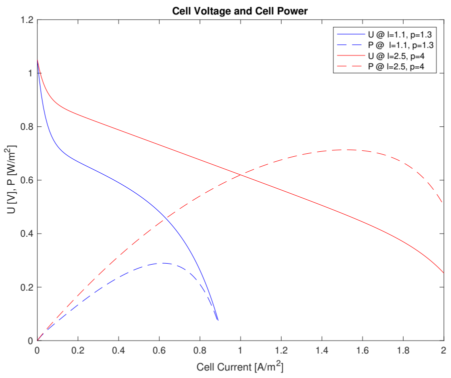
em–electric motor, ahp – humidifier pump, hp – hydrogen recirculation pump, cl – coolant pump, cf – cooling fan.



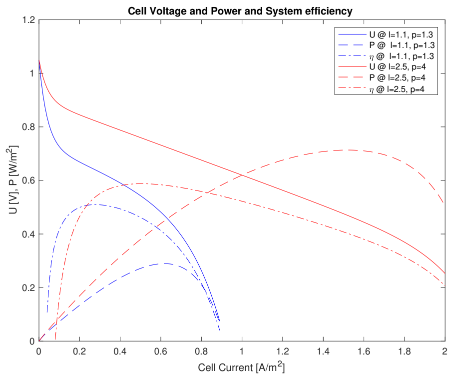
- Submodels for:
  Hydrogen circuit, air circuit, water circuit, and coolant circuit

Fuel Cell System Performance at Low and High P_c

Individual Cell



Fuel Cell System



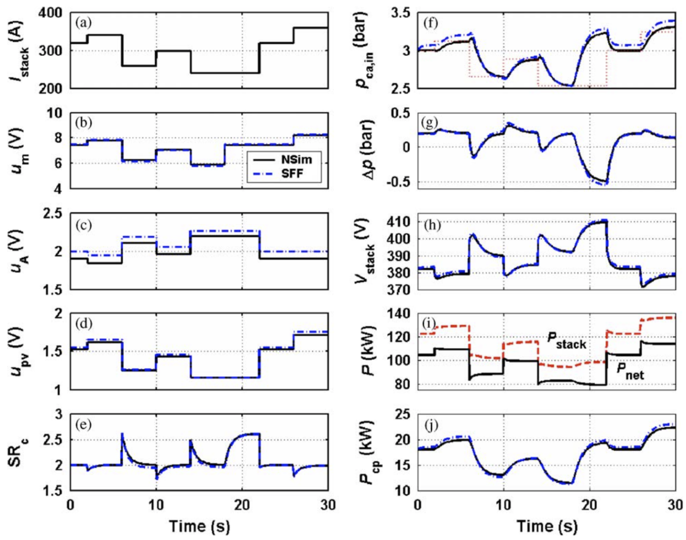
–Efficiency is highest at part loads towards low load.
–The system is stealing current to keep the cell operating.

Fuel Cell System Dynamics

Open Loop Steps on Inputs

Note

- λ, bottom left
- Pressure, top right
- Gap in Cell & Output Power
- Due to compressor power



The system has non-negligible dynamics.

Outline

Repetition

Fuel Cell Electric Vehicles
- Fuel Cell Basics
- Fuel Cell Types
- Reformers
- Applications

Fuel Cell Modeling

Practical aspects
- Examples of Components in a Technology Demonstrator

Fuel Cell Vehicles

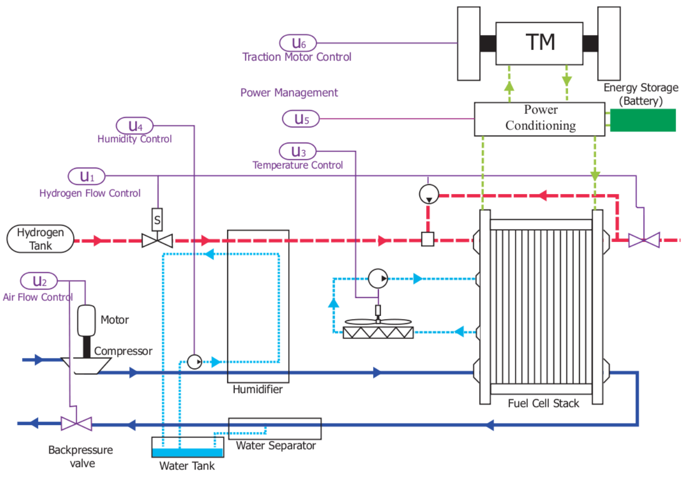
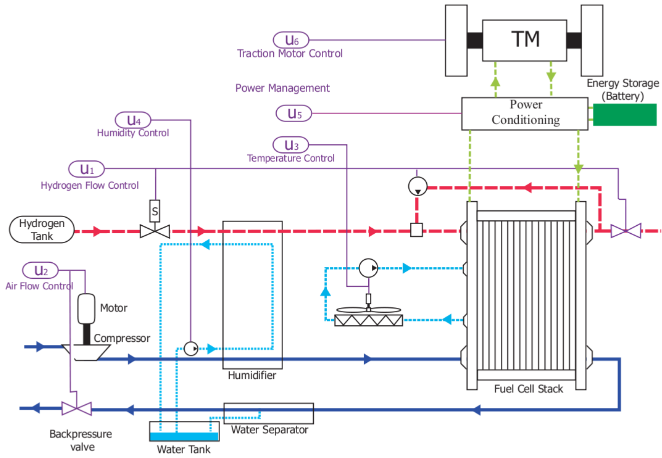


Illustration provided by Prof. Anna Stefanopoulou, University of Michigan.

Fuel Cell HEV – Short Term Storage

Short term storage

1. Recuperation, regenerative breaking
2. FC system has non-negligible time constants
3. Super capacitors
4. Batteries
5. Hybridization



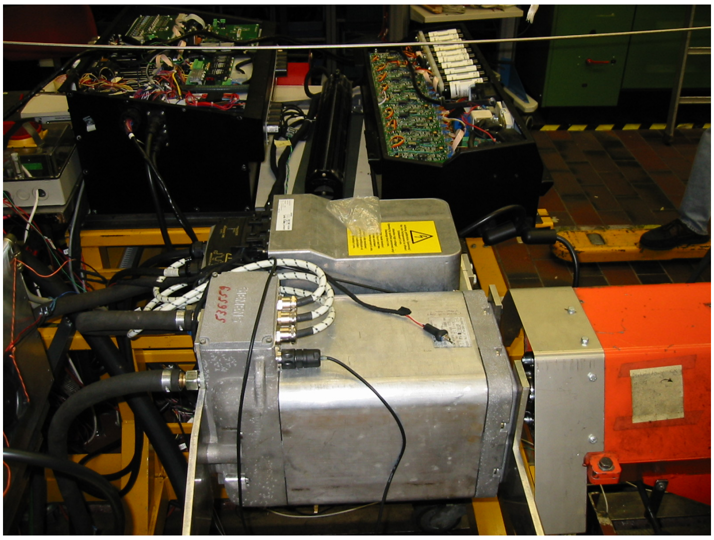
Fuel Cell Vehicle

The Hy.Power vehicle, going over a mountain pass in Switzerland in 2002.

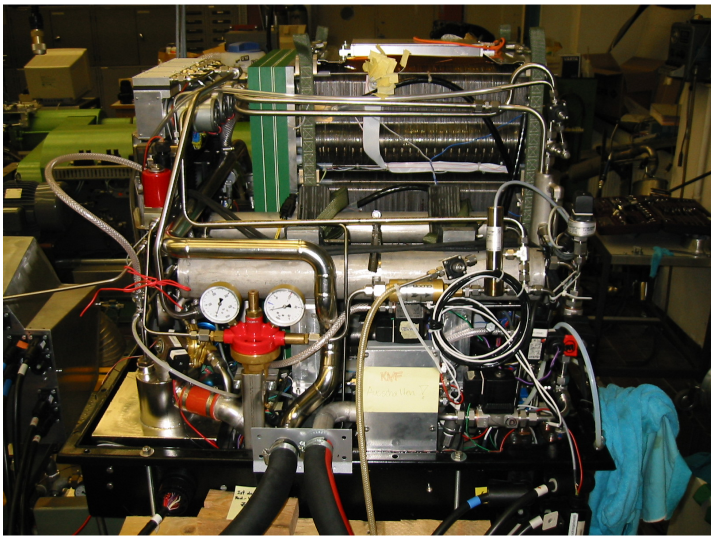
- Technology demonstrator
- Lower oxygen contents, 2005 m
- Cold weather

Let us look at the real components in the powertrain under the shell.

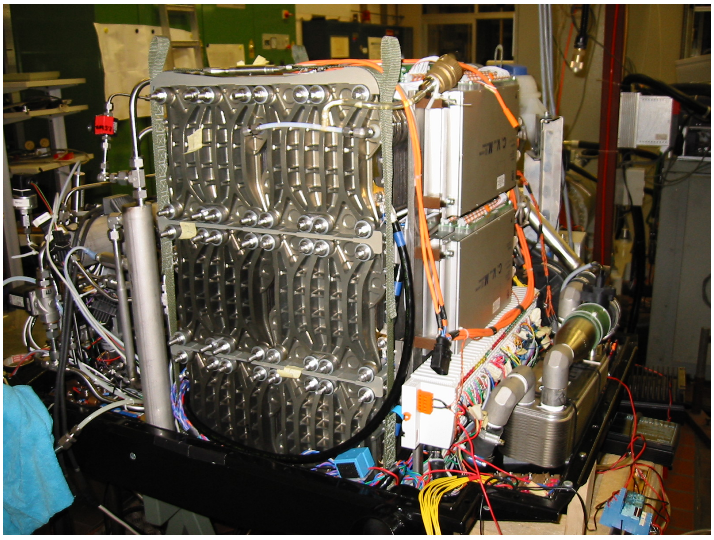
Components – Electric Motor



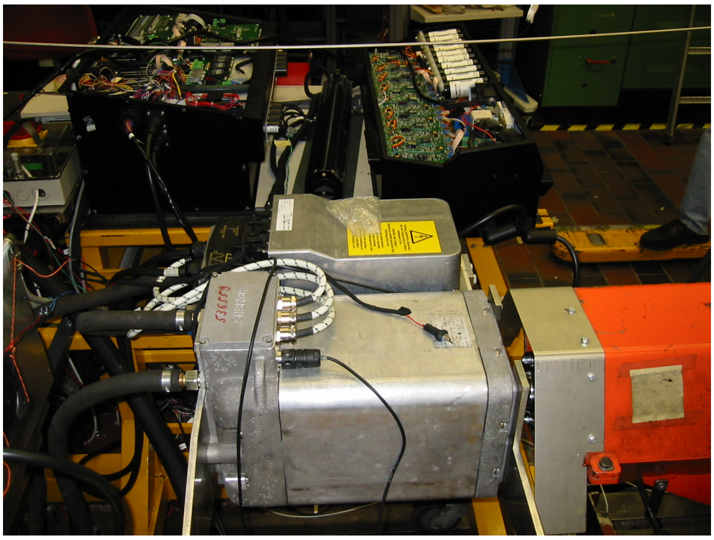
Components – Fuel Supply and Fuel Cell Stack



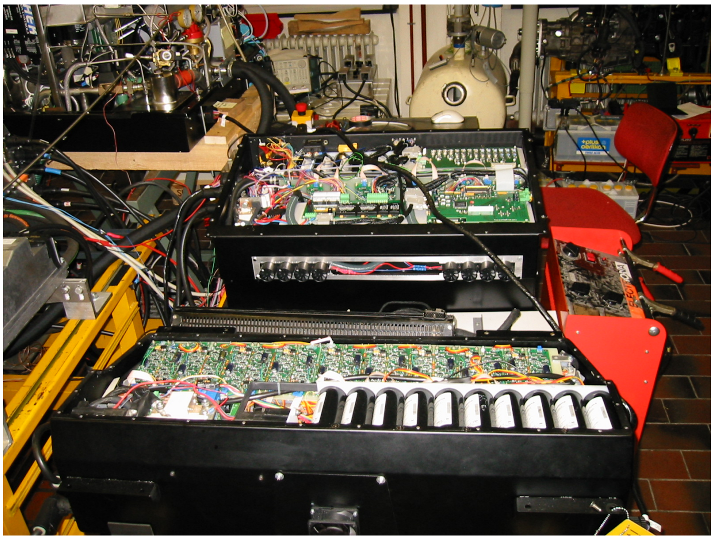
Components – Fuel Cell Stack, Heat Exchanger & Controller



Components – Fuel Cell Stack, Controller and Heat exchanger

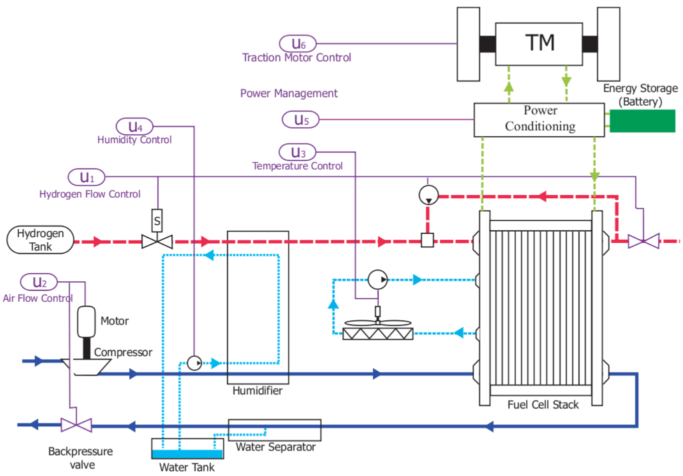


Components – Power Electronics and Super Caps



Lecture is a preparation for the future

Non trivial system that is about to boom in China...



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