Vehicle Propulsion Systems
Lecture 8
Fuel Cell Vehicles

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December 7, 2015

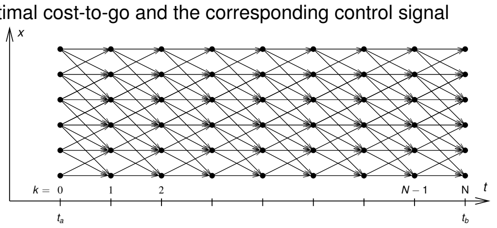
Outline

Deterministic Dynamic Programming – Basic algorithm

$$J(x_0) = g_N(x_N) + \sum_{k=0}^{N-1} g_k(x_k, u_k)$$

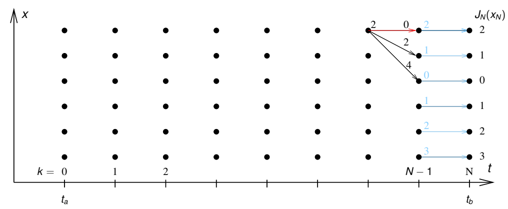
$$x_{k+1} = f_k(x_k, u_k)$$

Algorithm idea:
Start at the end and proceed backward in time to evaluate the optimal cost-to-go and the corresponding control signal

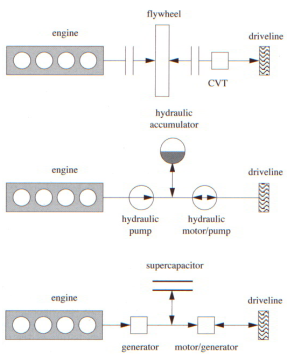


Deterministic Dynamic Programming – Basic Algorithm

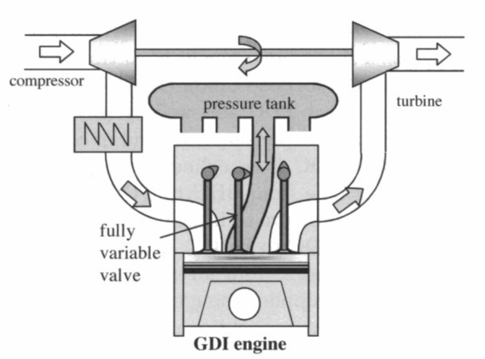
Graphical illustration of the solution procedure



Examples of Short Term Storage Systems

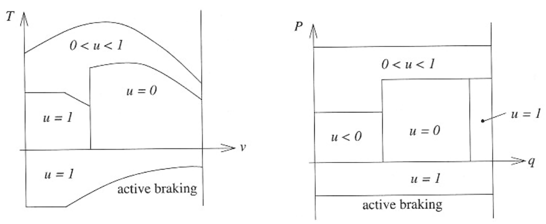


Pneumatic Hybrid Engine System



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

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

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

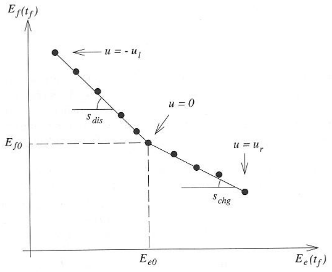
- Introduce equivalence factor (scaling) by studying battery and fuel power

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

ECMS – Equivalent Consumption Minimization Strategy

Determining Equivalence Factors II

- Collecting battery and fuel energy data from test runs with constant u gives a graph



- Slopes determine s_{dis} and s_{chg}

Outline

Repetition

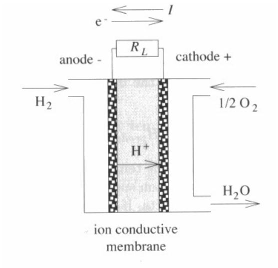
Fuel Cell Basics
- Fuel Cell Basics
- Fuel Cell Types
- Reformers
- Applications

Fuel Cell Modeling

Practical aspects
- Examples of Components in a Technology Demonstrator

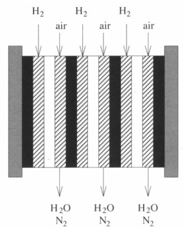
Fuel Cell Basic Principles

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

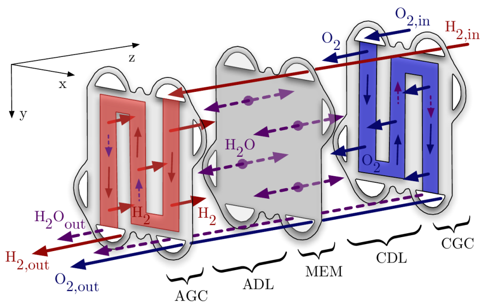


Fuel Cell Stack

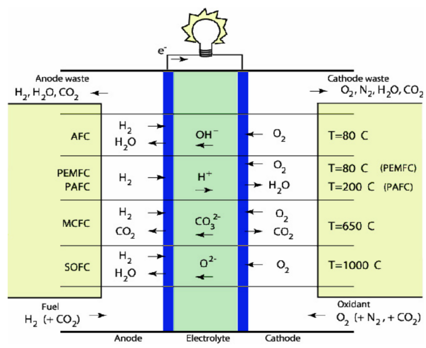
- The voltage out from one cell is just below 1 V.
- Fuel cells are stacked.



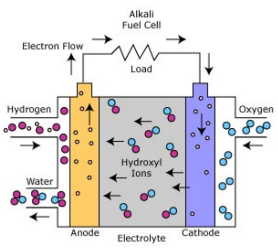
Components in a Fuel Cell Stack



Overview of Different Fuel Cell Technologies



AFC – Alkaline Fuel cell

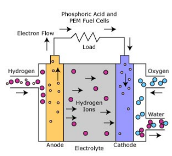


- Among the most efficient fuel cells 70%
- Low temperature 65-220°C
  - Quick start, fast dynamics
  - No co-generation
- Sensitive to poisoning

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:

- of the PEMFC 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 streams is important

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 problematic - 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% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces 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 corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized 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 corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

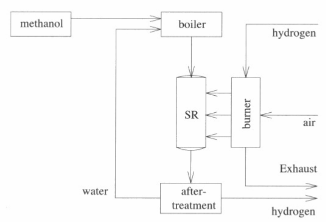
DMFC – Direct Methanol Fuel Cell

- 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.

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

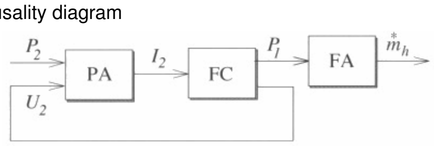


Fuel Cell Applications in USA – US DOE

Outline

Quasistatic Modeling of a Fuel Cell

- Causality diagram



- Power amplifier (Current controller)
- Fuel amplifier (Fuel controller)
- Standard modeling approach

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 voltages

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

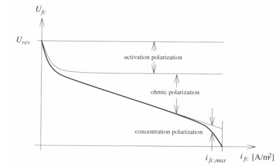
F – Faradays constant ($F = q\, N_0$)

- Heat losses under load – Cooling system

$$P_l = I_{fc}(t)\,(U_{id} - U_{fc}(t))$$

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

Single Cell Modeling

- 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

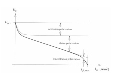
$$U_{act}(t) = c_0 + c_1 \ln(i_{fc}(t)), \text{ or } U_{act}(t) = \ldots$$

  - Ohmic – Resistance to flow of ions in the cell

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

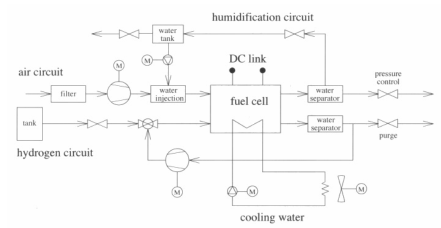
  - Concentration, change in concentration of the reactants at the electrodes

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



Fuel Cell System Modeling

- A complete fuel cell system



- Power at the stack with N cells

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

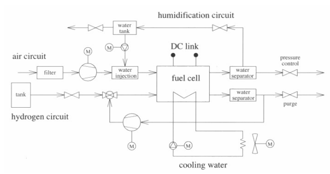
Fuel Cell System Modeling

- Describe all subsystems with models

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

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

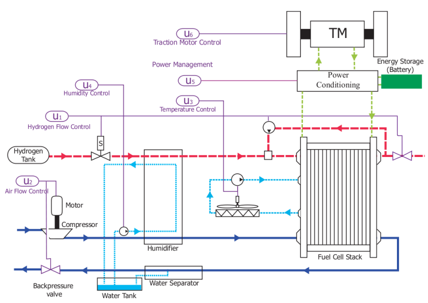
em–electric motor, ahp – humidifier pump, hp – hydrogen recirculation pump, cl – coolant pump, cf – cooling fan.



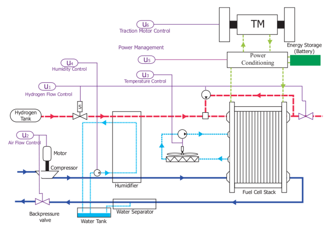
- Submodels for:
Hydrogen circuit, air circuit, water circuit, and coolant circuit

Outline

Fuel Cell Vehicles



Fuel Cell HEV – Short Term Storage



Short term storage

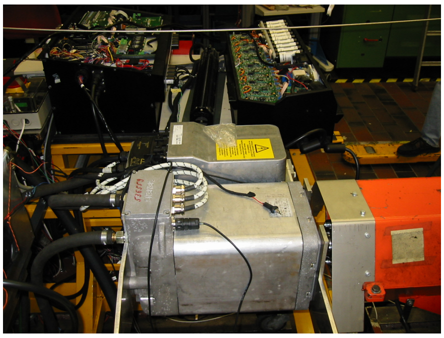
1. Recuperation
2. FC has long time constants

Fuel Cell Vehicle

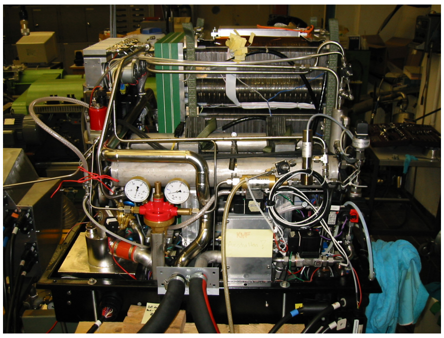
The Hy.Power vehicle, going over a mountain pass in Switzerland in 2002.

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

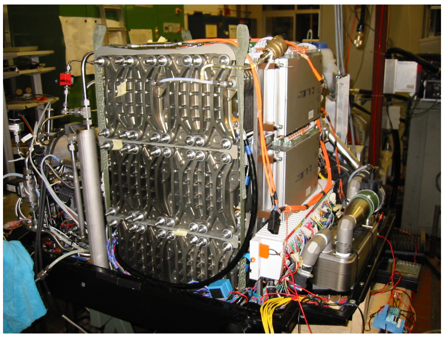
Components – Electric Motor



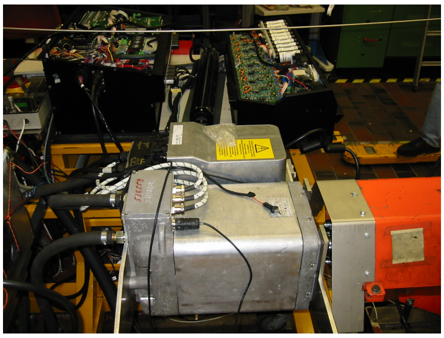
Components – Fuel Supply and Fuel Cell Stack



Components – Fuel Cell Stack and Heat Exchanger



Components – Fuel Cell Stack, Controller and Heat exchanger



Components – Power Electronics and Super Caps