

Vehicle Propulsion Systems

Lecture 8

Fuel Cell Vehicles

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1/40

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

2/40

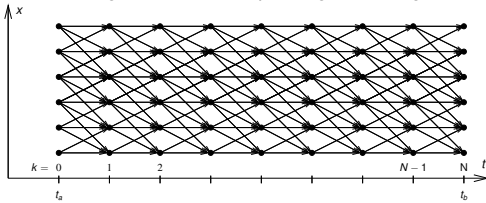
Deterministic Dynamic Programming – Basic algorithm

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

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

Algorithm idea:

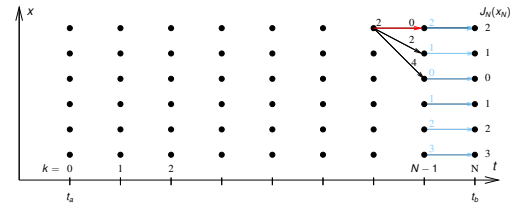
Start at the end and proceed backward in time to evaluate the optimal cost-to-go and the corresponding control signal



3/40

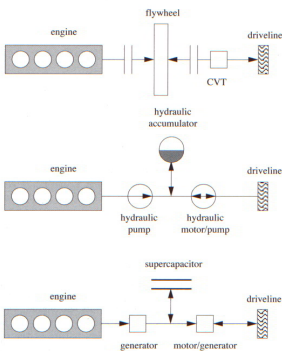
Deterministic Dynamic Programming – Basic Algorithm

Graphical illustration of the solution procedure



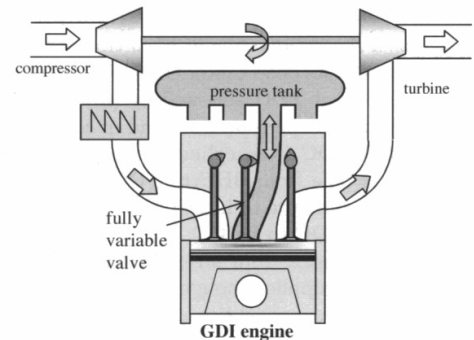
5/40

Examples of Short Term Storage Systems



6/40

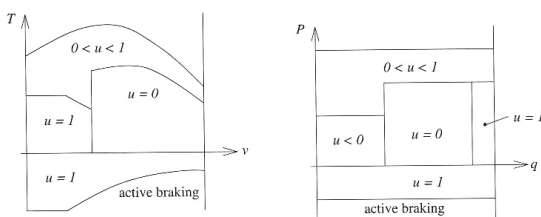
Pneumatic Hybrid Engine System



7/40

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

8/40

ECMS – Equivalent Consumption Minimization Strategy

- ▶ μ_0 depends on the (soft) constraint

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

- ▶ Different efficiencies

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

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

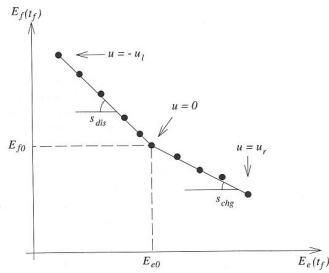
$$s(t) = -\mu(t) \frac{H_{LHV}}{V_b Q_{max}}$$

ECMS – Equivalent Consumption Minimization Strategy

9/40

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}

10/40

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

Fuel Cell Modeling

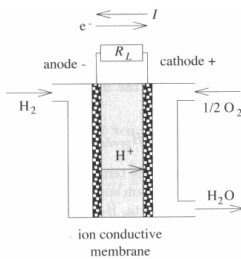
Practical aspects

Examples of Components in a Technology Demonstrator

11/40

Fuel Cell Basic Principles

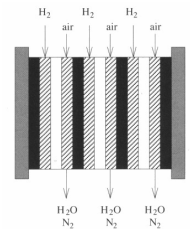
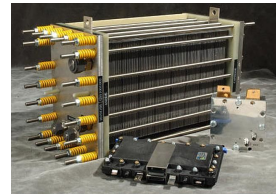
- ▶ Convert fuel directly to electrical energy
- ▶ Let an ion pass from an anode to a cathode
- ▶ Take out electrical work from the electrons



12/40

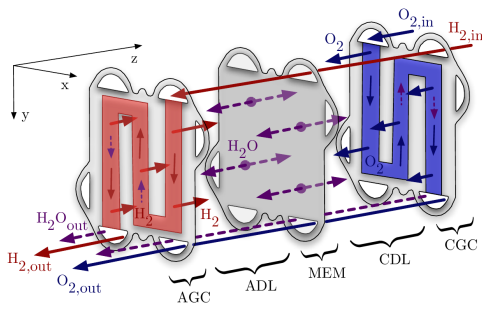
Fuel Cell Stack

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



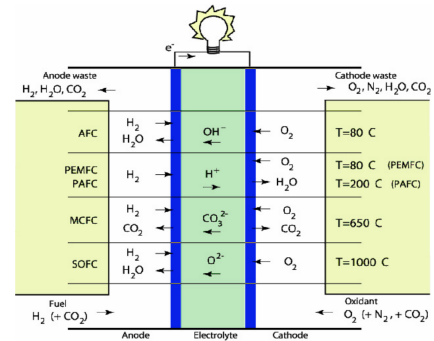
13/40

Components in a Fuel Cell Stack



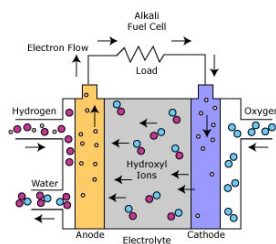
14/40

Overview of Different Fuel Cell Technologies



15/40

AFC – Alkaline Fuel cell



- ▶ Among the most efficient fuel cells 70%
- ▶ Low temperature $65\text{--}220^\circ\text{C}$
 - ▶ Quick start, fast dynamics
 - ▶ No co-generation
- ▶ Sensitive to poisoning

16/40

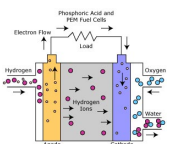
PEMFC – Proton Exchange Membrane Fuel Cell

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



17/40

- ▶ 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 storage is problematic - Challenging task.
- ▶ Some examples of different options.
 - ▶ Compressed Hydrogen storage
 - ▶ Liquid phase – Cryogenic storage, -253°C
 - ▶ Metal hydride
 - ▶ Sodium borohydride NaBH₄

Comparison of H₂ Fuel Cells – US DOE

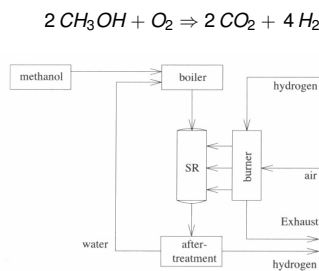
Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Sulfuric acid	50-100°C 122-212°F typically 80°C	<1kW-100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transportation • 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 1302-1832°F	1kW-2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHP • Hybrid/IGT 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: $3/2O_2 + 6H^+ + 6e^- \Rightarrow 3H_2O$
 - ▶ Overall Cell Reaction: $CH_3OH + 3/2O_2 \Rightarrow CO_2 + 2H_2O$
- ▶ 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.



Fuel Cell Applications in USA – US DOE

Fuel Cells for Stationary Power, Auxiliary Power, and Specialty Vehicles

The largest markets for fuel cells today are in stationary power, portable power, auxiliary power units, and forklifts.

~75,000 fuel cells have been shipped worldwide.

>15,000 fuel cells shipped in 2009

Fuel cells can be a cost-competitive option for critical-load facilities, backup power, and forklifts.

Fuel Cells for Transportation

In the U.S., there are currently:

- > 200 fuel cell vehicles
- ~ 20 active fuel cell buses
- ~ 60 fueling stations

Sept. 2009: Auto manufacturers from around the world signed a letter of understanding supporting fuel cell vehicles in anticipation of widespread commercialization, beginning in 2015.

Production & Delivery of Hydrogen

In the U.S., there are currently:

- ~9 million metric tons of H₂ produced annually
- > 1200 miles of H₂ pipelines

Source: US DOE 09/2010

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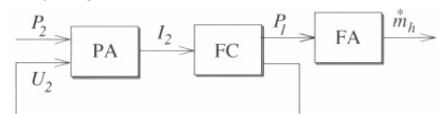
Fuel Cell Modeling

Practical aspects

Examples of Components in a Technology Demonstrator

Quasistatic Modeling of a Fuel Cell

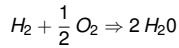
- ▶ Causality diagram



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

Fuel Cell Thermodynamics

- Starting point reaction equation



- Open system energy – Enthalpy H

$$H = U + pV$$

- Available (reversible) energy – Gibbs free energy G

$$G = H - TS$$

- Open circuit cell voltages

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

F – Faradays constant ($F = q N_0$)

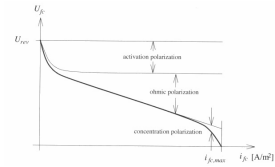
- Heat losses under load – Cooling system

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

26/40

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

27/40

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

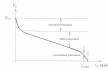
$$U_{act}(t) = c_0 + c_1 \ln(i_{fc}(t)), \text{ or } U_{act}(t) = \dots$$

- 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

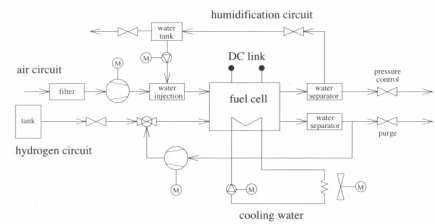
$$U_{conc}(t) = c_2 \cdot i_{fc}(t)^{c_3}, \text{ or } U_{conc}(t) = \dots$$



28/40

Fuel Cell System Modeling

- A complete fuel cell system



- Power at the stack with N cells

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

29/40

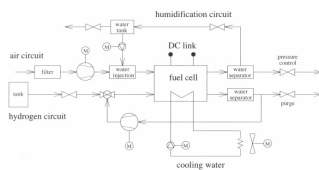
Fuel Cell System Modeling

- 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

30/40

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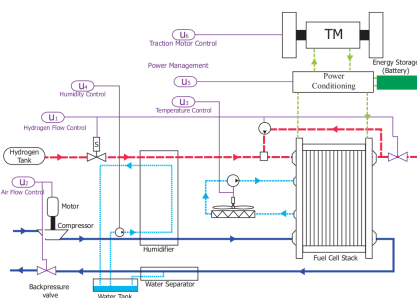
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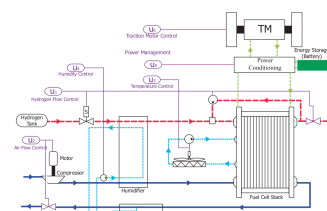
31/40

Fuel Cell Vehicles



32/40

Fuel Cell HEV – Short Term Storage



Short term storage

1. Recuperation
2. FC has long time constants

33/40

Fuel Cell Vehicle

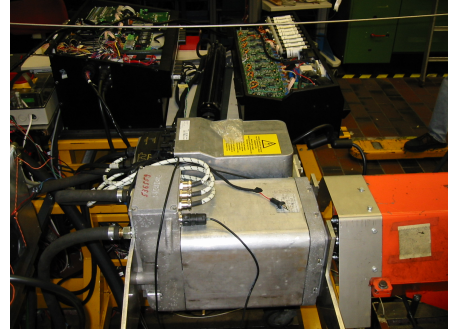
The Hy.Power vehicle, going over a mountain pass in Switzerland in 2002.



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

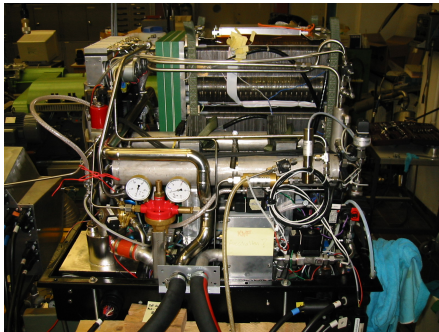
34/40

Components – Electric Motor



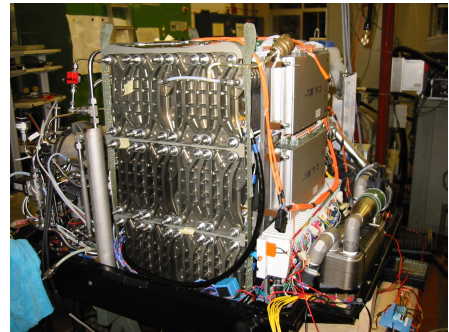
35/40

Components – Fuel Supply and Fuel Cell Stack



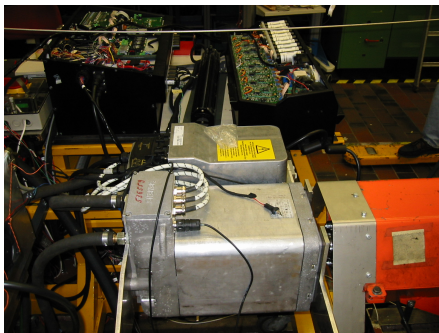
36/40

Components – Fuel Cell Stack and Heat Exchanger



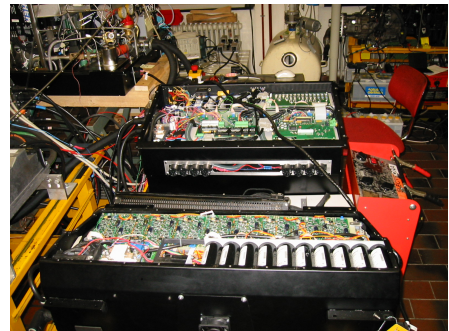
37/40

Components – Fuel Cell Stack, Controller and Heat exchanger



38/40

Components – Power Electronics and Super Caps



39/40