Vehicle Propulsion Systems
Lecture 8
Fuel Cell Vehicles

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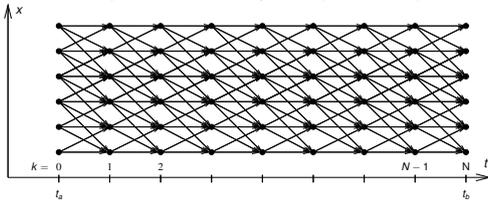
May 5, 2019

Outline

Deterministic Dynamic Programming – Basic algorithm

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

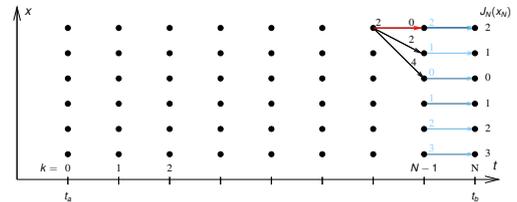$$x_{k+1} = f_k(x_k, u_k)$$

Algorithm idea:
Start at the end and proceed backward in time to evaluate the optimal cost-to-go and the corresponding control signal
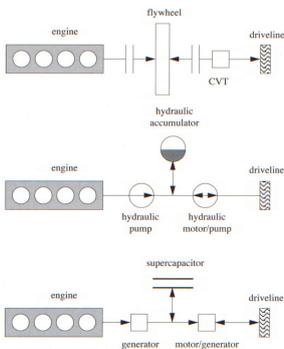
Deterministic Dynamic Programming – Basic Algorithm
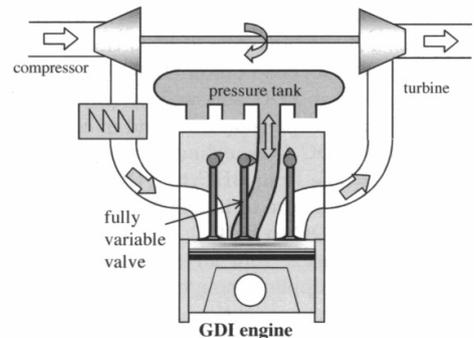
Graphical illustration of the solution procedure
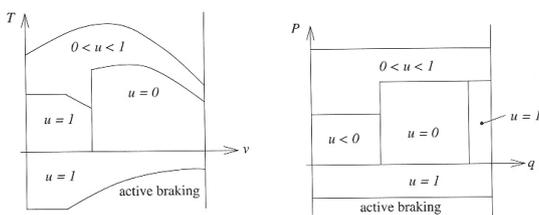
Examples of Short Term Storage Systems

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

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

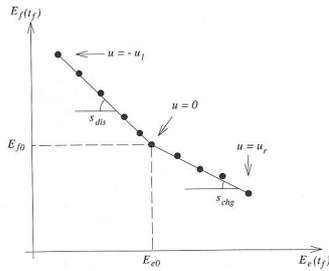▶ Introduce equivalence factor (scaling) by studying battery and fuel power

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

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

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
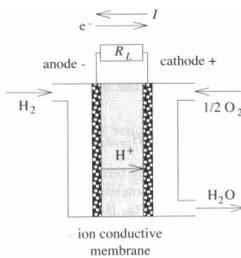
Fuel Cell Stack

- The voltage out from one cell is just below 1 V.
- Fuel cells are stacked.
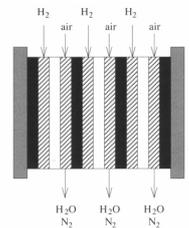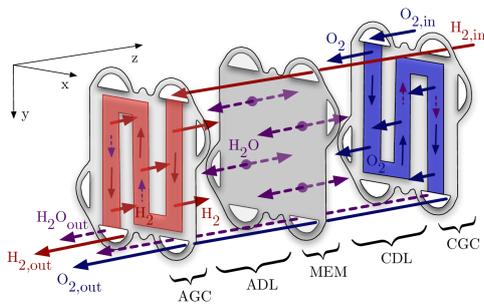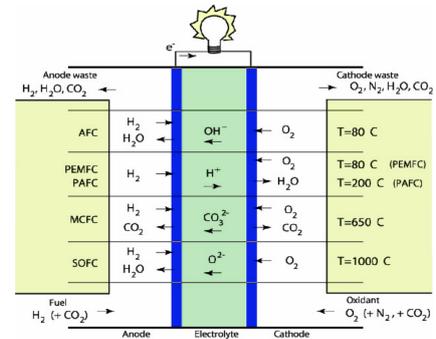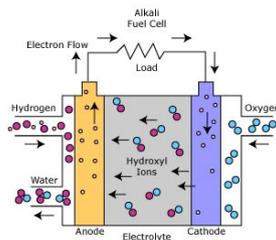
Components in a Fuel Cell Stack

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 100ºC
  –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
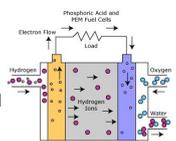
- ► Other fuel cell types are
  - ► PAFC – Phosphoric Acid Fuel Cell   175°C
  - ► MCFC – Molten Carbonate Fuel Cell   650°C
  - ► SOFC – Solid Oxide Fuel Cells   1000°C
- ► Hotter cells, slower, more difficult to control
- ► Power generation through co-generation

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 $NaBH_4$
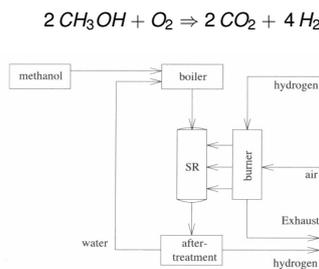
Comparison of H_2 Fuel Cells – US DOE

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% 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

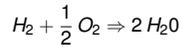## Quasistatic Modeling of a Fuel Cell

- ► Causality diagram
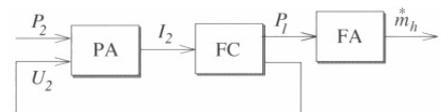
- ► Power amplifier (Current controller)
- ► Fuel amplifier (Fuel controller)
- ► Standard modeling approach

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

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

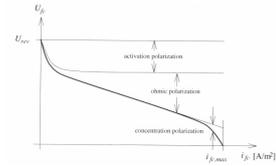F – Faradays constant ($F = q\, N_0$)

► Heat losses under load   –   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
  $$U_{act}(t) = c_0 + c_1 \ln(i_{fc}(t)), \text{ or } U_{act}(t) = \dots$$
  ► Ohmic – Resistance to flow of ions in the cell
  $$U_{ohm}(t) = i_{fc}(t)\, \tilde{R}_{fc}$$
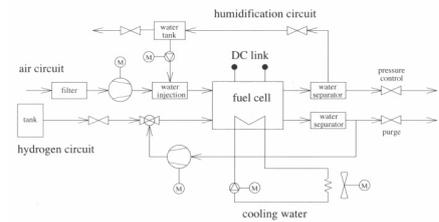 ► Concentration, change in concentration of the reactants at the electrodes
  $$U_{conc}(t) = c_2 \cdot i_{fc}(t)^{c_3}, \text{ or } U_{conc}(t) = \dots$$

Fuel Cell System Modeling

► A complete fuel cell system

► Power at the stack with N cells
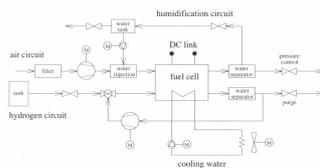
$$P_{st}(t) = I_{fc}(t)\, U_{fc}(t)\, N$$

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
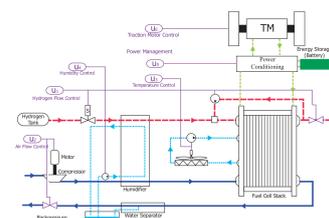
Fuel Cell Vehicles

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
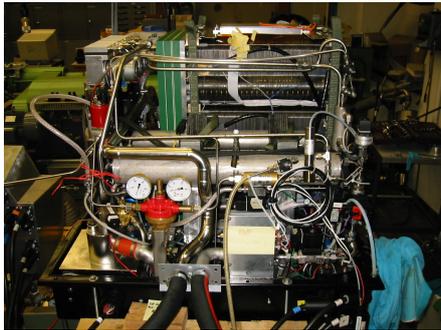- ► Lower oxygen contents, 2005 m
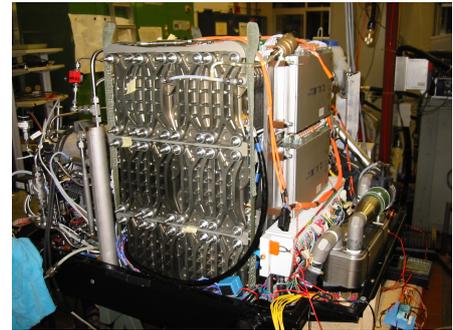- ► Cold weather

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