Vehicle Propulsion Systems
Lecture 10

Fuel Cell Modeling – Some More Details

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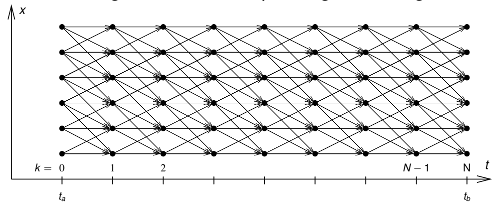
November 29, 2010

Deterministic Dynamic Programming – Basic algorithm

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

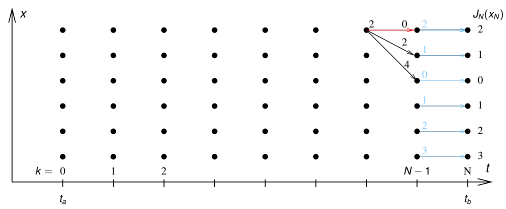
$$x_{k+1} = f_k(x_k, u_k)$$

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

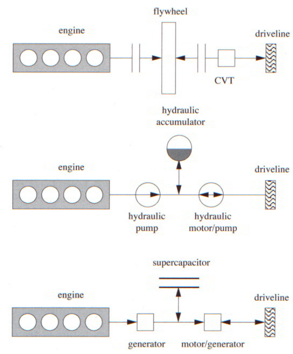


Deterministic Dynamic Programming – Basic Algorithm

Graphical illustration of the solution procedure

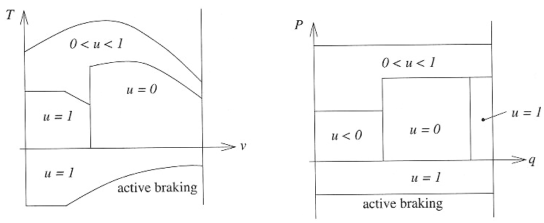


Examples of Short Term Storage Systems



Heuristic Control Approaches

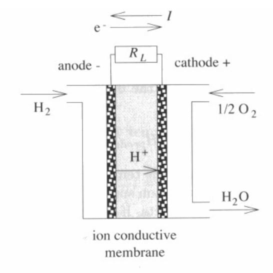
- Parallel hybrid vehicle (electric assist)

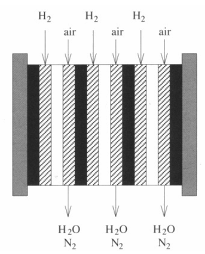


- Determine control output as function of some selected state variables:
  vehicle speed, engine speed, state of charge, power demand, motor speed, temperature, vehicle acceleration, torque demand

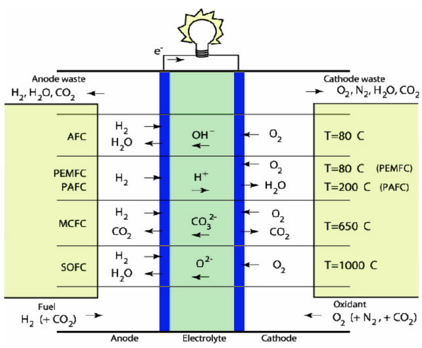
Fuel Cell Basic Principles

- Convert fuel directly to electrical energy
- Let an ion pass from an anode to a cathode
- Take out electrical work from the electrons
- Fuel cells are stacked ($U_{cell} \leq 1$V)





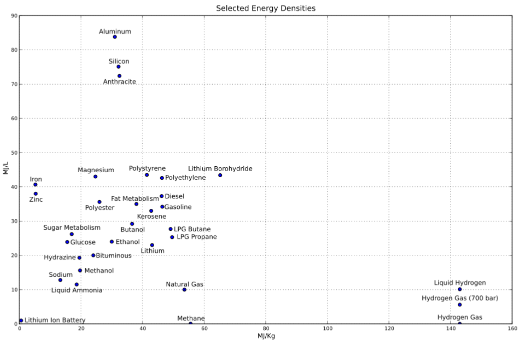
Overview of Different Fuel Cell Technologies



Hydrogen Fuel Storage

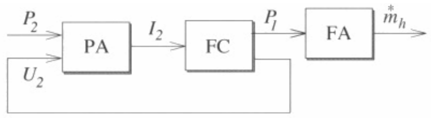
- Hydrogen storage is problematic - Challenging task.
- Some examples of different options.
  - High pressure bottles
  - Liquid phase – Cryogenic storage, -253°C.
  - Metal hydride
  - Sodium borohydride $NaBH_4$

Energy Contents – Hydrogen and others



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

$$H = U + pV$$

- Reversible energy – Gibbs free energy G

$$G = H + TS$$

- Open circuit cell voltages

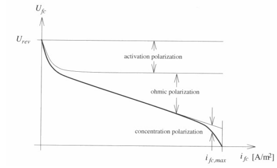
$$U_{rev} = -\frac{\Delta G}{n_e\, F}, \qquad U_{id} = -\frac{\Delta H}{n_e\, F}, \qquad U_{rev} = \eta_{id}\, U_{id}$$

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

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

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

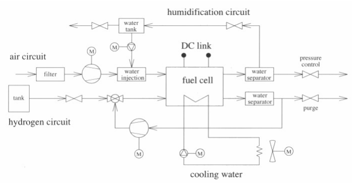
Fuel Cell System Modeling

- 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

Modeling of fuel cells from first principles

Modeling is done on the white board.