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Innovation and Creativity

Control of Fuel Cells

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Outline

Introduction

Electrochemistry

Buck-boost converters

Manifold composition and pressure control

Stack temperature control

Introduction

Fuel cells

- Devices to convert chemicals (hydrogen, oxygen) into electricity
- No polluting emissions, scalable, efficient, no moving parts. . .
- This thesis focuses on proton-exchange-membrane fuel cells

Motivation for control of fuel cells

- Any fuel cell outside a lab needs control!
- Commercial applications require automation
- Even in the lab it would be useful: many phenomena
- Most research on the topic focuses on only one aspect at a time

Choice of Control Variables

- Classical stumbling block: few fuel cell researchers are trained in control theory, let alone experts
- *What* do we want to control? *With what* are we going to do it?

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- Assuming current or voltage can be manipulated directly
- Choosing bad combinations: manipulate inflow to control power output (not strictly impossible)
- Considering only part of the system (this is difficult to escape)

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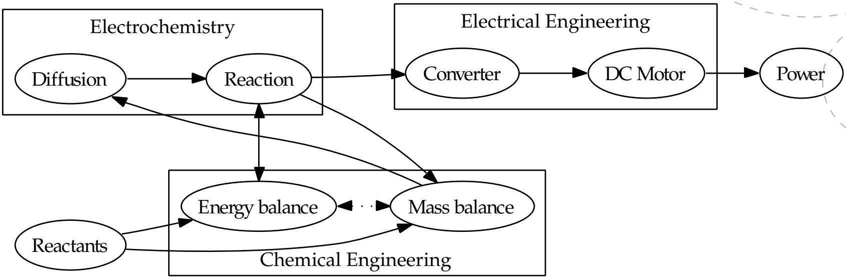
  - Choosing bad combinations: manipulate inflow to control power output (not strictly impossible)
  - Considering only part of the system (this is difficult to escape)
- We first have to consider what the fuel cell is going to be used for, and how it will be connected
- Control insight may actually suggest design modifications to improve the system's controllability

Advantages of Polybenzimidazole Membranes

- Pbi works at higher temperatures (125–200 °C) than ordinary Nafion (80–90 °C):
  - We simply don't have any water management
  - Streams contain more heat: no dedicated cooling loop?
  - Increased tolerance to CO
- Pbi cells look better for control, but there are some issues:
  - Not as off-the-shelf as Nafion, less reproducibility
  - Less experimental data (influence of CO?)

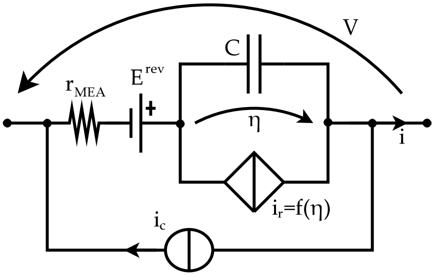
Fuel-Cell Dynamics

— Many assume that there is only one dynamics of fuel cells: in fact, there are many dynamic modes



— Users are really interested only in the *last part*, the rest is "under the hood"

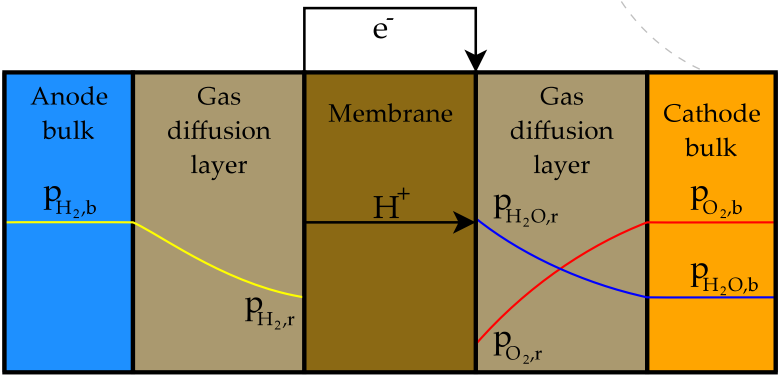
The Electrochemical Model



- A common model for a fuel cell, with cathode only
- It consists of generator E^{rev}, internal resistance R_{MEA}, charge double layer C, Butler-Volmer law $f(\eta)$, crossover current density generator i_c

Multicomponent Diffusion

Can we simplify the Stefan-Maxwell and continuity equations?



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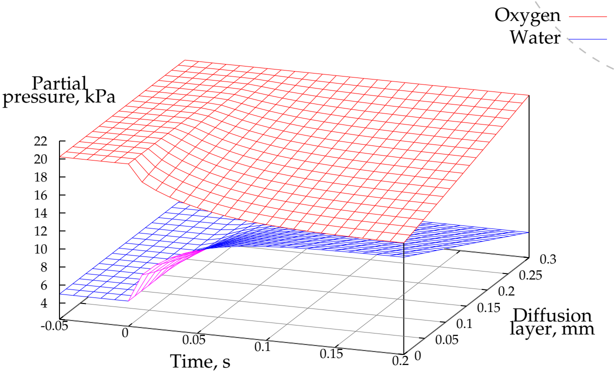
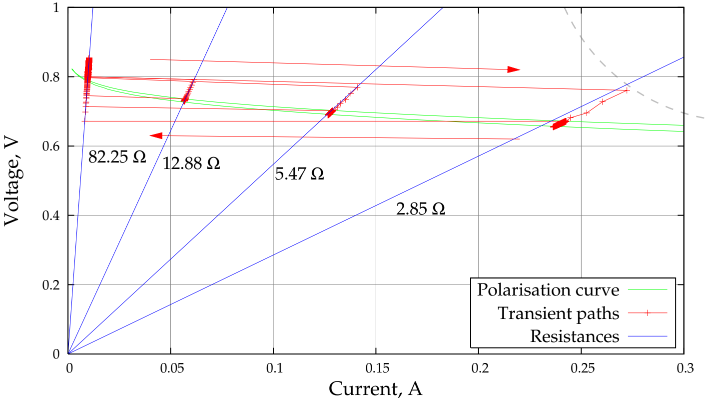


— Transients are fast enough to be neglected, especially since these transients lag behind other ones

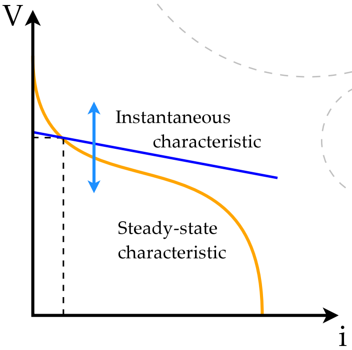
Stepping the Resistance Load



- Markers spaced by ≈ 0.06 s
- Notice the similar pattern for all transients!

The Instantaneous Characteristic

- The points in the i-V plane a cell can immediately reach
- Moves up and down with values of $\eta(i_r)$; inclination depends on r
- The actual voltage and current depend on the load's characteristic as well



The Instantaneous Characteristic

- The points in the i-V plane a cell can immediately reach
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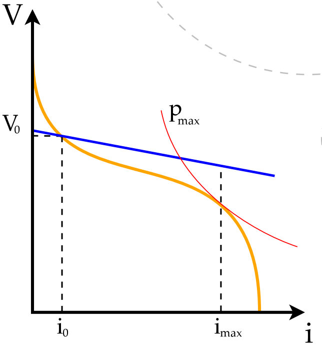
- The actual voltage and current depend on the load's characteristic as well
- It is possible to step power output instantaneously to any value



Control of Reaction Rate

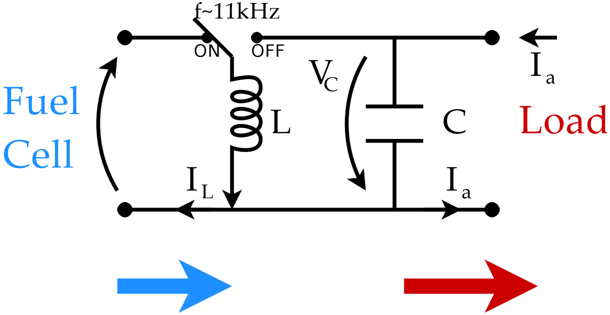
- Control of reaction rate i_r means control of the overvoltage η

$$\dot{\eta} = \frac{i + i_c - i_r}{C}$$

- The only variable we can modify (albeit indirectly) is the external current i:
- To control the reaction rate, we will manipulate the external circuit and its relation $i(V)$
  - Mosfet
  - Rheostat
  - Converter
  - . . . Anything that modifies the external circuit's characteristic

Converters

— Converters work by switching between two configurations
— Buck-boost converter: can deliver higher or lower voltages
— Neither configuration delivers power at steady-state



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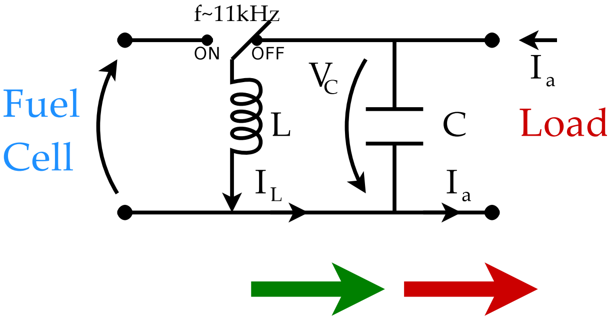

Converter Control

- Not a simple problem: no steady state
- Two strategies considered:
  - Pulse-width modulation: we use a continuous variable for the fraction of time we are in the ON mode
  - Switching rules: the switch is set ON and OFF according to some rule

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- Pulse-width modulation is better for calculations, but gives a nonlinear problem of difficult solution
- The switching rules have a better performance, but their simulation is very slow

Composition and pressure control

- Two separate equations for cathode and anode
- Cathode side must be open-ended (water production)
- Anode side may be dead-ended if hydrogen is (reasonably) pure, possibly with periodic purging
- Reactant concentration does not determine the rate of reaction—It is *the reaction* that requires a certain concentration!

Dead-End Flows

— Typical case for an anode fed on pure hydrogen

— Fairly simple balance on a single component:

$$\frac{d\,n_{H_2}}{d\,t} = \dot{n}_{H_2}^{in} - \frac{i_r\,A}{2\,F}$$

— $\dot{n}_{H_2}^{in}$ is our manipulated variable, and we have to maintain n_{H_2} despite variations in i_r

— We control anode pressure, but the system is unstable and needs feedback

Control Pi feedback controller with a pressure measurement with a feedforward component

Open-End Flows

- Typical with inert components such as nitrogen, or taking up product water (air, impure hydrogen)
- Assume perfect mixing in the bulk (CSTR)
- Diffusion will occur, and with it mass-transport barriers
- Mass-transport barriers will move to higher values of current for higher reactant concentration in the bulk

Control of Open-End Flows

— Mole fraction dynamics for a generic component i:

$$\frac{p\,\mathcal{V}}{R\,T}\frac{d\,x_i}{d\,t} = \overbrace{\dot{n}^{in}\,\left(x_i^{in} - x_i\right)}^{\text{Feed}} + \frac{i_r\,A}{F}\left(\overbrace{\nu_i}^{\text{Reaction}}\overbrace{-\,x_i\,\sum_i \nu_i}^{\text{Dilution}}\right)$$

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Control Pure feedforward

Temperature control

- Enthalpy balance:

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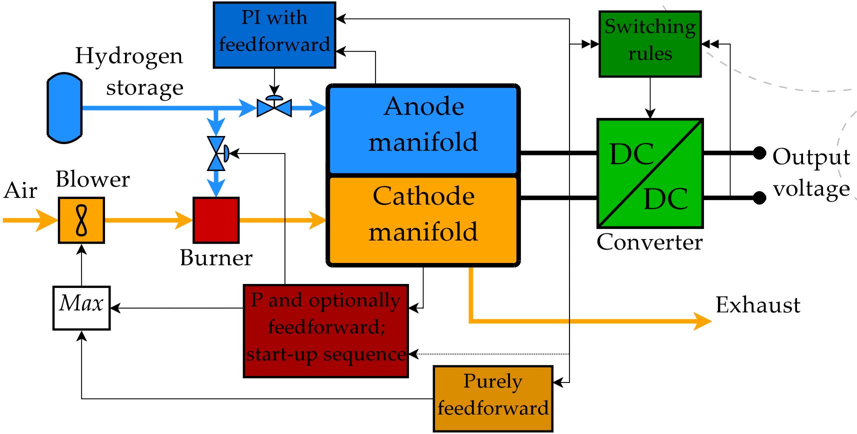
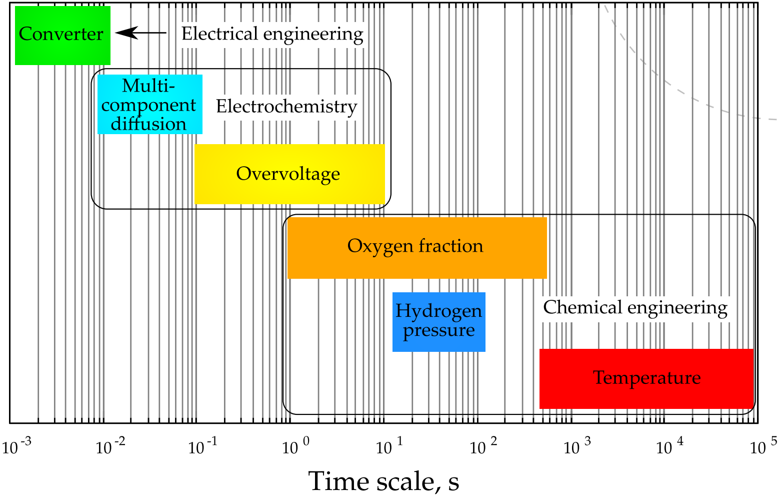
- No additional requirement on air flow capacity

Overall Control Structure



Time Scales of Fuel-Cell Dynamics



Conclusions

- Fuel-cell systems can deliver power very rapidly; there are slower *internal* dynamics
- The electrochemical transient's nature allows perfect control of power output from a cell
- Simple control algorithms for pressure, composition and temperature are good enough
- Converter control is somewhat less friendly, and is critical for system performance

Acknowledgements

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