Coordination of DC-DC Converter & Fuel Cell Controllers

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Introduction

- Modeling, coordination and control of fuel cell electric hybrid power system
  - Simple, but accurate fuel cell system model
  - Considering physical implementation
    - Parasitic losses
    - DC-DC converter is controlled for voltages / currents
    - Depends on electric configuration

Fuel cell hybrid system

- Components
  - Fuel cell stack
    - Main power source for the vehicle
    - Slow and complex dynamics due to the reactions between reactant flow and heat transfer
  - Battery or ultracapacitor
    - Secondary power source that gives additional power stored mainly from regenerative braking
  - DC-DC converter - Matches voltage or current from power source to load
  - Inverter / motor - Major load that drives the vehicle
  - Auxiliary load - Necessarily power for stack operation (Ex. air supply compressor)

Contents

- Fuel cell power system
- FC electric hybrid configurations
- Fuel cell dynamics
- DC-DC converter dynamics
- Control problem formulation
  - Decentralized control
  - Coordinated control
- Conclusions and Future work
Control of fuel cell power

- Previous works on fuel cell power
  - Control of fuel cell system
    - Passive filter application
    - Active filter application
      - "Load governor for fuel cell oxygen starvation protection: A robust nonlinear reference governor approach", J. Sun & I. Kolmanovsky, ACC 2004
      - "Model predictive control for starvation prevention of a hybrid fuel cell system", A. Vahidi, A. Stefanopoulou & H. Peng, ACC 2004
  - Control of DC-DC converter
    - "Design of a wide input range DC-DC converter with a robust power control scheme suitable for fuel cell power conversion", M. Todorovic, L. Palma & P. Enjeti, 2004 Applied Power Electronics Conference and Exposition

FC electric hybrid configuration

- Electric configuration
  - Coordinates current flow split between fuel cell stack and battery from the power demand of higher lever controller or energy management system
  - Provides regulated voltage and current to inverter that drives the propulsion motor and auxiliary load
  - Protects the fuel cell stack from sudden current draw changes before the stack is ready
  - Maintains battery state of charge for proper working condition

Fuel cell hybrid vehicle

- Fuel cell system with DC-DC converter
  - DC-DC converter boosts the fuel cell stack voltage to the battery voltage
  - Current drawn from fuel cell is controlled by DC-DC converter
- Application - DC, Honda
  - Fuel cell system that supports the load directly
    - Low voltage battery is used with converter in boost mode for discharging, in buck mode for charging
- Application - Ford, Toyota
  - Fuel cell produces variable electric power which depends on CURRENT, temperature, pressure and humidity

PEM Fuel cells

- I-V curve
  \[ v_F = E(P, T, i) - v_{act}(P, T, i) - v_{con}(T, \phi, i) - v_{conv}(P, T, i) \]

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Fuel cell dynamics

- Ideal gas law
- Controlled temperature (80°C) and humidity (=1)
- Controlled anode pressure (same as cathode pressure)
- Nozzles between supply manifold & cathode, cathode outlet & atmosphere
- DC motor drive for the compressor
  - Static voltage/torque map

Dynamic states
\[
\frac{dp_c}{dt} = \frac{RT}{M_c V_c} (W_{c,in} - W_{c,end} - W_{c,end})
\]
\[
\frac{dp_{N_c}}{dt} = \frac{RT}{M_{N_c} V_{c}} (W_{N_c,in} - W_{N_c,end})
\]
\[
\frac{dp_{o,c}}{dt} = \frac{1}{J_{o,c}} (\tau_{o,c} - \tau_{o,c})
\]
\[
\frac{dp_{o,m}}{dt} = \frac{RT}{M_{o,m} V_{o,m}} (W_{o,m} - W_{o,m})
\]

Parameters
- Volumes
- Orifices
- Motor
- Compressor map

Model validation
- Simulation comparisons with

Fuel cell air supply system

- Considering compressor power
  - w/o compressor power load
  - w/ compressor power load

Compressor power is drawn from the stack (ideal power transformer assumption)
\[
I_o = I_{o,in} + I_{o,cm}
\]
\[
I_{o,cm} = \frac{P_{cm}}{V_{o,cm}} (V_{o,cm} \cdot \cdot \cdot)
\]

Fuel cell air supply control

- Setpoint Map + Feedforward/feedback controller

Feedback control limitations in air supply due to the compressor power loss (Mufford and Strasky, 1999)
- Non minimum phase zero from compressor control to power (Purkrushpan et al, 2004)
DC-DC boost converter dynamics

- Switching operation
  - SW1 = ON
  - SW1 = OFF
- Static analysis with duty ratio
  - Power \( P_{\text{IN}} = P_{\text{OUT}} \)
  \( V_{\text{IN}} I_{\text{IN}} = V_{\text{OUT}} I_{\text{OUT}} \)
- Charge
  \( I_{\text{IN}} (1 - D) = I_{\text{OUT}} \)

\[ V_{\text{OUT}} = V_{\text{IN}} I_{\text{OUT}} (1 - D) \]

DC-DC boost converter dynamics

- Dynamic model
  - SW1 = ON
  - SW1 = OFF
- Average model

\[ L \frac{d^2 i(t)}{dt^2} + R \frac{dv(t)}{dt} + C \frac{dv(t)}{dt} = E - (1 - D) \bar{v}(t) \]

\[ P_{\text{IN}} = P_{\text{OUT}} \]

Elements of power electronics, P.T. Krein, 1997

DC-DC voltage regulation

- Escobar, IEEE Control Systems Magazine, 1999
- Nonlinear plant model
  \[ L \frac{d^2 i(t)}{dt^2} + R \frac{dv(t)}{dt} + C \frac{dv(t)}{dt} = E - (1 - D) \bar{v}(t) \]
- LQR with integral control acts as current filter to the FC
  \[ d_1 = -K_D I_{\text{IN}} - K_P V_{\text{OUT}} - K_I \int V_{\text{OUT}} \, dt \]

Elements of power electronics, P.T. Krein, 1997

Decentralized vs. Coordinated control

- Control objectives
  - Oxygen excess ratio
  - Output voltage

Elements of power electronics, P.T. Krein, 1997
Multivariable control technique

- Design a controller using LQ technique
  \[ \dot{x} = Ax + Bu + B_w \]
  \[ y = Cx \]
  \[ u = -K_p x \]  
  State feedback

- Closed loop system. Choose k based on pole placement or LQ

State feedback

\[ \dot{x} = (A - B_p K_p) u + B_w \]
\[ y = C_x \]

- Use measurement

\[ \dot{x} = A \hat{x} + Bu + L(y - \hat{y}) \]
\[ \hat{y} = C_x \hat{x} \]

- The error in estimation

\[ \hat{x} = x - \hat{x} \]
\[ \hat{x} = (A - LC_x) \hat{x} \]

Multivariable control technique

- State estimator design

\[ \dot{\hat{x}} = A \hat{x} + B_u \]
\[ \dot{\hat{y}} = C_x \hat{y} \]

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Minimize the quadratic cost function

\[ J = \int_0^{\infty} (x'Qx + u'Ru) dt \]

- The result will make the states go to equilibrium fast

Multivariable control technique

- State estimator design

\[ \dot{x} = Ax + Bu \]
\[ \dot{\hat{x}} = C_x \hat{y} \]

- Use measurement

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- The error in estimation

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Combined system model

- Linear fuel cell power system model

\[ \dot{x} = Ax + Bu + B_w \]
\[ y = C_x + D_w u \]
\[ z = C_z x + D_z u \]
\[ \dot{v}_c = C_{v_c} x + D_{v_c} u \]
\[ \dot{v}_m = C_{v_m} x + D_{v_m} u \]
\[ \dot{q}_c = C_{q_c} x + D_{q_c} u \]
\[ \dot{q}_m = C_{q_m} x + D_{q_m} u \]

- Control Input

\[ [v_c, \dot{v}_m, q_c, \dot{q}_m, \dot{q}_m, \dot{q}_m] = [k_{c_1} \ldots k_{c_13} k_{c_14} \ldots k_{c_112} k_{c_113} k_{c_114} q_1] \]

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\[ \dot{x} = Ax + Bu + B_w \]
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\[ [v_c, \dot{v}_m, q_c, \dot{q}_m, \dot{q}_m, \dot{q}_m] = [k_{c_1} \ldots k_{c_13} k_{c_14} \ldots k_{c_112} k_{c_113} k_{c_114} q_1] \]

Simulation results

- Simulation results

\[ R_{out}(\Omega) \]
\[ v_{in}(V) \]
\[ v_{out}(V) \]
\[ v_{in}(V) \]
\[ k_{out}(V) \]
\[ k_{out}(V) \]
\[ k_{out}(V) \]
\[ k_{out}(V) \]

Simulation results

- Simulation results

\[ I_{in}(A) \]
\[ I_{out}(A) \]
\[ I_{out}(A) \]
\[ I_{out}(A) \]
\[ I_{out}(A) \]
\[ I_{out}(A) \]
\[ I_{out}(A) \]
\[ I_{out}(A) \]
Conclusions

- Control-oriented model for fuel cell reactant supply is developed.
- Electric configurations of fuel cell vehicle are formulated with fuel cell system, converter & battery.
- Fundamental limitations in fuel cell air supply control arise from the compressor and fuel cell electric coupling.
- Multivariable control achieved better performance from the physics-based models of the combined fuel cell system and DC-DC converter.

Future work
- Extend to the various electric configurations
  - Application to hybrid system
  - Application to voltage controlled fuel cell system

Question & Open discussion

FC dynamics

- Mass balances
  \[
  \frac{dp_{O_2}}{dt} = \frac{RT}{M_O} (W_{O_2,in} - W_{O_2,out} - W_{O_2,act})
  \]
  \[
  \frac{dp_{N_2}}{dt} = \frac{RT}{M_N} (W_{N_2,in} - W_{N_2,out})
  \]
  \[
  W_{ca,out} = \frac{C_a A_e}{\sqrt{RT}} f(p_{ca}, p_{aim})
  \]

- Electrochemistry
  \[
  W_{O_2,act} = M_O \times \frac{nI}{4F}
  \]

- Manifold filling
  \[
  \frac{dp_{air}}{dt} = \frac{RT_{air}}{M_{air} V_{air}} (W_{air,air} - W_{air,act})
  \]
  \[
  W_{act,air} = k_{air,act} (p_{air} - p_{air})
  \]

- Compressor motor
  \[
  J_{cp} \frac{d\omega_{cp}}{dt} = \tau_{sw} - \tau_{cp}
  \]
  \[
  \tau_{sw} = \frac{k_f}{R_{sw}} (v_{sw} - k_s \omega_{cp})
  \]

- Stack voltage
  \[
  V_{act} = n(E - v_{act} - v_{aim} - v_{con})
  \]