Power Control for a Polymer Electrolyte Membrane Fuel Cell

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Outline

➢ PEMFC Model
  • Mat. & Energy Balances and Electrochemistry
  • Operating Characteristics

➢ Controller Design
  • Power Set-Point Tracking
  • Temperature / Humidity Regulation
  • Oxygen Regulation
What is a Fuel Cell?

Answer:

A device that converts fuel directly into electrical power
Polymer Electrolyte Membrane Fuel Cell (PEMFC)

Generated power due to enthalpy released by the reaction:

\[ H_2 + \frac{1}{2} O_2 \rightarrow H_2O \]

\( \Delta H \sim 58 \text{ kcal/mole } H_2 \)
Dynamic Model of PEMFC

- Parameters based on 50 kW scale.
- Pure hydrogen feed
- Air cooling is assumed.
Material Balances in the Cathode

\[ V_{\text{cat}} \frac{dC_{H_2O}}{dt} = F_{\text{cat}}^{\text{in}} C_{H_2O}^{\text{in}} - F_{\text{cat}} C_{H_2O} + r_{H_2O} A_{\text{mem}} \]

\[ V_{\text{cat}} \frac{dC_{O_2}}{dt} = F_{\text{cat}}^{\text{in}} C_{O_2}^{\text{in}} - F_{\text{cat}} C_{O_2} - \frac{1}{2} r_{H_2O} A_{\text{mem}} \]

\[ V_{\text{cat}} \frac{dC_{N_2}}{dt} = F_{\text{cat}}^{\text{in}} C_{N_2}^{\text{in}} - F_{\text{cat}} C_{N_2} \]

\[ F_{\text{cat}} C = F_{\text{cat}}^{\text{in}} C + \frac{1}{2} r_{H_2O} A_{\text{mem}} \]
Energy Balances

Cathode Chamber Gas

\[ V_{cat} \frac{dT_{cat}}{dt} = F_{cat}^\text{in} T_{cat}^\text{in} - F_{cat} T_{cat} + \left( \frac{UA}{\rho C_p} \right)_\text{cat} (T_{sol} - T_{cat}) \]

Cooling Jacket Gas

\[ V_{jac} \frac{dT_{cat}}{dt} = F_{jac}^\text{in} T_{jac}^\text{in} - F_{jac} T_{jac} + \left( \frac{UA}{\rho C_p} \right)_\text{jac} (T_{sol} - T_{jac}) \]

Solid Material

\[ \left( \rho C_p \right)_\text{sol} V_{sol} \frac{dT_{sol}}{dt} = \left( UA \right)_\text{cat} (T_{cat} - T_{sol}) + \left( UA \right)_\text{jac} (T_{jac} - T_{sol}) + \left( UA \right)_\text{eff} (T_{amb} - T_{sol}) + Q_{gen} A_{mem} \]
Rates

Rate of Reaction:
(production of water per area of membrane)

\[ r_{H_2O} = -\frac{j}{2F} \]

Heat Generation Rate:
(per area of membrane)

\[ Q_{gen} = (\Delta H_{f,H_2O}) r_{H_2O} - P_e \]

Power Generation:
(electrical energy generation rate per area of membrane)

\[ P_e = j E_{cell} \]
Current Density Depends on the Load

The fuel cell looks like a battery to the electrical world.

\[ I = j \cdot A_{cell} \]
Changing the Reaction Rate

\[
E_{\text{load}} = E_o - R_{\text{int}} \cdot I
\]

\[
E_{\text{load}} = R_{\text{load}} \cdot I
\]

\[
r_{H_2O} = - \frac{I / A_{\text{mem}}}{n \cdot F}
\]
Electrochemistry

\[ E_{\text{cell}} = E_{\text{ner}} - E_{\text{act}} - E_{\text{ohm}} - E_{\text{mt}} \]
Electrochemistry

\[ E_{\text{cell}} = E_{\text{ner}} - E_{\text{act}} - E_{\text{ohm}} - E_{\text{mt}} \]

Nernst Potential:

\[ E_{\text{ner}} = E_o + \frac{RT_{\text{sol}}}{2F} \ln \left( \frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}} \right) \]
Electrochemistry

\[ E_{cell} = E_{ner} - E_{act} - E_{ohm} - E_{mt} \]

Ohmic Loss:

\[ E_{ohm} = IR = jA_{mem} \left( \frac{t_{mem}}{A_{mem} \sigma} \right) \]

- \( \sigma \sim \) ionic conductivity of the membrane
- \( \sigma \) depends on humidification levels
Ohmic Resistance

Ionic conductivity, $\sigma$, increases with humidity.

$$RH = x_{H_2O} \frac{P}{P^{sat}(T)}$$

$x_{H_2O} = 0.35$
Partial PEMFC Polarization Curve

\[ E_{cell} = E_{ner} - E_{act} - E_{ohm} - E_{mt} \]
**PEMFC Polarization Curve**

\[ E_{\text{cell}} = E_{\text{net}} - E_{\text{act}} - E_{\text{ohm}} - E_{\text{mt}} \]
PEMFC Polarization Curve

\[ E_{cell} = E_{net} - E_{act} - E_{ohm} - E_{mt} \]

**Activation Loss:**

\[ E_{act} = \frac{1}{\alpha} \frac{RT_{sol}}{2F} \ln\left( \frac{j}{j_o} \right) \quad j_o = j_o^{o} \left( \frac{C_{O_2}^{(s)}}{C_{O_2}^{o}} \right)^{\gamma} \]

**Mass Transfer Loss:**

\[ E_{mt} = -\frac{1}{2} \frac{RT_{sol}}{2F} \ln\left( \frac{C_{O_2}^{(s)}}{C_{O_2}^{o}} \right) \]
Surface Concentrations

Mass Transfer Rate:
(assuming \( O_2 \) is the rate limiting species)

\[
(1/2)r_{H_2O} = K(C^{(s)}_{O_2} - C_{O_2})
\]

Mass Transfer Coefficient:

\[
K = K_o \left(1 - e^{\left(\frac{RH - 1}{\psi}\right)}\right)
\]

• \( \psi \sim \) porosity coefficient
Flooding Resistance via the MTC

\[ \psi = 0.25 \]
\[ \psi = 0.075 \]
\[ \psi = 0.025 \]
Efficient Operation

Ionic conductivity, $\sigma$, increases with humidity.

\[ x_w = 0.35 \]
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  • Temperature / Humidity Regulation
  • Oxygen Regulation
Power Set-Point Tracking

Transportation Applications

![Car Image]

\[
P_e^{(sp)} \rightarrow \text{Power Controller} \rightarrow MV \rightarrow \text{PEMFC}
\]

\[P_e\]
Selecting the Power Output

![Graph showing the relationship between current density (mA/cm²), cell voltage (V), and power density (watts/cm²). The graph includes two curves: one representing cell voltage and the other representing power density. The curves are labeled as $P_e$ and $E_{cell}$, respectively.](image-url)
Selecting the Power Output

![Graph showing current density vs. cell voltage and power density](image)

- Current Density (mA/cm\(^2\))
- Cell Voltage (V)
- Power Density (watts/cm\(^2\))

Equations:
- \( P_e \)
- \( E_{cell} \)
Selecting the Power Output

![Graph showing the relationship between current density and cell voltage and power density.](image)
Selecting the Power Output

![Graph showing the relationship between Current Density and Power Density]
Power Controller

\[ j^{(sp)} \]  \rightarrow \text{PI}  \rightarrow E_{\text{cell}}  \rightarrow \text{PEMFC}  \rightarrow j  \rightarrow P_e

\[ P_e^{(sp)} \]

Graph:

- Cell Voltage (V) vs. Power Density (watts/cm$^2$)
- Current Density (mA/cm$^2$) vs. Cell Voltage (V)
- Power Density (watts/cm$^2$) vs. Current Density (mA/cm$^2$)
Power Controller
Power Controller

![Graph showing Power Density vs Time (seconds)]

- $P_e$
- $P_e^{(sp)}$

Power Density (watts/cm$^2$)

Time (seconds)
Power Controller

![Graph showing the relationship between current density and cell voltage over time, and power density with current density.](graph.png)
Power Controller Flooding

![Graph showing the change in temperature and relative humidity over time. The graph plots temperature (Celsius) and relative humidity (%). The x-axis represents time in seconds, ranging from 0 to 25 seconds. The y-axis represents temperature, ranging from 64°C to 74°C, and relative humidity, ranging from 90% to 100%. The graph shows a decrease in temperature and an increase in relative humidity over time.]
Power Controller

- $P_e$ (solid line)
- $P_e^{(sp)}$ (dotted line)

Power Density (watts/cm$^2$) vs. Time (seconds)

- $P_e$: 0.18, 0.20, 0.22
- $P_e^{(sp)}$: 0.19, 0.20, 0.22
Power Controller Failure

![Graph showing current density and cell voltage over time](image)
Power Controller

![Graph showing power density over time]

- $P_e$ (solid line)
- $P_e^{(sp)}$ (dotted line)

Power Density (watts/cm²)

Time (seconds)
Power Controller Failure
Power Controller Failure

![Graph showing Power Controller Failure](image)

- Current Density (mA/cm²)
- Cell Voltage (V)
- Power Density (watts/cm²)
- $P_e$
- $E_{cell}$
Temperature / RH Controller

Power Controller

PEMFC

$P_e^{(sp)}$ $E_{\text{cell}}$ $P_e, j$

$T_{\text{cat}}^{(sp)}$ $F_{\text{jac}}$

$T_{\text{cat}}$

$RH^{(sp)}$

$RH$

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Temperature / RH Controller

- Power Controller
  - $P_e^{(sp)}$
  - $E_{cell}$
  - $P_e, j$

- PEMFC
  - $F_{jac}$

- Temperature / RH Controller
  - $T_{cat}^{(sp)}$
  - $R_{H}^{(sp)}$

- PI
  - $T_{cat}$

- RH
Temperature / RH Controller

\[ P_e^{(sp)} \rightarrow \text{Power Controller} \rightarrow E_{cell} \rightarrow \text{PEMFC} \]

\[ P_e, j \]

\[ T_{cat}^{(sp)} \rightarrow \text{PI} \rightarrow F_{jac} \]

\[ T_{cat} \]

\[ RH^{(sp)} \rightarrow RH \]

\[ RH \]
Temperature / RH Controller

Power Controller

$E_{cell}$

$P_{e}$

$P_{e,j}$

PI

$F_{jac}$

$T_{cat}$

$T_{cat}^{(sp)}$

$P_{e}^{(sp)}$

RH

$T_{cat}$

$RH^{(sp)}$

Cooling
Air In
Jacket
Exhaust

MEA

Solid Material

Current Collector

H$_2$

O$_2$

$H_2O$

$N_2$

Anode

H$_2$ In

Cathode

Air In

Cathode

Exhaust

H$_2$

$H_2$ In

Insulator

Jacket

Exhaust

Current Collector

$E_{cell}$
Temperature / RH Controller

![Graph showing the power density (watts/cm²) over time (seconds)].

- \( P_e \) (solid line)
- \( P_{(sp)} \) (dashed line)

- **Y-axis (Vertical):** Power Density (watts/cm²)
- **X-axis (Horizontal):** Time (seconds)
Temperature / RH Controller

![Graph showing temperature and relative humidity over time]

- Temperature (Celsius) vs. Time (seconds)
- Relative Humidity (%) vs. Time (seconds)
- Lines represent:
  - $T_{\text{cat}}$
  - $T_{\text{cat}}^{(sp)}$
  - $RH$

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Oxygen Controller

Power Controller

\( P_e^{(sp)} \)

\( E_{cell} \)

\( P_e, j \)

PEMFC

\( F_{jac} \)

\( RH, T_{cat} \)

RH Controller

\( x_{O_2} \)

\( x_{O_2}^{(sp)} \)

\( + \)

PI

\( F_{cat} \)
Oxygen Controller

- **Power Controller**
  - $P_e^{(sp)}$
  - $E_{cell}$
  - $P_e, j$

- **PEMFC**
  - $F_{jac}$
  - $RH, T_{cat}$

- **RH Controller**
  - $RH^{(sp)}$

- **PI**
  - $F_{cat}$
  - $x_{O_2}^{(sp)}$

- **$x_{O_2}$**

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Oxygen Controller

\[
\begin{align*}
\text{Power Controller} & \quad P_e^{(sp)} \quad \rightarrow \quad E_{cell} \\
\text{PEMFC} & \quad F_{jac} \quad \rightarrow \quad RH^{(sp)} \\
\text{RH Controller} & \quad \leftarrow \quad RH, T_{cat} \\
\text{PI} & \quad \leftarrow \quad F_{cat} \\
\end{align*}
\]

\[
\begin{align*}
E_{cell} & \quad \rightarrow \quad F_{jac} \\
F_{cat} & \quad \rightarrow \quad RH^{(sp)} \\
\end{align*}
\]

\[
\begin{align*}
P_e^{(sp)} & \quad \rightarrow \quad E_{cell} \\
\end{align*}
\]

\[
\begin{align*}
x_{O_2}^{(sp)} & \quad \rightarrow \quad x_{O_2} \\
\end{align*}
\]
Oxygen Controller

![Graph showing the relationship between Power Density (watts/cm$^2$) and Time (seconds). The graph includes two lines: one dotted line labeled $P_e^{(sp)}$ and one solid line labeled $P_e$. The x-axis represents time in seconds, ranging from 0 to 400, while the y-axis represents power density, ranging from 0 to 0.6.]
Oxygen Controller

![Graph showing the mole fraction of oxygen over time. The graph illustrates a decreasing trend with fluctuating oscillations.](image-url)
Oxygen Controller

Time (seconds)

Temperature (Celsius)

Relative Humidity (%)

0 100 200 300 400

40 50 60 70 80 90 100
Effective Operation

Definition of Efficiency:

\[ \eta = \frac{E_{cell}}{E_{eq}} \]

where

\[ E_{eq} = \frac{\Delta H_{f,H_2O}}{2F} \]
Available Power and Efficiency

Power Control

Efficiency (%)

Power Density (watts/cm$^2$)

0.17 0.18 0.19 0.2 0.21 0.22

55 60 65 70 75

PEMFC

$E_{cell}$

$P_e$

$P_{(sp)}$

$P_{(sp)}$

PI

PI

Diagram showing the relationship between power density and efficiency with power control.
Available Power and Efficiency

Power & Humidity Control

Power Control
Available Power and Efficiency

Power, Humidity & Oxygen Control

Power Control

Power & Humidity Control
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