Proton Exchange Membrane Fuel Cell System Identification and Control –

Part I: System Dynamics, Modeling, Identification and Adaptive Control

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Outline

- Background
- Objective
- Fuel Cell System Modeling
- System Identification
- System Model with Time-Varying Parameters
- Adaptive Controller Design
- Summary and Conclusions

Background

Modeling system dynamics

- Steady state property:
  - the performance prediction for the purpose of designing cell components, choosing operating points and describing the steady state property.
- Transient dynamics:
  - air compressor, manifold filling dynamics, gas flow in the anode and cathode and its electro-chemical reactions.

Complexity and difficulty: Modeling system dynamics precisely is impossible

- electrochemistry, fluid dynamics, thermodynamics and heat transfer, time-varying and spatial physical properties, etc.

Complexity and Difficulty of Fuel Cell Control

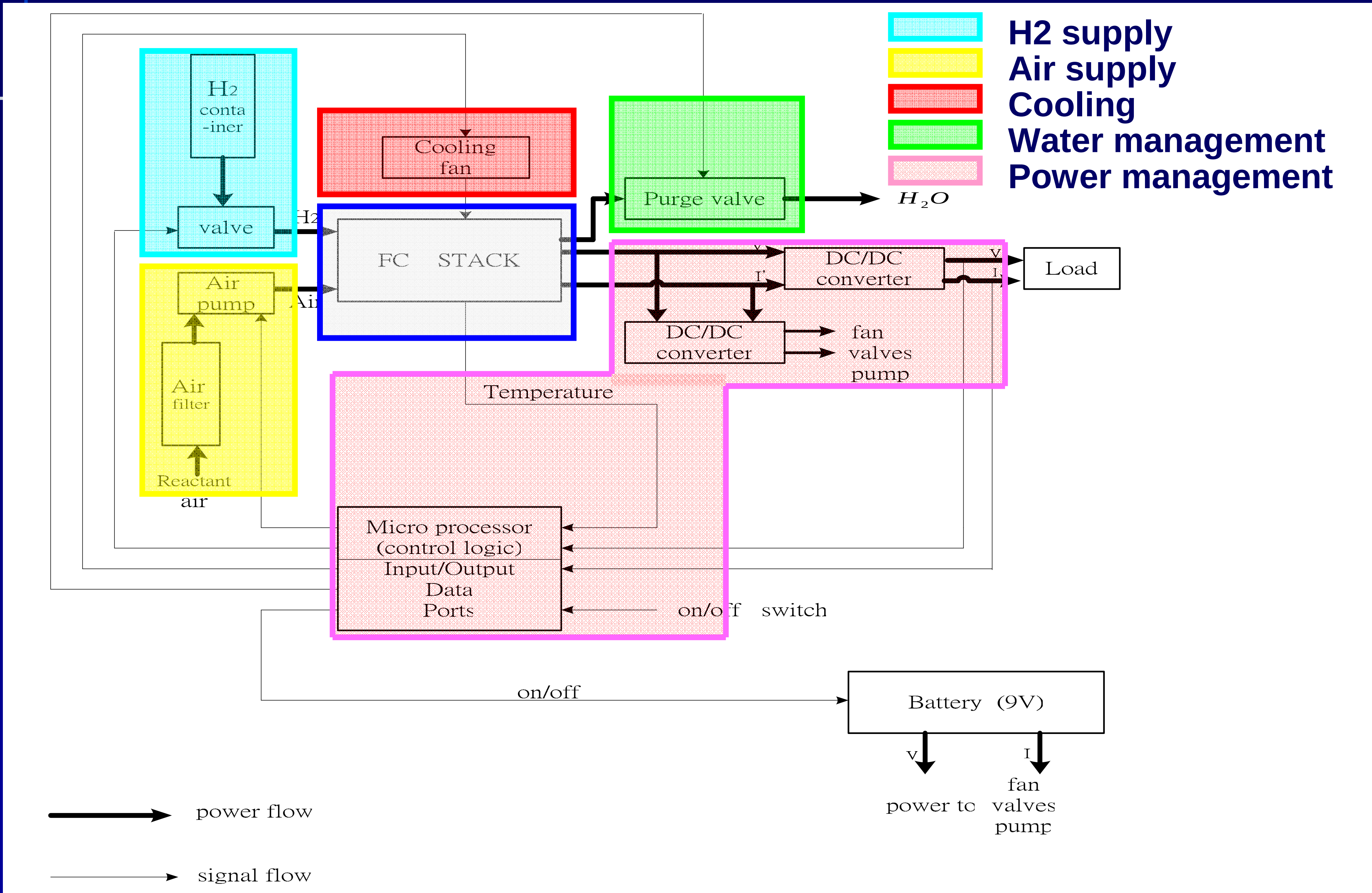
- Control of fuel cells
  - Control of operation process
    - Valve, switch, fan, gas and water purge, over-voltage, over-current, emergency shut-off, etc.
  - Control of output power toward the load
    - electronics design of inverter and converter
    - Stable power supply
- Control of fuel cell stack performance
  - Less mentioned, no feasible model for controller design
  - Critical issue: stable power supply as well as efficient usage of fuel

Objective

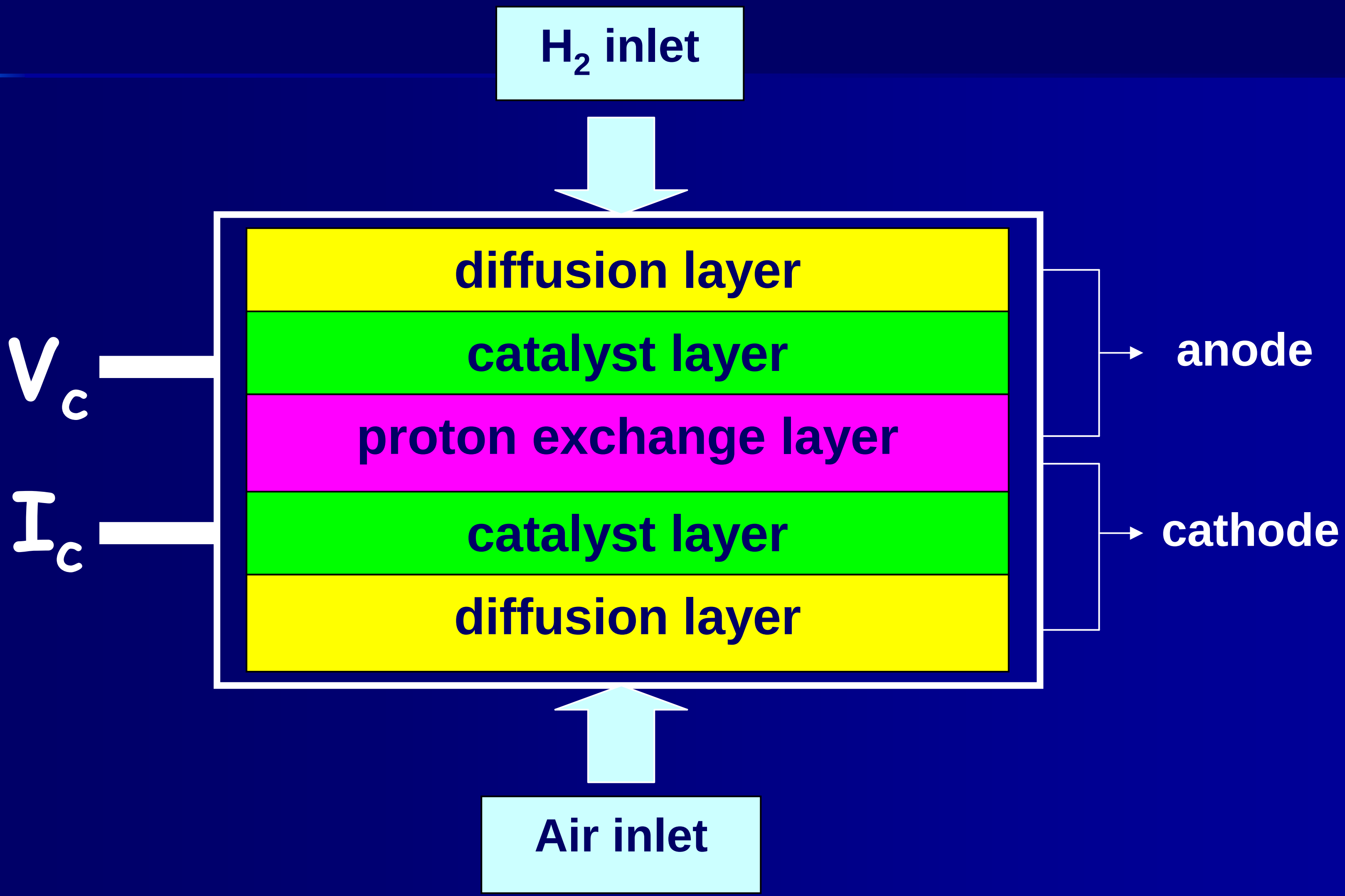
- To identify PEM fuel cell stack dynamics in a linearized, discrete-time, input and output model
- To control the system through on-line parameter estimation and adaptive control

To adjust air and hydrogen flow rate to stablize the output voltage under various load requirements.

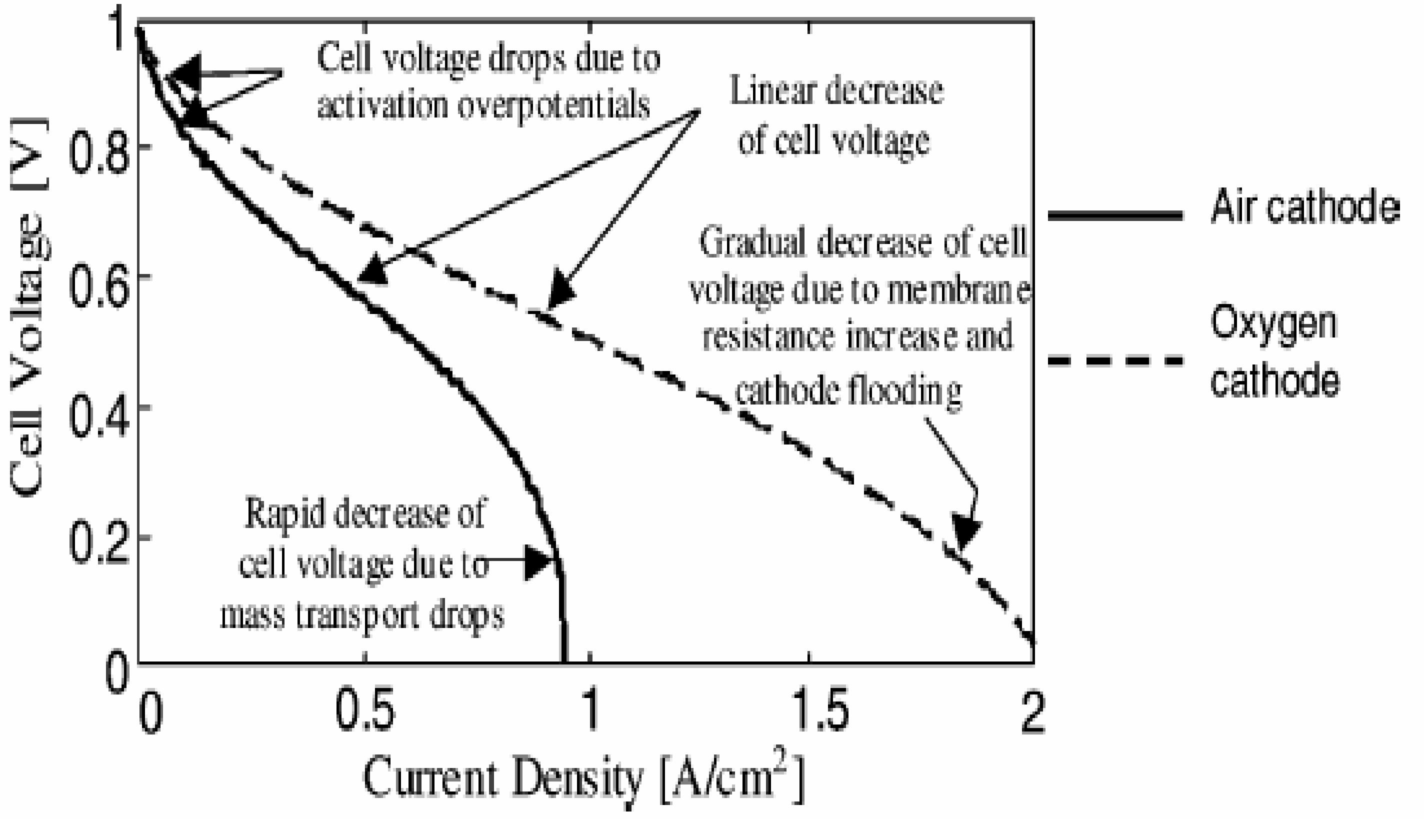
Fuel Cell System Fundamentals



Fuel cell stack model

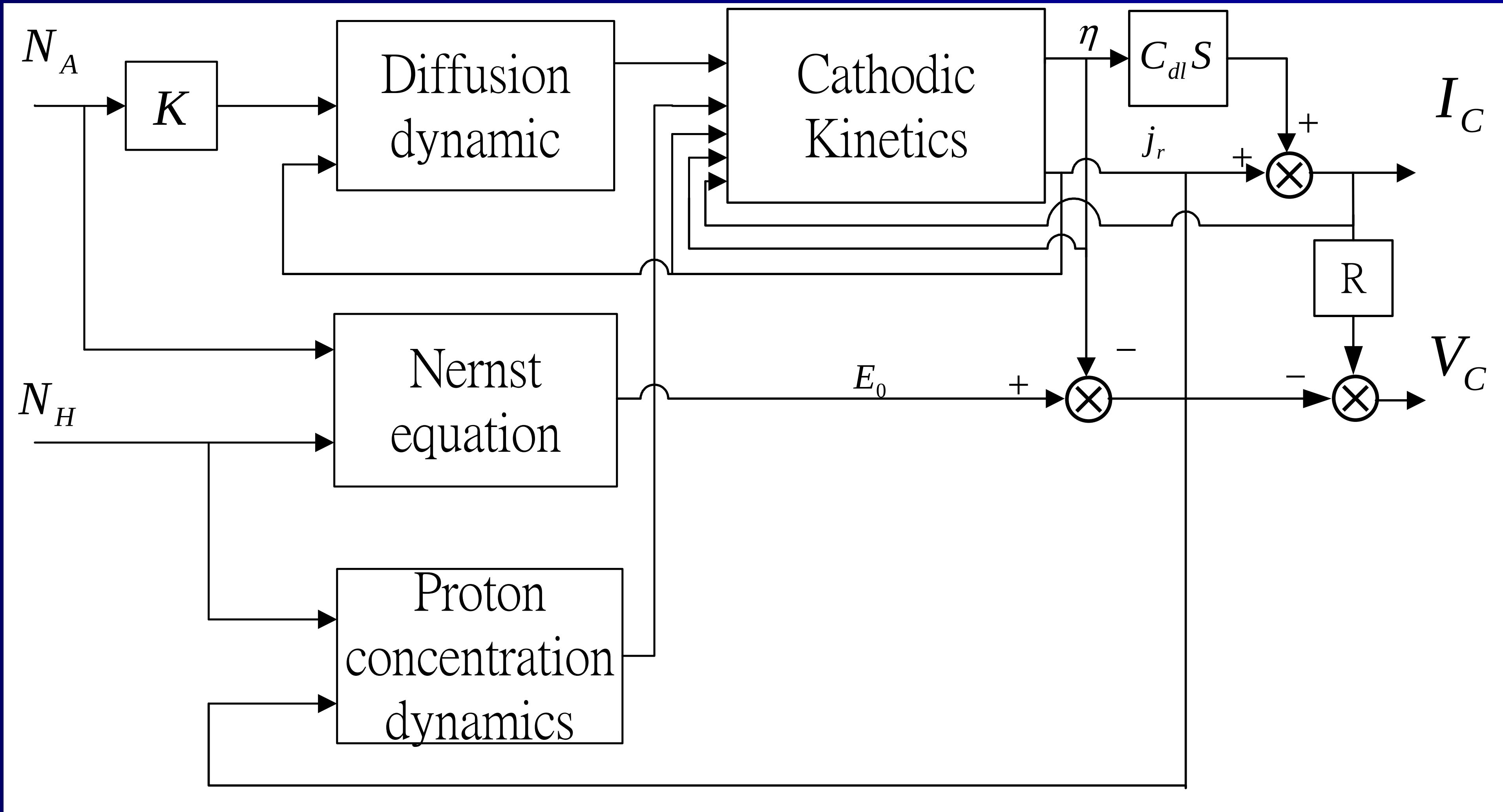


Typical VI curve (steady-state)



Typical cell voltage vs. current density plots for PEM fuel cells and a common interpretation for the voltage drop.

Background of PEMFC System Modeling



Cathode Diffusion Dynamics

- Continuity equation

$$\frac{\varepsilon_g}{RT}\frac{\partial p_i}{\partial t}+\frac{\partial N_i}{\partial y}=0$$

- Stefan Maxwell equation

$$\frac{\varepsilon_g}{\tau^2}\frac{\partial p_i}{\partial y}=\sum_{k=1}^{3}\frac{RT}{p_c D_{ik}}(p_i N_k - p_k N_i)$$

- Simplified as cathode diffusion equation

$$\frac{\partial p_1}{\partial t}=\omega\frac{\partial^2 p_1}{\partial \xi^2}-\psi\frac{j_r}{4F}\frac{\partial p_1}{\partial \xi}$$

where

$$\omega=\frac{1}{\tau^2 L_d^2\left(\left(p_{sat}/d_{12}\right)+\left(p_c-p_{sat}\right)/d_{13}\right)}\qquad \psi=\frac{RT}{\varepsilon_g L_d\left(p_c-p_{sat}\right)}$$

pde: variation of partial pressures in terms of space and time, flow rate,material and geometric property of diffusion layers

Cathode Kinetics

- Butler-Volmer equation

$$j_r = j_0 A_r \left\{ \frac{p_1}{p_{10}} \frac{[H^+]}{[H^+]_0} \exp\left(\frac{\eta}{b}\right) - 1 \right\}$$

- Overpotential on cathode

$$\eta = E_{0C} - \Delta\phi_{ce} = E_0 - V_{cell} - R_{ohm} j$$

- Current density charge on double-layer

$$j = j_r + C_{dl} \frac{\partial \eta}{\partial t}$$

pde: relationship between current density, over-potential, proton concentration, catalyst contact area, etc.

Proton concentration dynamics

$$u\left(-\frac{\partial c_{H^+}}{\partial t}\right)\cdot\frac{\partial c_{H^+}}{\partial t}+\frac{c_{H^+}}{\tau_{H^+}}=\frac{1+\alpha_{H^+}\cdot j^3}{\tau_{H^+}}$$

where $c_{H^+}=\left[H^+\right]/\left[H^+\right]_0$

τ_{H^+} is the time constant

Nonlinear pde: j^3, u(.) - Heaviside function

Nernst equation

$$E = E_{ref} + \frac{dE^0}{dT}(T - T_{ref}) + k\frac{RT}{2F}\ln(P_{H_2}P_{O_2}^{\frac{1}{2}})$$

Where E^0 is the open loop voltage, …

Internal resistance

$$R_{ohm} = R_{ref} + \alpha_T(T - T_{ref})$$

Air compressor

$$J_{cp}\frac{d\omega_{cp}}{dt} = \tau_{motor} - \tau_{cp}$$

$$N_A = F(\omega_{cp})$$

Other dynamics

Mass transportation, energy conservation of the reactant flows and pressures in the cathode and anode, water condensation, evaporation and generation, as well as quasi-steady-state temperature profile.

In summary

PEMFC dynamic model features:

- Complex physical phenomenon: principles of electrochemistry, fluid dynamics, thermodynamics and heat transfer, etc.
- Nonlinear dynamics: partial differential equations in terms of space and time, material coefficients and universal constants
- Approximation under various assumptions and constraints.
- Time-varying parameters
- Multi-input multi-output (MIMO) system
- Subject to external disturbances and unmodeled dynamics

Linearized MIMO system

V_{cp}

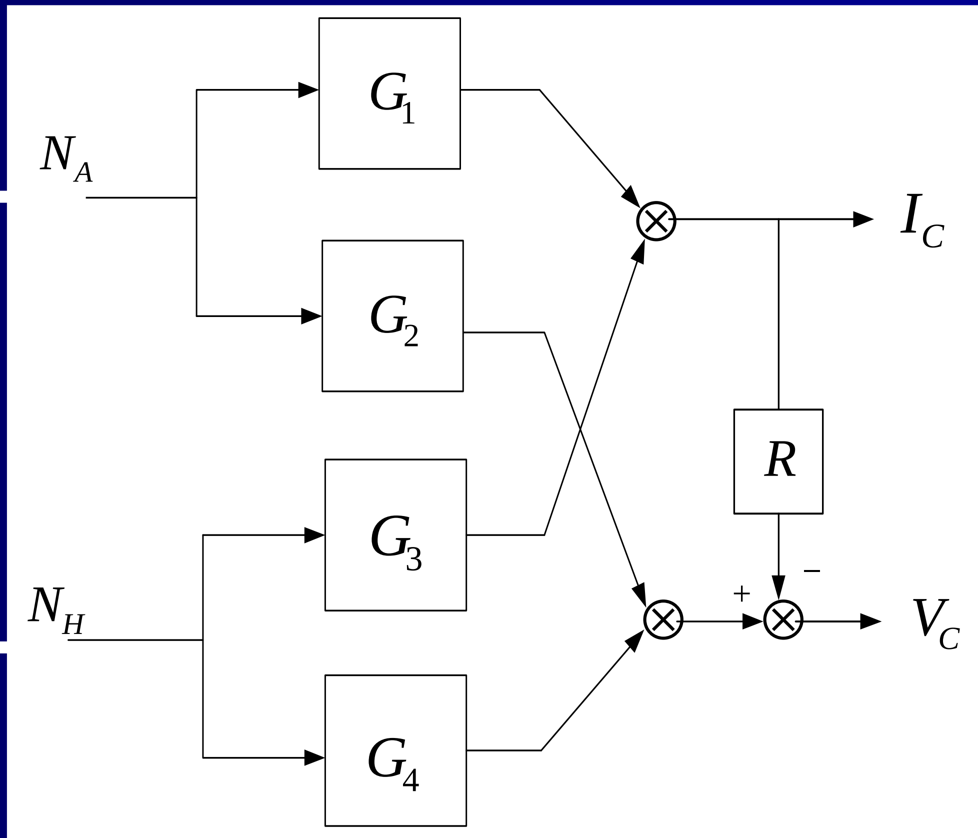
Air pump

Flow rate of air N_A

(partial pressure of oxygen)

(air pressure)

Flow rate of hydrogen N_H



Fuel cell output current I_c

Internal resistance R

Fuel cell output voltage Vc

$$I_C = G_1 N_A + G_3 N_H$$

$$V_C = G_2 N_A + G_4 N_H + R \cdot I_C$$

Linearized MIMO System

(without considering the auxiliary input part)

$$G_1(s) = \frac{I_C}{N_A}$$

$$G_2(s) = \frac{V_C}{N_A}$$

$$G_3(s) = \frac{I_C}{N_H}$$

$$G_4(s) = \frac{V_C}{N_H}$$

MIMO

Linear

Time-varying

Coupled

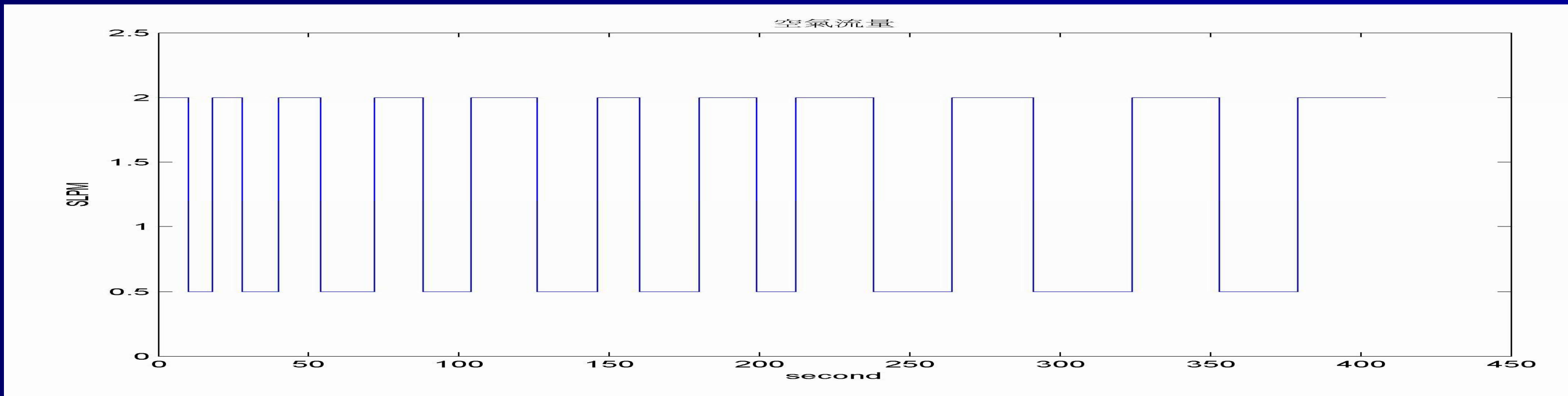
Transfer functions

At some operating point

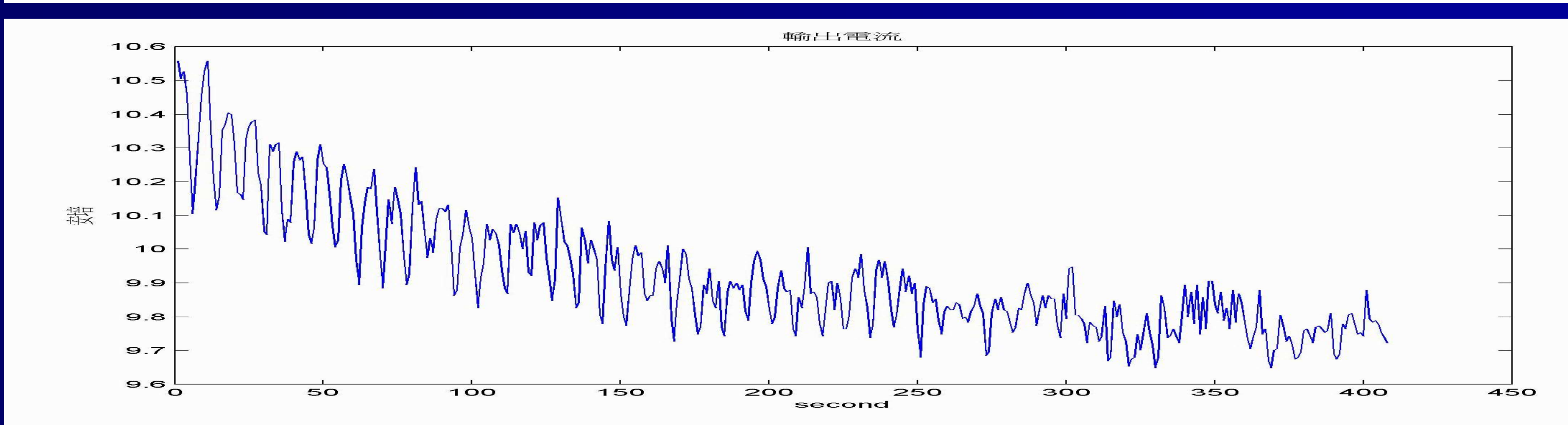
System identification

- Persistently exciting the system with pseudo-random binary sequence (PRBS)

Air flow rate (PRBS)



Output current



ARMAX Model
(discrete time model of G_1, G_2, G_3, and G_4)

$$A(q,k)y(k) = B(q,k)u(k) + C(q,k)W(k)$$

Auto-regression part: A(q,y) y(k)

$$A(q,k) = a_0(k) + a_1(k)q^{-1} + a_2(k)q^{-2} + \cdots + a_r(k)q^{-r}$$

Moving average part: B(q,k) u(k)

$$B(q,k) = b_1(k)q^{-1} + b_2(k)q^{-2} + \cdots + b_r(k)q^{-r}$$

Auxiliary input part: C(q,k) e(k) –unmodelled dynamics

$$C(q,k) = C_0(k) + C_1(k)q^{-1} + C_2(k)q^{-2} + \cdots + C_r(k)q^{-r}$$

Recursive Least Squares Algorithm

- Parameterization

$$\hat{y}(k) = \phi^T(k-1)\hat{\theta}(k-1)$$

$$\phi^T(k-1) = [-y(k-1) \ldots -y(k-m)\; u(k-1) \ldots u(k-n)\; w(k-1) \ldots w(k-r)]$$

$$\hat{\theta}^T = [\hat{a}_1 \ldots \hat{a}_r\; \hat{b}_1 \ldots \hat{b}_r\; \hat{c}_1 \ldots \hat{c}_r]$$

$$w(k) = y(k) - \hat{y}(k)$$

- Parameter estimation

$$\hat{\theta}(k) = \hat{\theta}(k-1) + K(k)[y(k) - \phi^T(k-1)\hat{\theta}(k-1)]$$

$$K(k) = P(k-1)\phi(k-1)\left[\lambda + \phi^T(k-1)P(k-1)\phi(k-1)\right]^{-1}$$

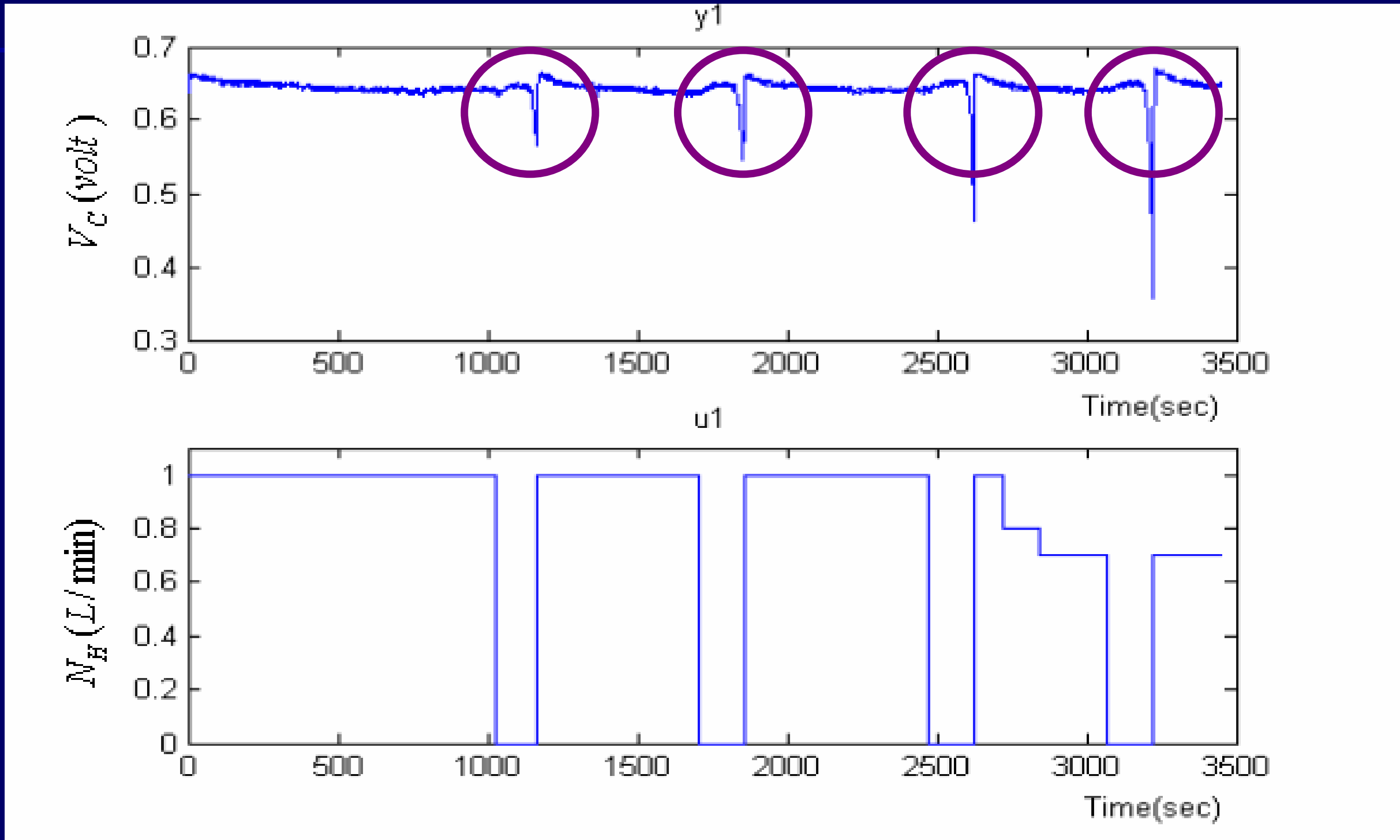
$$P(k) = \left[I - K(k)\phi^T(k-1)\right]P(k-1)/\lambda$$

where λ is the forgetting factor

Experiments:
Single Cell Specifications

Rated power	6W
Rated voltage	0.6V
Rated current	10 A
Active area per cell	50 cm^2 (5 cm x 10 cm)
Anode reactant	Pure compressed hydrogen
Cathode reactant	Humidified air (50C, 1 atm)
Operating temperature	295K (22C)
Ambient temperature	293K (20C)
Current density	0.2A/cm^2
Cell voltage	0.63V

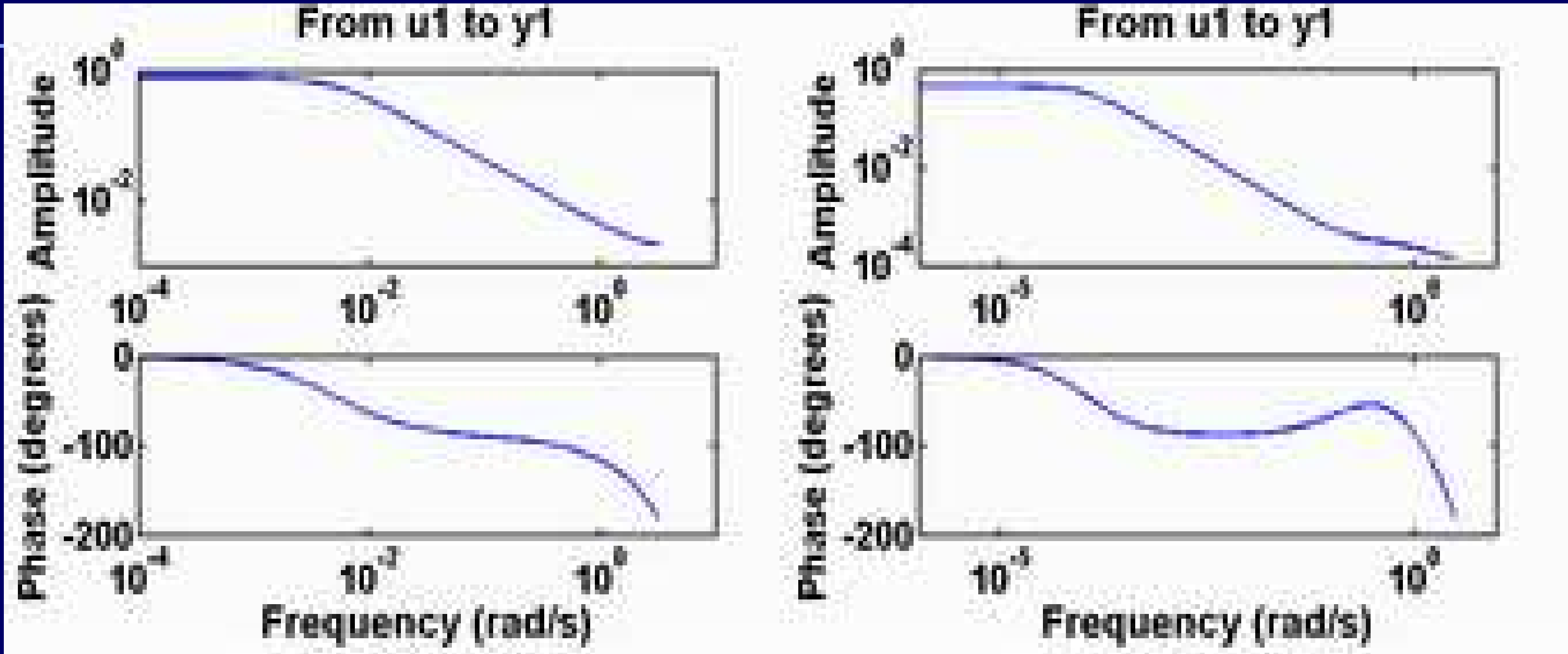
Determination of System Order



Hydrogen flow rate vs. fuel cell voltage

2nd order is assumed

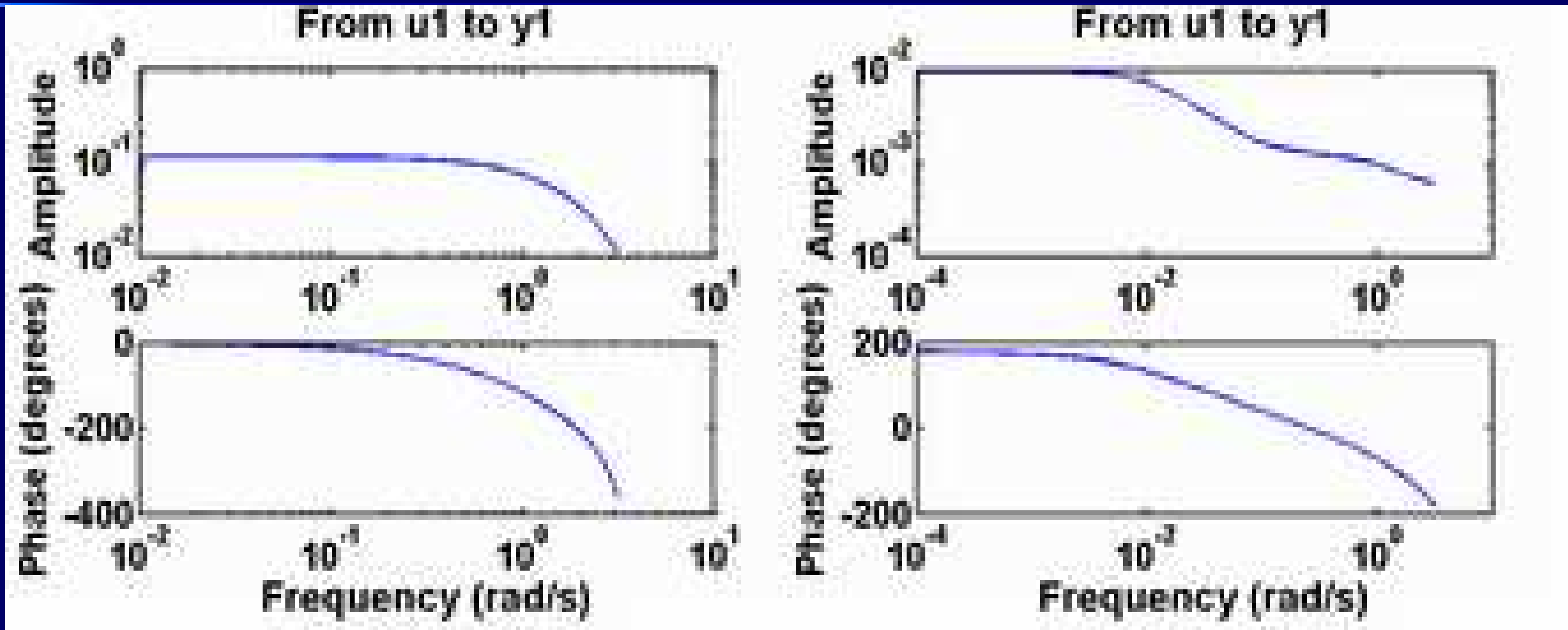
Identified Frequency Response



G_1 (I_c / N_A)
Bandwidth: 0.005 rad/sec,
Operation conditions:
N_{H2}=0.5 SLPM, V_c=0.6V

G_2 (V_c / N_A)
Bandwidth: 6.3e-4 rad/sec,
Operation conditions:
N_{H2}=0.5 SLPM, I_c=10A

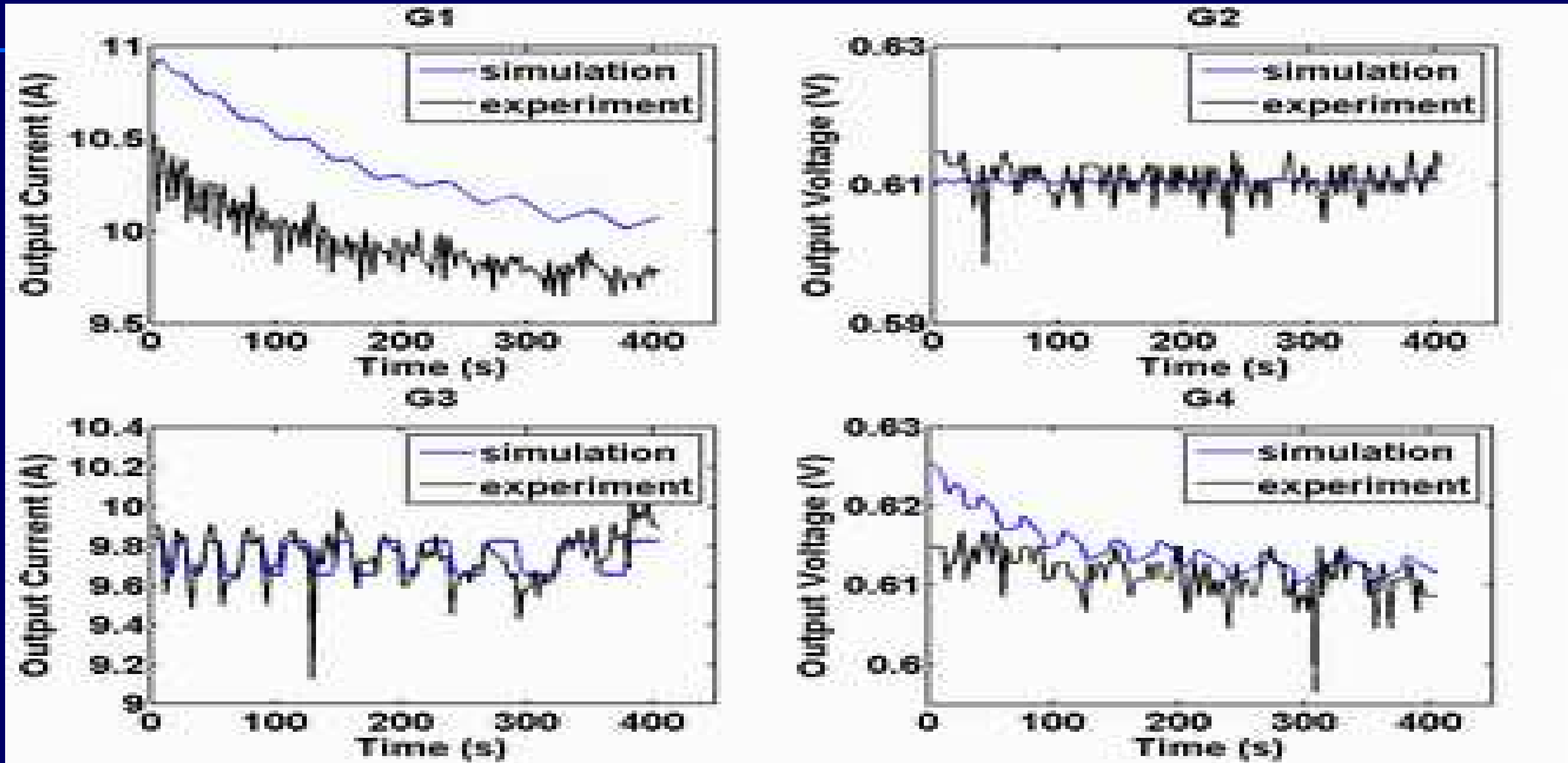
Identified Frequency Response



G_3 (I_c / N_H)
Bandwidth: 0.814 rad/sec,
Operation conditions:
N_{air}=3 SLPM, V_c=0.6V

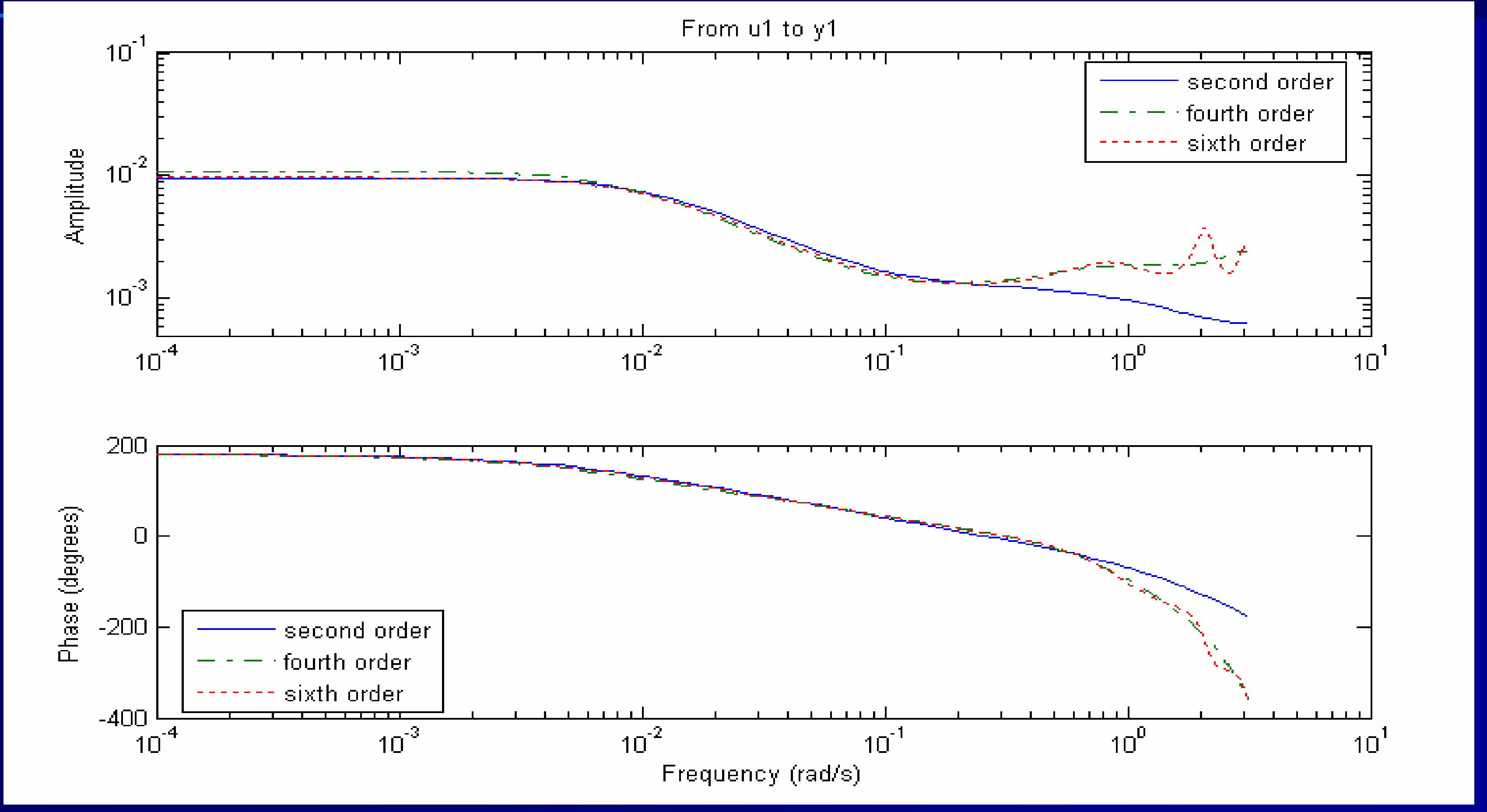
G_4 (V_c / N_H)
Bandwidth: 0.011 rad/sec,
Operation conditions:
N_{air}=3 SLPM, I_c=10A

Response Curve Fitting with Fixed Parameters



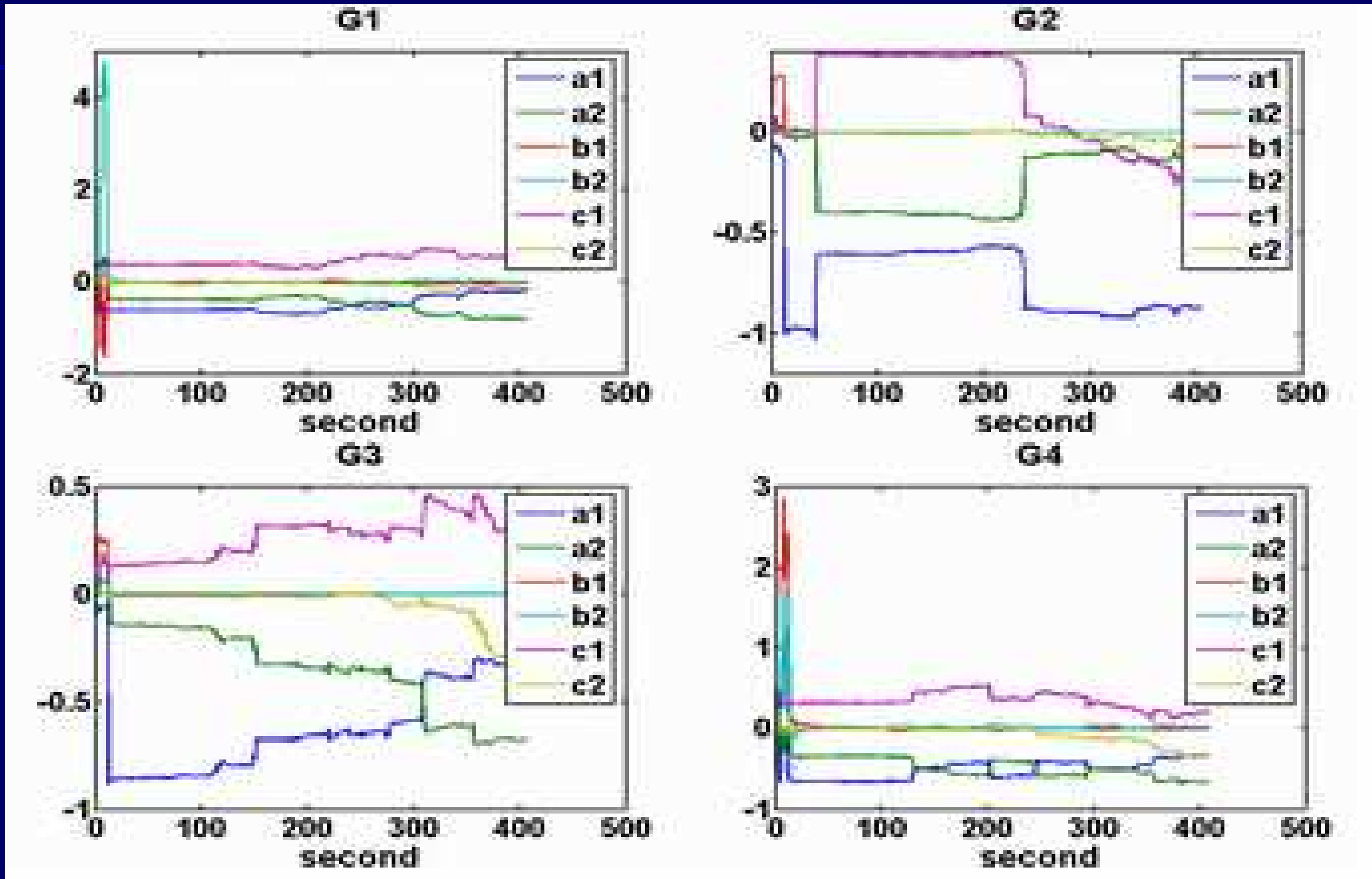
Simulated response with transfer function of fixed parameters does not fit well with real or experimental response.

System Identification with Higher Orders (G_4)



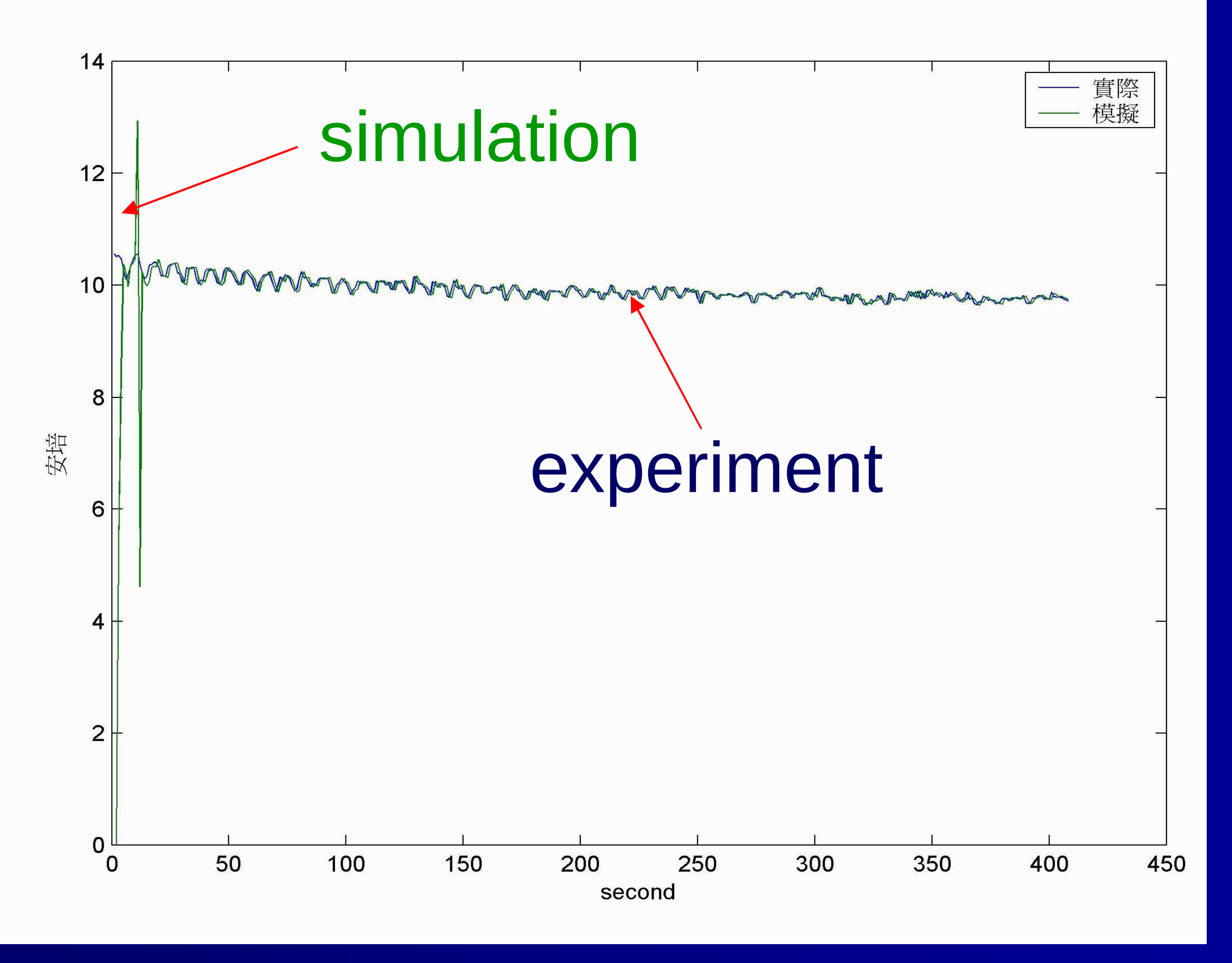
2nd order approximation is reliable

Time varying characteristic

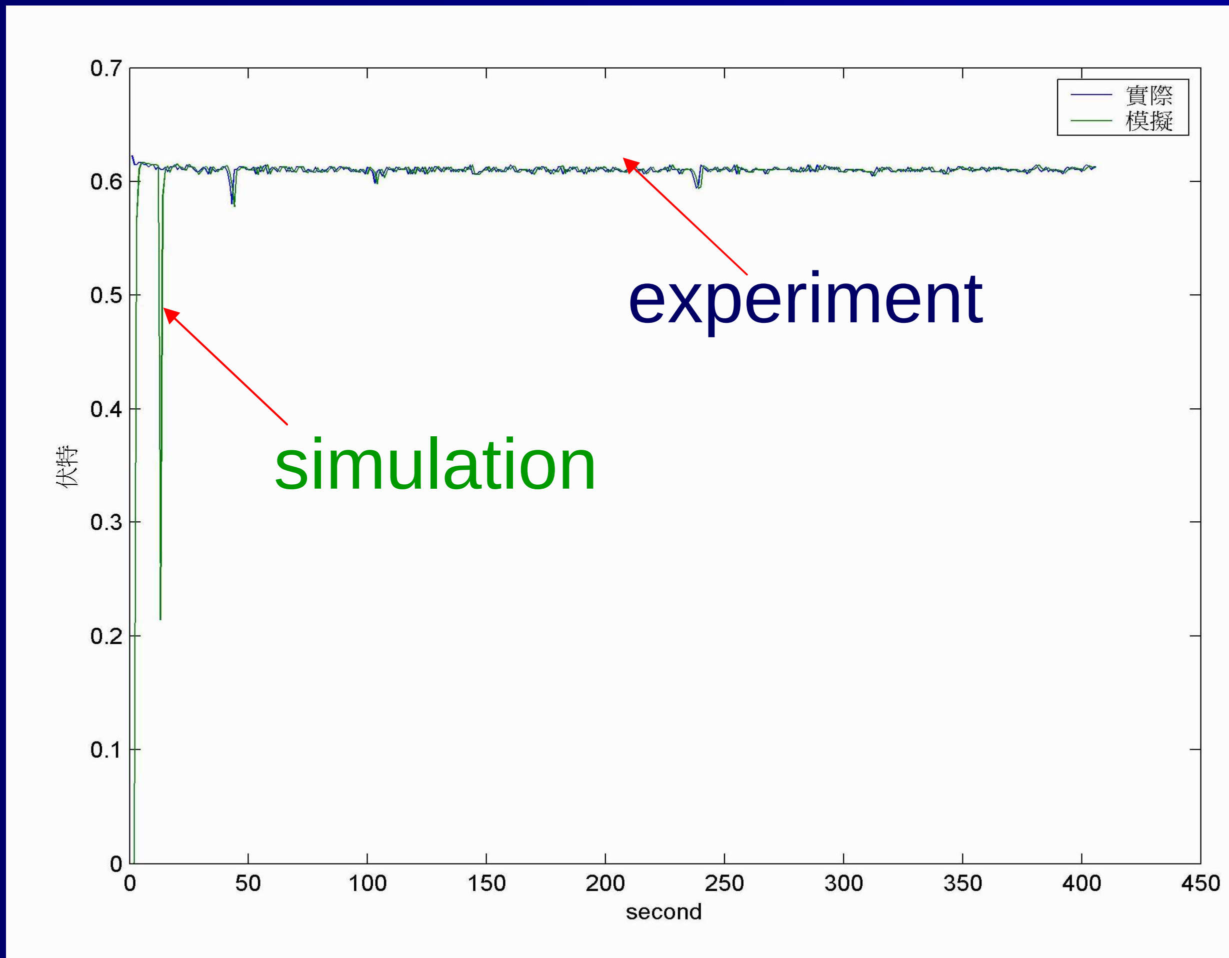


A set of constant parameters may not accurately reflect system inherently nonlinear and time-varying properties.

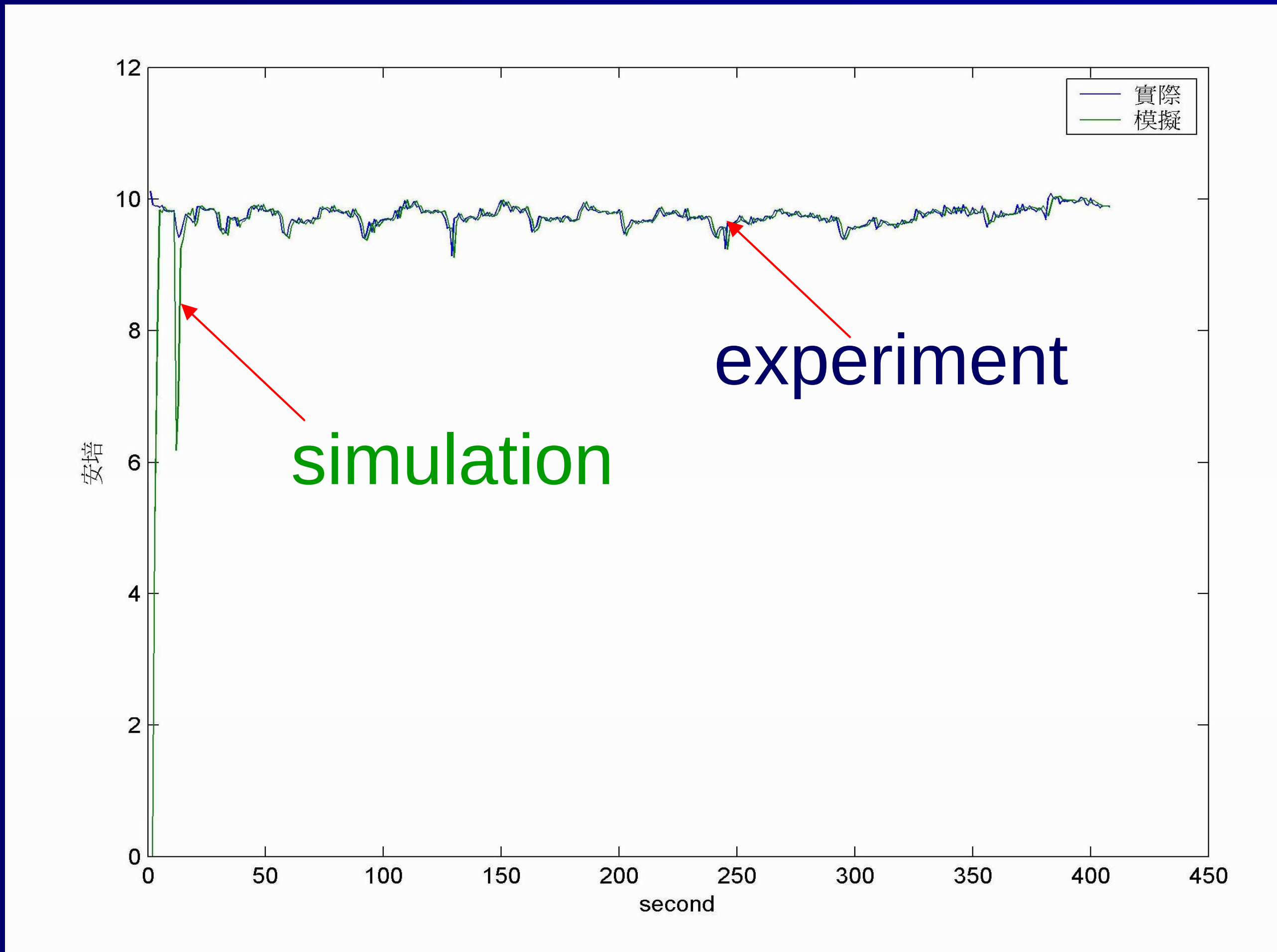
Response Curve Fitting with Time-Varying Parameters (G_1)



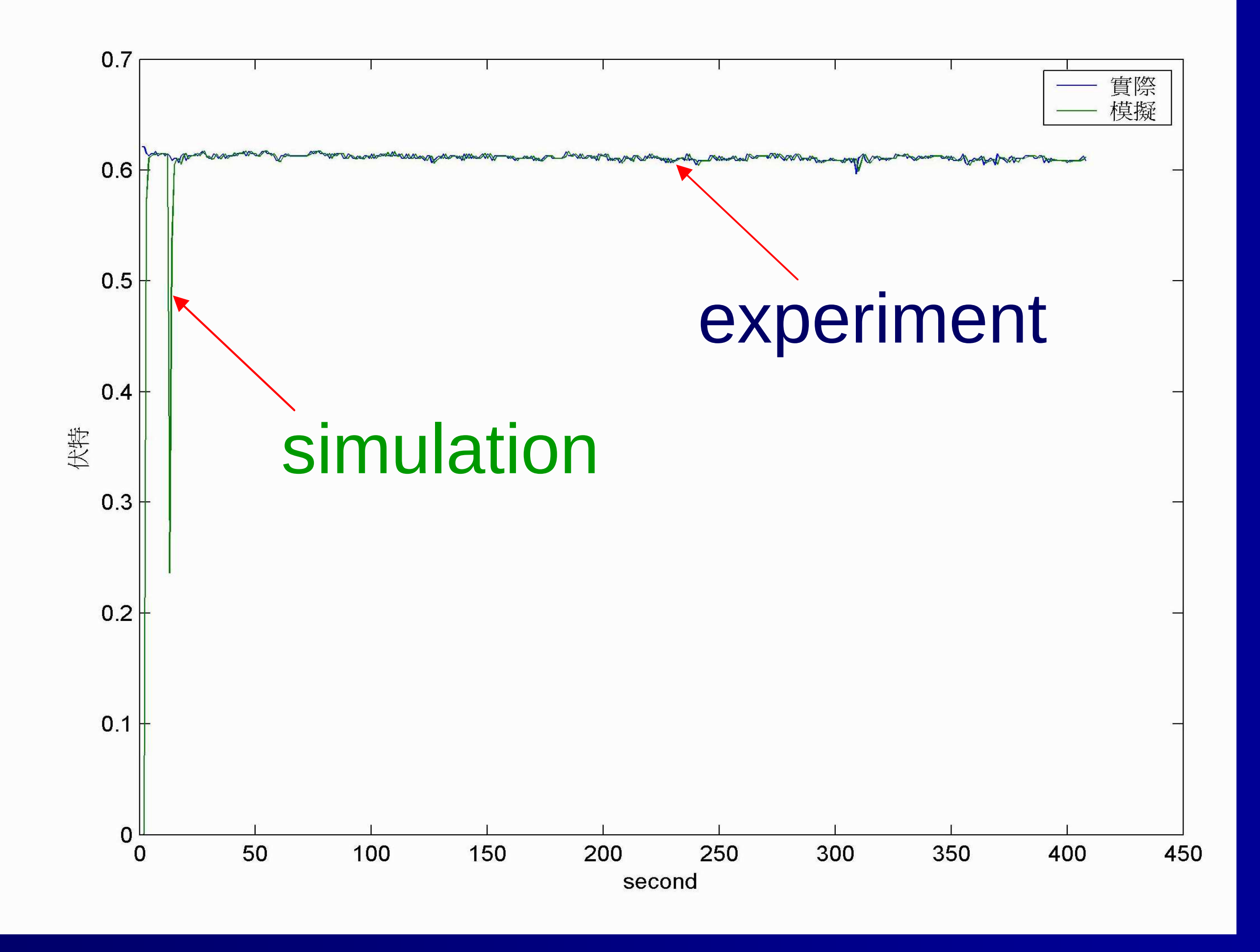
Response Curve Fitting with Time-Varying Parameters (G_2)



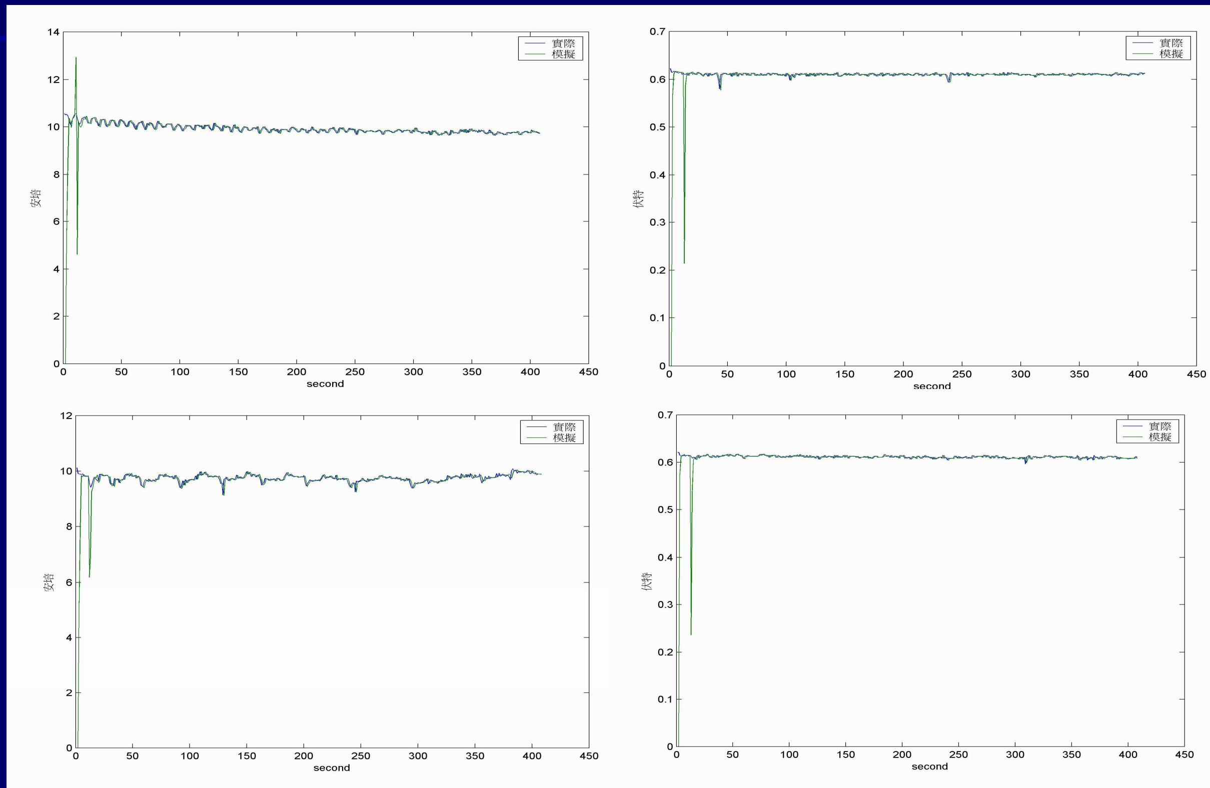
Response Curve Fitting with Time-Varying Parameters (G_3)



Response Curve Fitting with Time-Varying Parameters (G_4)

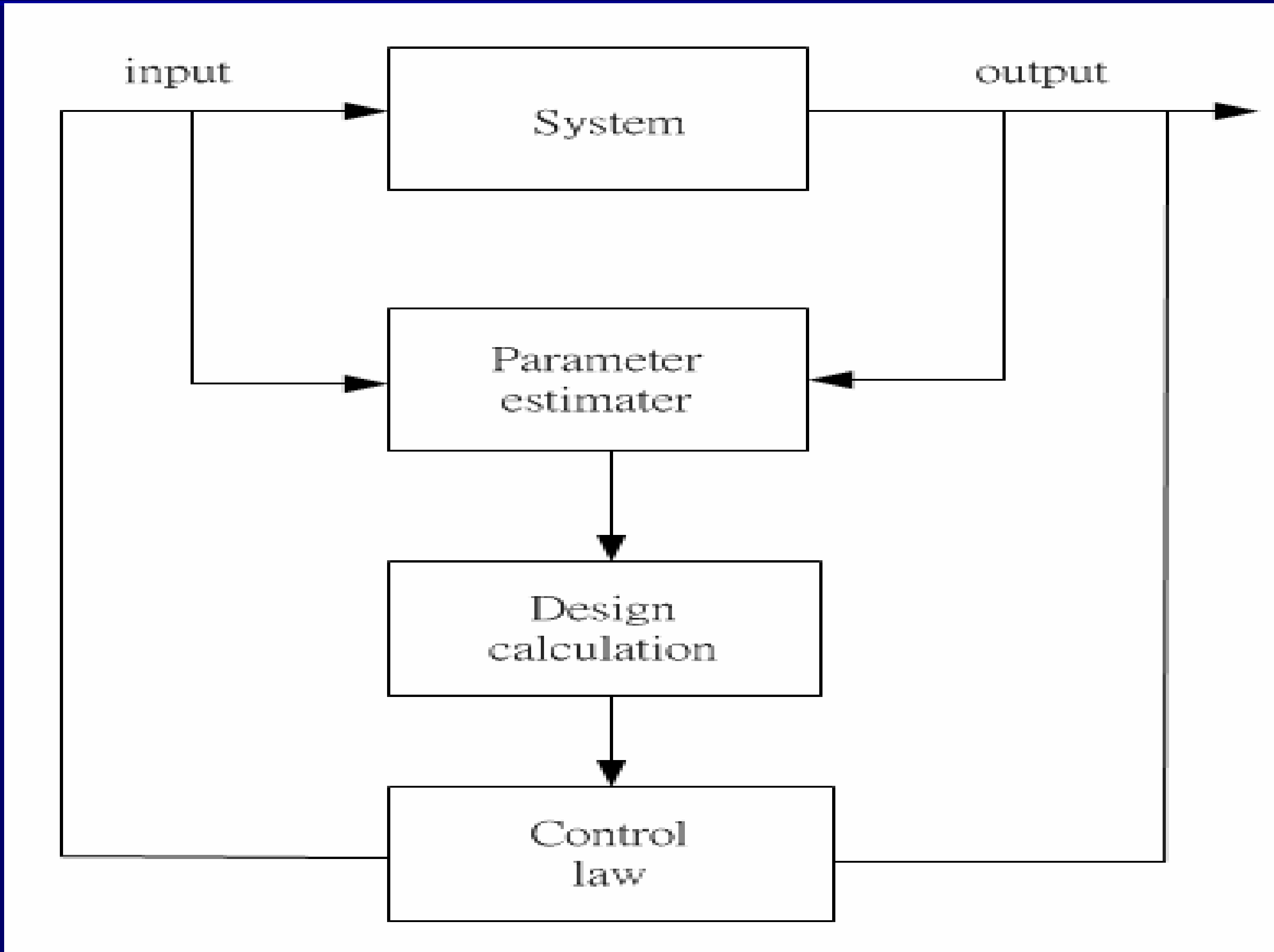


Response Curve Fitting with Time-Varying Parameters



This evidence of excellent response curve fitting with time-varying parameters provides a strong basis on the application of adaptive control to improve fuel cell system performance.

Adaptive control strategy



Adaptive Controller Design

- Fuel cell 2nd order model

$$G(z) = \frac{b_0 z + b_1}{z^2 + a_1 z + a_2}$$

- Controller model

$$G_c(z) = \frac{B_0 + B_1 z}{A_0 + A_1 z}$$

- Closed-loop transfer function

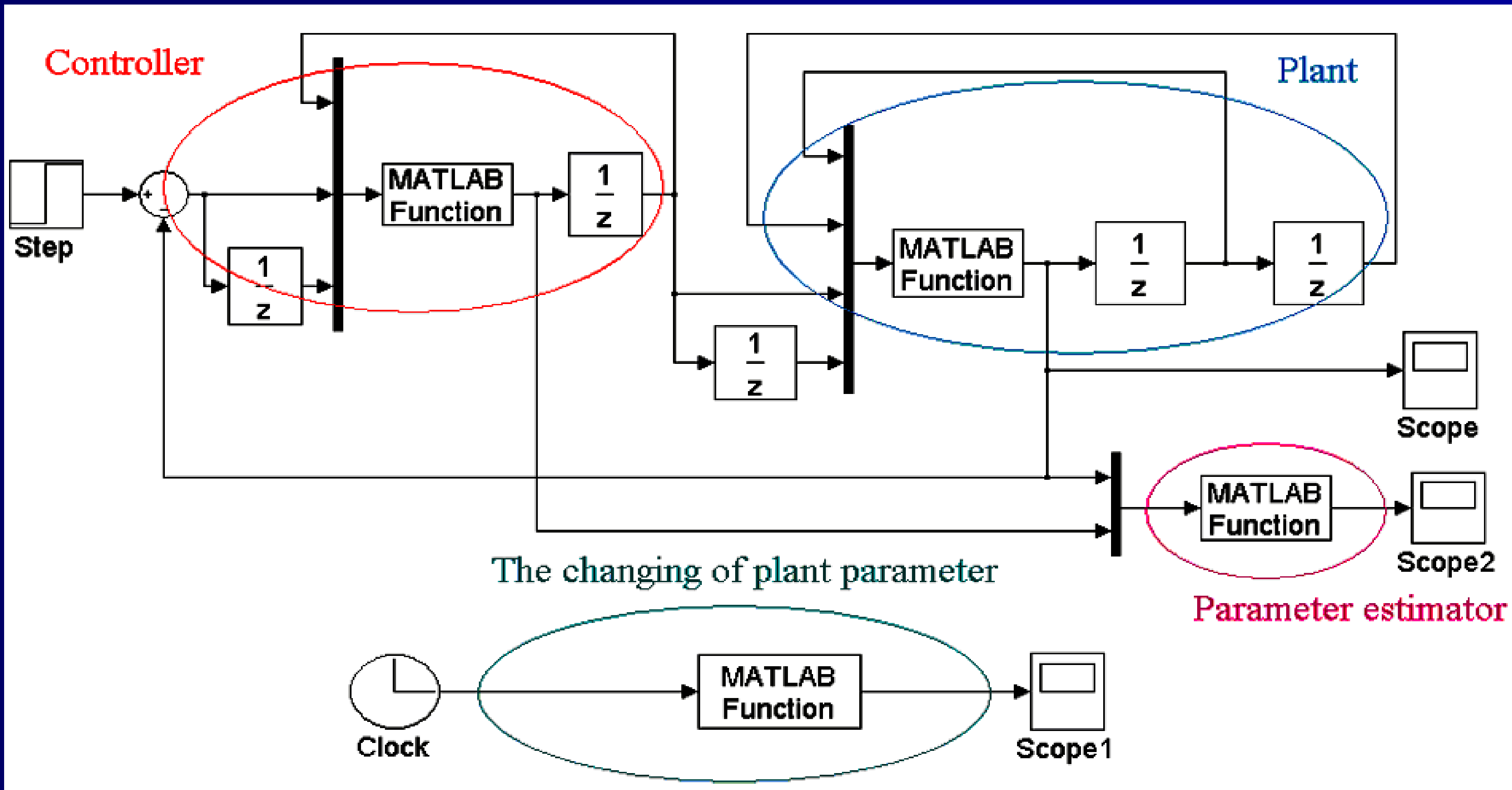
$$T(z) = \frac{G(z)G_c(z)}{1 + G(z)G_c(z)}$$

- Desired closed loop poles

F(z) = (A0+A1z)(z2+a1z+a2)+(B0+B1z)(b0z+b1)
= (z+a)(z+b+jc)(z+b-jc),

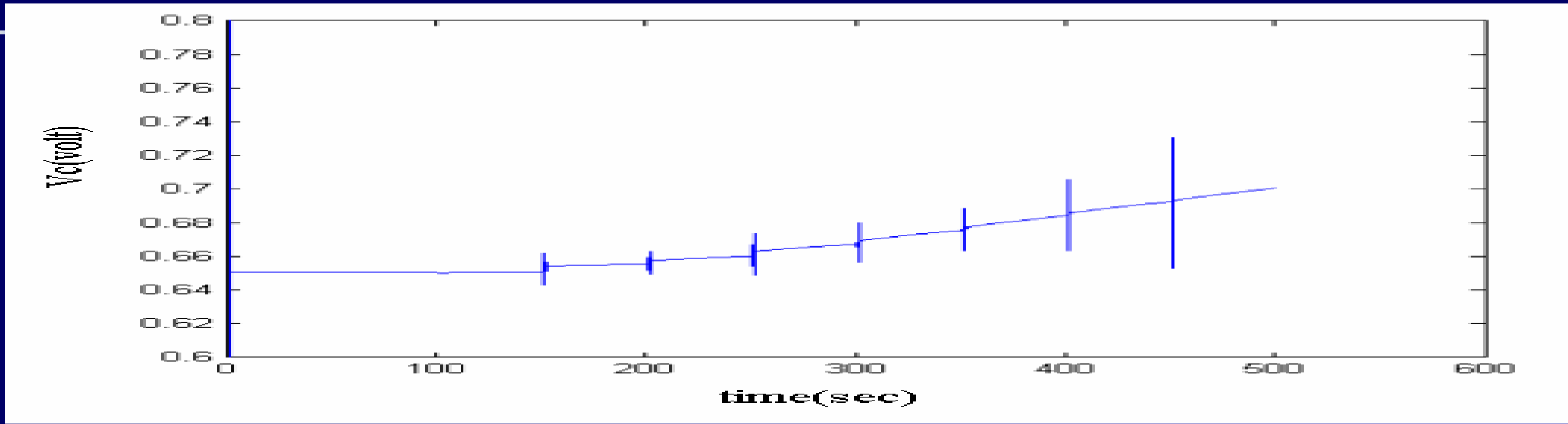
where *a*, *-b+jc*, *-b-jc* are desired closed-loop poles.

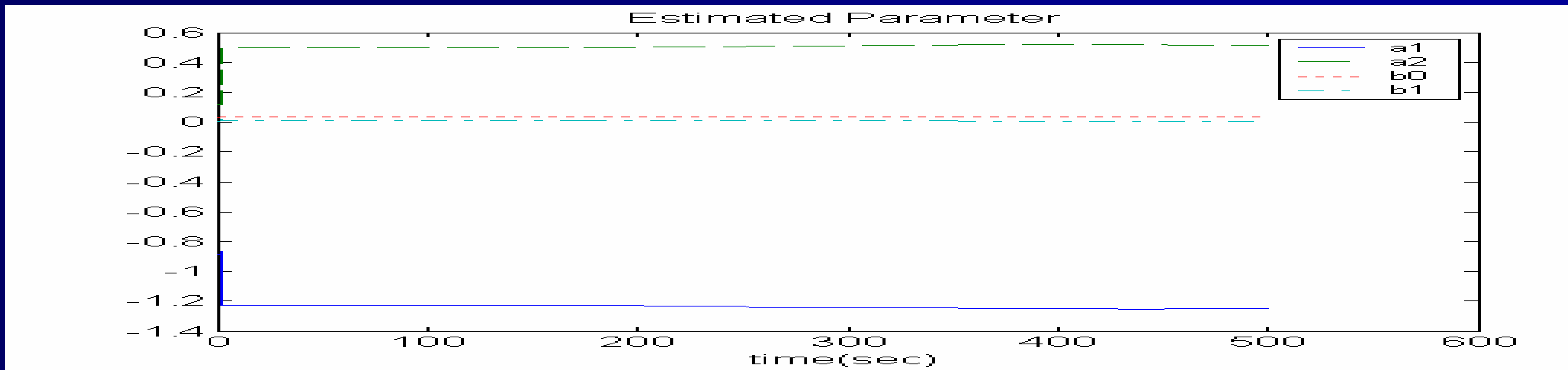
Adaptive Control Simulation Configuration (Simulink)



Simulation

(G_2 between cell voltage V_C and air flow rate N_A)





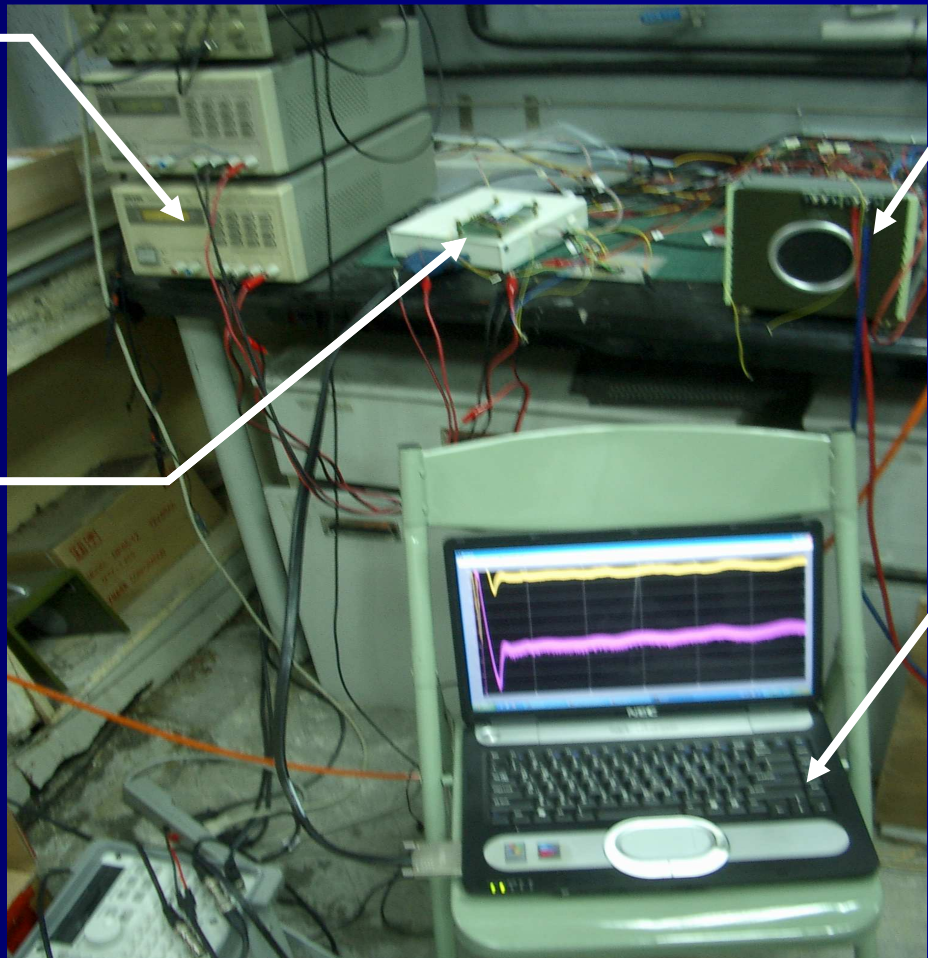
The plant varies at 150, 200, 250, 300, 350, 400, and 450 second.

Experiments

(very exciting result)

Load meter

DAQ card

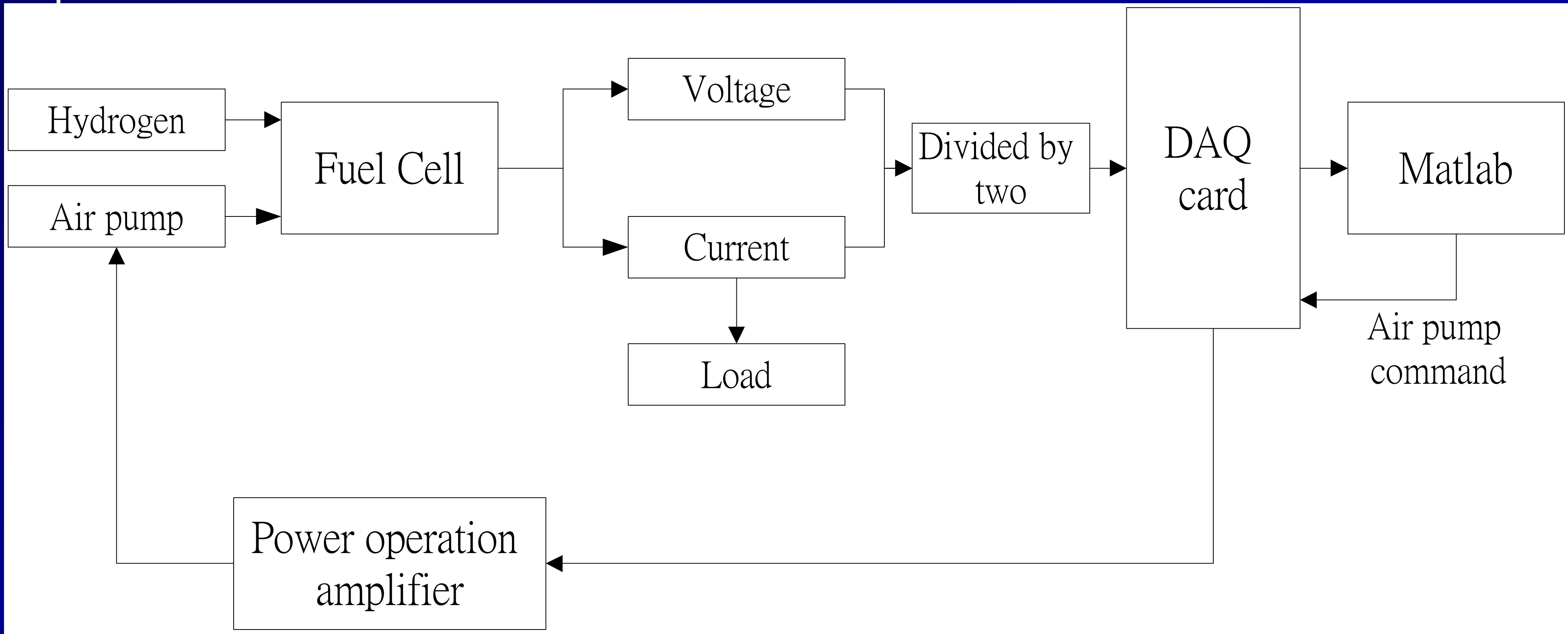


100W fuel cell stack

Parameter identification and adaptive control

Experiments

(Block diagram of experiment)



Experiments

(specifications)

- Fuel cell stack: 100W, 12V
- Fuel cell model:

  1st order ARMA model instead of ARMAX
- Adaptive controller: 1st order
- Electronic load-meter:

  output current is adjustable

- Control objective:

  To control the air flowrate to regulate the output cell voltage to a desired level by fixing the hydrogen flowrate while the load current varies

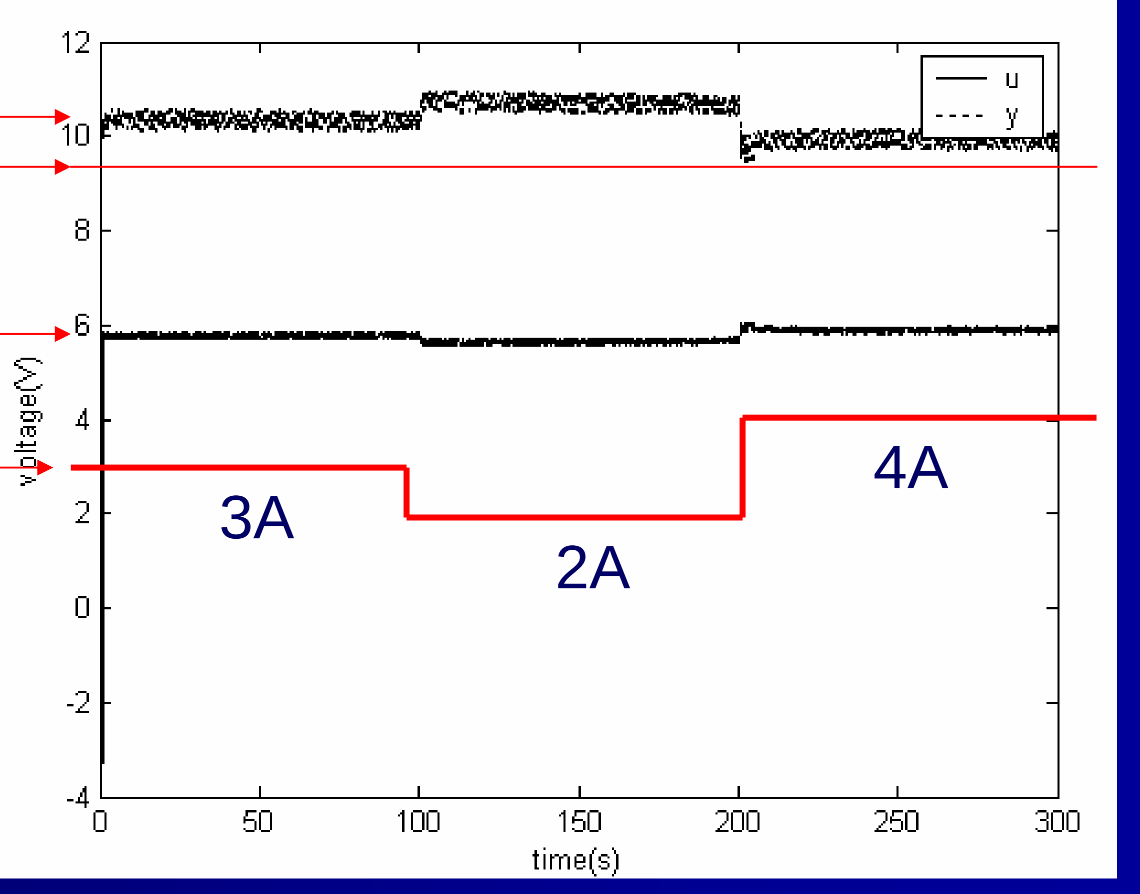
Controller with Time-Invariant Parameters

Cell voltage

Reference 9V

Air pump voltage

Load current

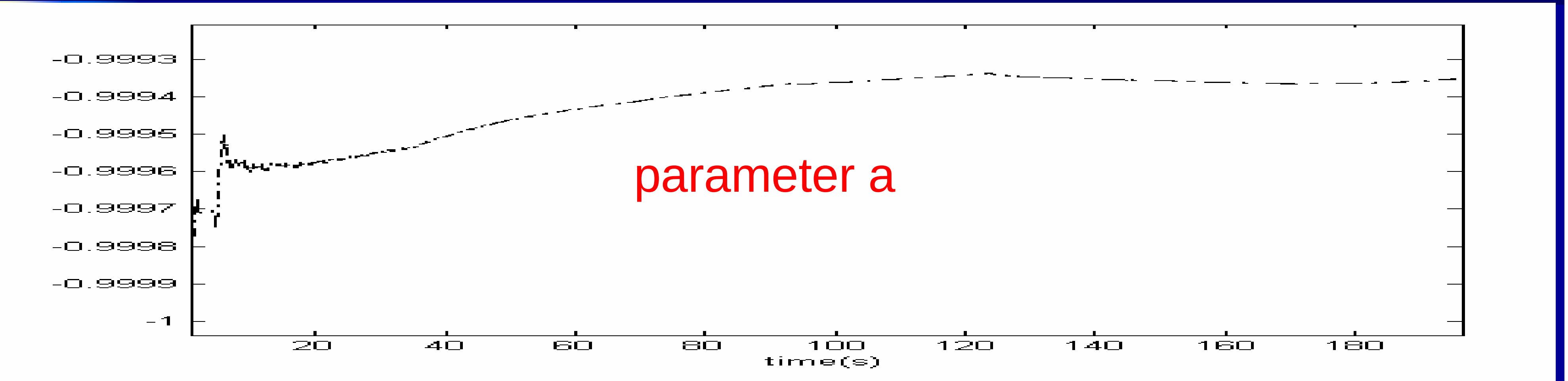


Controller

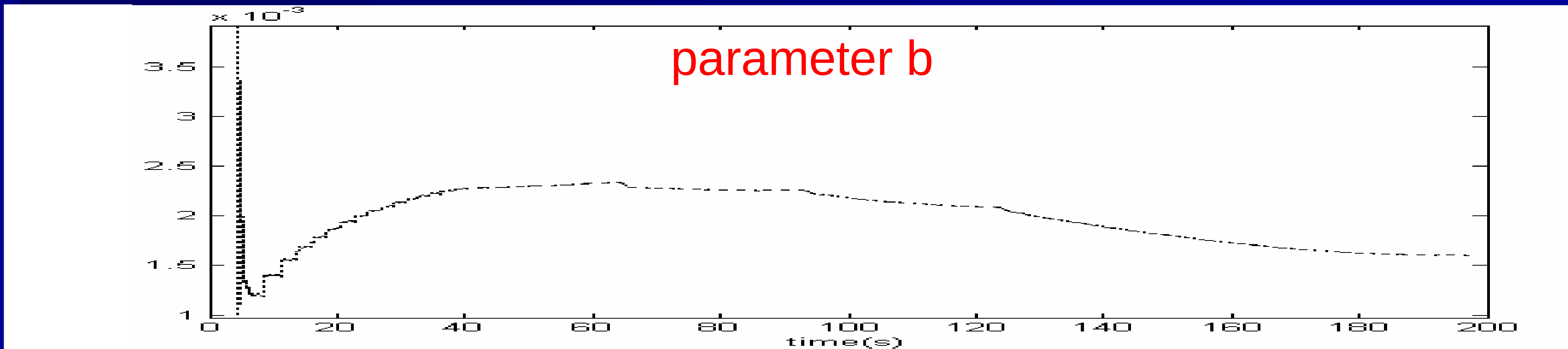
$$C_{(z)} = \frac{-0.3234\,z + 0.2878}{z - 0.8862}$$

Adaptive Control

Parameter Variation

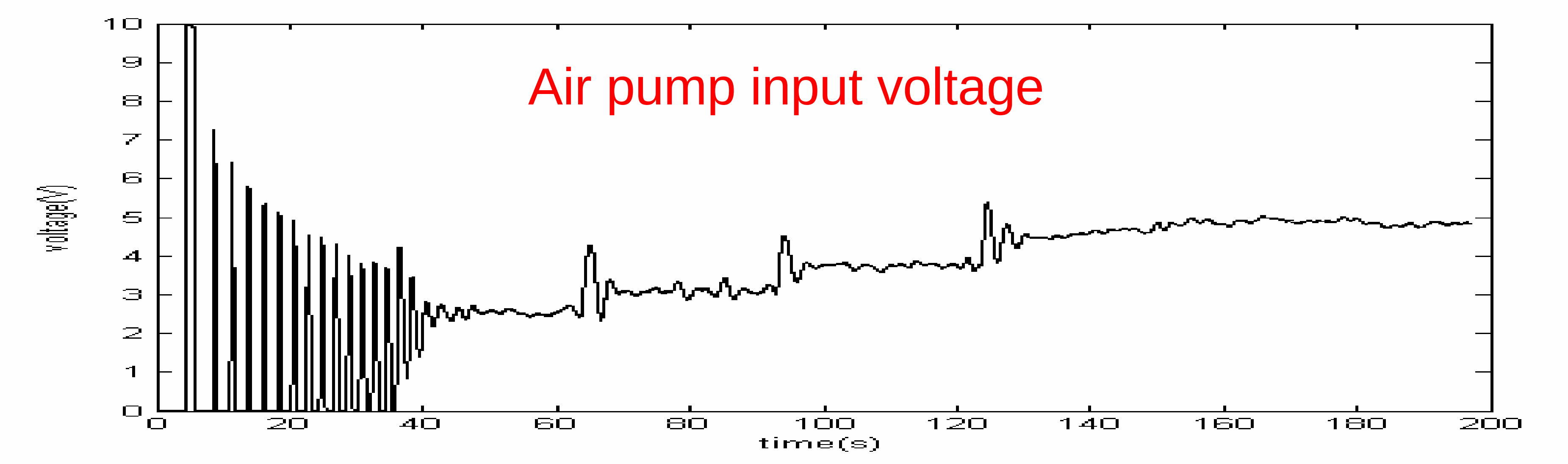


Load setting |----1A----|--2A--|--3A---|--4A---|---5A-----------------|

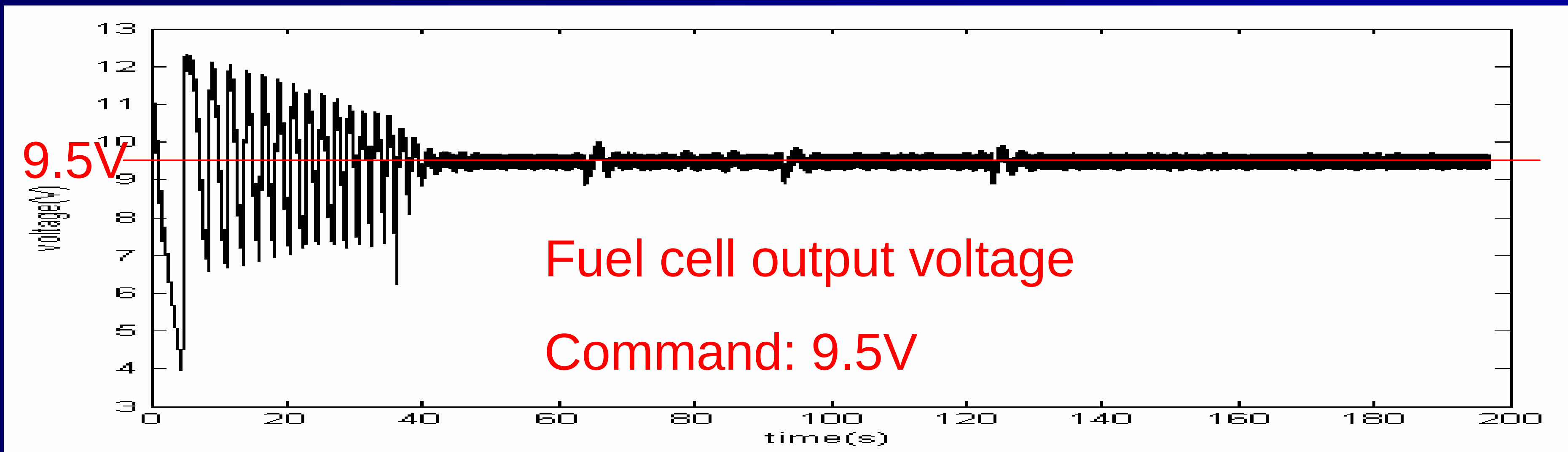


Adaptive Control

Performance of fuel cell



load setting|----1A----|--2A--|--3A---|--4A---|---5A----------------|



Summary and Conclusions

- System identification with a linear time-varying ARMA model is successfully performed
- First order adaptive control is verified sufficient to regulate system output voltage to a desired level

- Future task:
  - MIMO adaptive control to adjust air flowrate and hydrogen flowrate to reach the desired voltage and load current
  - Higher order model for system identification and adaptive controller design
  - Control of cell temperature and gas humidity
  - Application to the higher power fuel cell
  - Implementation on electric vehicles

Thank you for your attention!

2nd Order System Approximation

- Linear dynamics around a certain operating point – for a short time span
- Sufficient information on transient time response – overshoot, rise time, etc.
- Frequency domain information – bandwidth, output/input magnitude ad phase
- Basis of controller design