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MULTI-TIME SCALE DYNAMICS DECOMPOSITION AND ANALYSIS OF FUEL CELL POWER SYSTEM

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ABSTRACT

The dynamic responses of Solid oxide fuel cell (SOFC) power system across multiple time scales from micro seconds to minutes due to the phenomena of different nature that governing. Mismatching the time scale differences may lead to fuel starving and thermal shock during the fast load following. In this paper, the singular perturbation (SP) theory was introduced for modeling the mutli-time scale system dynamics. The dynamic model of SOFC power system in the coordinates in which slow and fast variables were explicitly defined and exactly separated. The resulting multi-single time scale models facilitate a better understanding of system dynamics, key parameters and their interactions, such as temperature, mass flow rate, current and voltage. Effective SOFC power system controllers can be designed based on these results.

Keywords: advanced energy technologies, energy systems for power generation, SOFC， Multi-time scale, singular perturbation

1. INTRODUCTION

SOFC is an electrochemical device that generate electrical energy directly from chemical reactions, the efficiency can be as high as 40–55%. The SOFC power system can be easily scaled up by stacking several cells or stacks in various configurations, does not have major moving parts, runs silently and environmentally friendly. If runs on hydrogen, water is the only by-product. For end users, the actual power delivery is the only relevant metrics of system performance, the mass balances and thermal dynamics will be hidden from the users, but they can become critical to system performance and lifetime under certain circumstances.

Large amount of research has been conducted on the modeling of SOFC from various viewpoints, such as fuel cell design, performance evaluation and controller design. [1][2][3] A simple SOFC power system model, as shown in Fig 1 can be built based on the first principle, time delays in reformer, blower and stacks caused by mass flow and diffusion are considered. The model can be used to simulate both steady-state or dynamic behaviors. The work presented in [4][5] investigated transient behavior of a planer SOFC due to load change using a multi-dimension time-dependent model and it is more useful for simulating fuel cell behavior in a time scale of minutes, and it might become less accurate in the scale of seconds and lower.

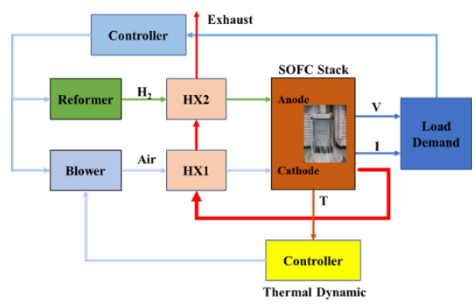

Fig 1 Structure of SOFC Power System Model

Since mismatching the time scale differences between slow and fast dynamics may lead to fuel starving and thermal shock, especially during the fast load following. To date, very a few attentions have been made to investigate the dynamic response of SOFC from multi-time scale perspective. In this paper, SOFC power systems with slow and fast variables will be decomposed and decoupled based on singularly perturbation theory [6], multi-time scale dynamic analysis will be conducted on these single time scale subsystems.

2. MULTI-TIME SCALE DYNAMIC MODEL OF SOFC POWER SYSTEM

2.1 *SOFC Power System Modelling*

In a planer SOFC stack, cells are stacked and connected in series. Stack performance can be evaluated by semi-empirical model using the Nernst equation incorporating polarization losses fitted by real experimental data. Fig2 give the characteristic of a 3-cells short stack semi-empirical model running at 1073K.

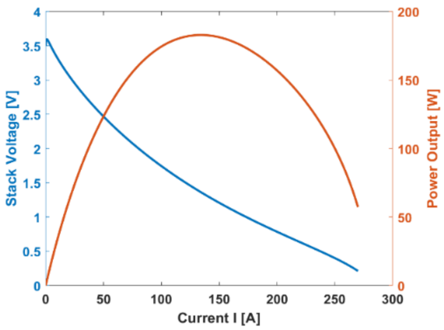

Fig2 Characteristic of a 3-cells stack model at 1073 K

2.1.1 Load following Fuel Sub-model

This sub-model updates the input fuel flow according to the load change with optimal fuel utilization. Assuming the optimal utilization factor is $U_{f\_optimal}$, the reference input mass flow rate of fuel can be controlled by reference current i_{ref}, which is equal to P_{desire} divided by stack voltage V_{stack}:

$$q_{CH_4}^{in\_ref} = \frac{\frac{K_r}{U_{f\_optimal}}}{1+\tau_f} i\_ref \tag{1}$$

where τ_f is the fuel supply lagging time.

2.1.2 Linearized Model of SOFC

A MATLAB Simulink model was built based on Fig1 with six states $x = \left[pH_2\, pH_2O\ pO_2\ q_{\mathrm{Air}}^{in}\ q_{H_2}^{in}\ T_o\right]^T$. $pH_2\ pH_2O\ pO_2$ are the effective partial pressures of hydrogen, water steam and oxygen, q_{Air}^{in}, $q_{H_2}^{in}$ are the mass flow rates of air and hydrogen produced by reformer and blower, T_o is the temperature of tail gas at both anode and cathode. Three control variables including stack current I, mass flow rate of the fuel $q_{CH_4}^{in}$, and the blower input command u_b . The output y is defined by $\mathrm{y} = [T_s, \mathrm{V}_s, U_f]$, where T_s is the stack temperature, V_s represents the stack voltage.

To investigate the dynamics of SOFC power system, feedback linearization method is used to linearize the system during the load variations, the corresponding linearized systems are represented in state space form as Equation (2).

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(\tau) &= Cx(t) + Du(t) \end{aligned} \tag{2}$$

Matrix A contains the dynamics of the system, the time domain response can be represented as

$$\begin{aligned} x_i(t) &= e^{\lambda_i t} x_{0,i} + \int_0^t e^{\lambda_i (t-\tau)} b_i u(\tau) d\tau \\ y(t) &= \sum_{i=1}^{n} C_i x_i(t) + Du(t) \end{aligned} \tag{3}$$

where λ_i are the eigenvalues of matrix A.

The eigenvalues located in the left half plane indicates the linearized systems are asymptotically stable. And the widely spread eigenvalues, from being close to origin to far away indicate the presences of slow and fast dynamic modes in SOFC power system, as shown in Fig 3.

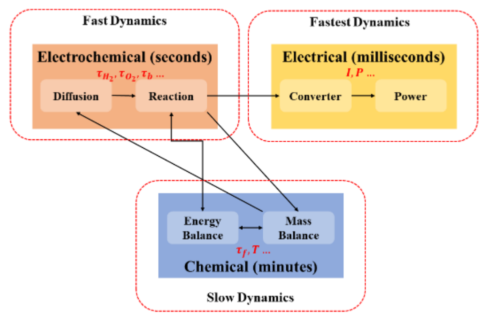

Fig3 The main dynamic modes of SOFC power system

2.2 *Multi-time Scale Decomposition*

A typical linear SP system can be represented in the fast time scale τ, where $\tau = t/\varepsilon\ (t = \varepsilon\tau, dt = \varepsilon d\tau)$:

$$\begin{aligned} \dot{x}(\tau) &= A_{11}x(\tau) + A_{12}z(\tau) \\ \varepsilon\dot{z}(\tau) &= A_{21}x(\tau) + A_{22}z(\tau) \end{aligned} \tag{3}$$

By using the Chang transformation, denoted as T_C, One can decompose a linearized SOFC power system dynamic model into independent slow (A_s) and fast (A_f) subsystems [8]. The definition of slow and fast is relative, one can decompose a same system in different ways.

3. RESULTS AND DISCUSSION

This section consists of simulation results obtained in Simulink for the system shown in Fig.1 and afterward are the comments.

3.1 Load Following Ability

In this study, a SOFC power system initially operating at 1000[K] with stable load, and a series of sudden power demand changes is required. The framework of load change is assumed at [0 500,2500, 4500, 6500, 8500] instance and the respective power are [20 60 100 140 100 20] [W].

3.2 Open loop SOFC Power System Performance

As the plots in Fig 4, The system initially operates under $q_{H_2}^{in}$ =1E-3L/min, $q_{Air}^{in} = 5\text{E} - 3\text{L/min}$, anode and cathode inlet temperature at 950K and 850K. Open loop load following capability is evaluated with 0.8V/cell as the preferred operating voltage. The tracking performance is very poor under open loop frame, although the current can follow the variations of power demands without any delay, considered as the fastest variable in SOFC power system, but other key parameters, such as temperature and voltage, will take longer to reach the steady states, which causes the load following problem of SOFC. And because of the possible losses inside the stack, final power output may deviate a lot from the desired output. Settling time is the time required for the response curve to reach and stay within a range of certain percentage (~2%) of the steady state value. It can be used as an indicator of dynamic response in time domain. In Fig5, after the power step change at 500 seconds, the current change right away, but it took about 450 seconds for the stack temperature reaches steady state. Here, comparing to the current, dynamic response of temperature is considered as in slow time scale.

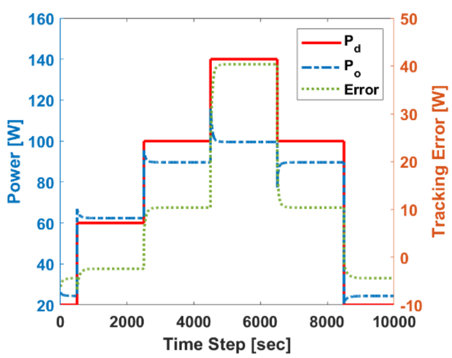

Fig 4 Open loop load following ability

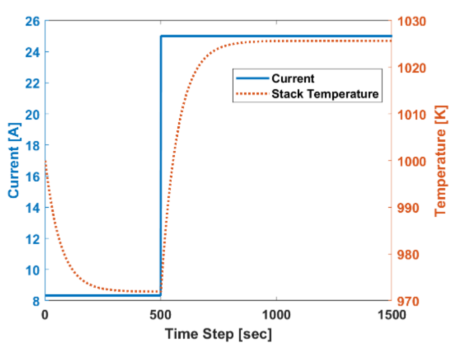

Fig 5 Stack temperature variation during load following

3.3 SOFC Power System Model Decomposition

To have a better understanding of system dynamics, key parameters and their interactions, the model will be decomposed and decoupled into subsystem models at different time scale. The linearized model at time step 4800 is used here as an example, the state space matrices are given by

$$A = \begin{bmatrix} -0.1667 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.3333 & 0 & 0 & 0 & 0 \\ 0 & 220 & -0.3672 & 0.1365 & 0 & 0 \\ -849.8 & -0.06928 & -5.938E-6 & -0.6682 & 7.983E-8 & -2.124E-8 \\ 1.698E+4 & 0 & 0 & -0.224 & -0.009416 & 0 \\ 1.698E+6 & 0 & 0 & 0.2041 & 0 & -0.02825 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.000744 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -116.2 & 0 \\ 0 & 0.4343 & 0 \\ 0 & 52.79 & 0 \\ 0 & -52.79 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 2.26E-5 & 0.003613 & -3.038E-7 & 8.084E-8 \\ -2.517 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -0.01766 & 0 \\ 0 & 0.001158 & 0 \end{bmatrix}$$

where the states x are in the order of $[q_{\text{Air}}^{in}\ q_{H_2}^{in}\ pO_2\ T_o\ pH_2\text{O}\ pH_2]$.

The eigenvalues of matrix A are: -0.6682, -0.3672, -0.3333, -0.1667, -0.0283, -0.0094. The distribution of eigenvalues clearly indicates the presence of slow and fast modes. By following the steps in [7][8], this model can be decomposed into two sub-system A_{fast} and A_{slow} at two-time scales with Chang transformation T_C:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & -1.1745E-18 & 8.7398E-13 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 5.7075E-8 & -2.984E-8 \\ 0 & 0 & 0 & 1 & 1.3031E-7 & 4.3831E-8 \\ -6.1115E+5 & -0.4322 & -3.1917E-5 & 1.9781 & 1 & -6.2084E-7 \\ -6.0097E+7 & 0.3986 & 3.6217E-5 & -1.8024 & -2.3479E-7 & 0.9999 \end{bmatrix}$$

$$\frac{A_{fast}}{\varepsilon} = \begin{bmatrix} -0.9837 & 0 & 0 & 0 \\ 0 & -1.9668 & 0 & 0 \\ 0 & 1.2982E+3 & -2.1668 & 0.8055 \\ -5.0073E+3 & -0.4088 & -3.5039E-5 & -3.943 \end{bmatrix}$$

$$A_{slow} = \begin{bmatrix} -0.0094 & 7.1202 \\ 2.4384 & -0.0283 \end{bmatrix}$$

The corresponding fast states are q_{Air}^{in}, $q_{H_2}^{in}$, pO_2, T_o, slow states are $pH_2\text{O}$, pH_2.

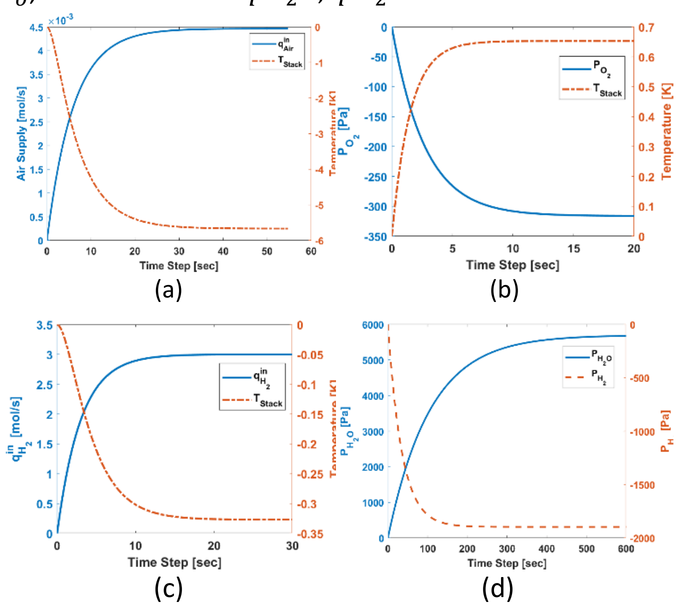

Fig 6 Step responses of fast and slow state due to Input

(a) Step response of stack inlet mass flow rate of air q_{Air}^{in} and stack temperature *T_stack* due to blower command u_b
(b) Step response of partial pressure of oxygen p_{O_2} and stack temperature *T_stack* due to current I
(c) Step response of stack inlet mass flow rate of hydrogen $q_{H_2}^{in}$ and stack temperature *T_stack* due to reformer fuel supply
(d) Step response of effective partial pressure of water steam (p_{H_2O}) due to current *I*

Table 1 Settling times of each states (secs)

	Input1: u_b	Input 2: I	Input 3: $q_{CH_4}^{in}$
q_{Air}^{in}	23.5	23.5	-
$q_{H_2}^{in}$	-	-	11.7
pO_2	28.8	10.7	16.7
T_o	25.2	5.93	14.2
pH_2O	415	11	150
pH_2	139	10.2	48

Table 1 summarized all settling times for each states subject to each input, it is clear that the dynamic response of SOFC power system across multiple time scales, from micro-second (current) to hundreds of seconds (effective partial pressure).

3.4 Feedback Controller Design fast load following

To have a better load following ability and preventing deterioration by rapid thermal change. Two feedback control loops can be built for controlling the system power out and to keep the temperature inside the safe zone. As shown in Fig 7, control technique of load following ability is to send the error signal between actual power output and desired output to a PI controller, by changing the fuel supply rate, both the anode inlet mass flow and stack temperature will be changed, and it will further affect the voltage output. By picking the right PI gains, the tracking error of SOFC power system can be largely decreased. The operating temperature is to send excess air to the fuel cell. Because the output voltage depends largely on operation temperature, when the temperature variation is kept under control, the output voltage therefore is more stable. Combined with real SOFC power unit configuration, the manufacture can decide the appropriate amount of air based on this result.

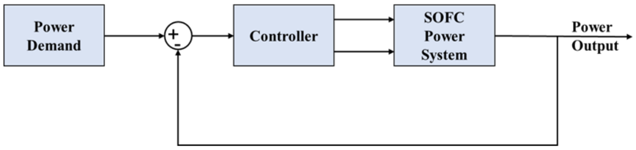

Fig6 Feedback control diagram for SOFC power system

4. CONCLUSION AND FUTURE WORK

An effective approach to decouple and decompose the multi-time scale dynamics of SOFC Power System was presented and studied in two-time scale. The resulting sub models with different time scale facilitate a better understanding of the SOFC system dynamics and the interactions in-between key parameters. Reduced order feedback controllers can be designed based on the above results. Combine this decomposition approach with system identification techniques is expected for real experiment data and applications.

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