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SPS Smart Grid Power Systems Laboratory

Data-Driven Dynamic Model Identification for Synchronous Generators

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Outline

- Introduction
  - Motivation
  - Objectives
- Input/output Identification Model
  - Synchronous generator model derivation
  - System identification for generator parameters
  - Case study
- Output Only Identification Model
  - Single generator to infinity bus model derivation
  - Grey-box model building
  - Case study
- Q&A

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Introduction

- Motivation
  - As the major work horse in the modern power grid for electricity generation, synchronous generators are important
  - Accurate estimation of the generator parameters is important and of practical interest
  - With a large amount of Phasor Measurement Units (PMUs) installed in the power grid, the measurement data is easier than ever to be collected and analyzed

- Objectives
  - PMU-based data-driven system identification methods may be applied for dynamic model parameter estimation
  - Achieve the accurate parameter estimation of synchronous generator via collected time-series data from dynamic model simulation

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Input/output Identification Model

- Synchronous generator model derivation
  - Small signal dynamic model

$$\begin{cases} \Delta\dot{\delta} &= \omega_0 \Delta\omega \\ \Delta\dot{\omega} &= \frac{1}{2H}(\Delta P_m - \Delta P_e - D_1(\Delta\omega - 1)) \\ \Delta\dot{P}_m &= \frac{1}{T_g}(\Delta P_{\text{ref}} - \frac{1}{R}\Delta\omega - \Delta P_m) \end{cases}$$

  - State-space model after discretization at step size of "h"

$$\begin{bmatrix} \Delta\delta_{k+1} \\ \Delta\omega_{k+1} \\ \Delta P_{m_{k+1}} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & \omega_0 h & 0 \\ 0 & 1-\frac{D_1 h}{2H} & \frac{h}{2H} \\ 0 & -\frac{h}{T_g R} & 1-\frac{h}{T_g} \end{bmatrix}}_{A} \begin{bmatrix} \Delta\delta_k \\ \Delta\omega_k \\ \Delta P_{m_k} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ -\frac{h}{2H} \\ 0 \end{bmatrix}}_{B} \boxed{\Delta P_{e_k}}$$

$$\boxed{\Delta\omega_k} = \underbrace{\begin{bmatrix} 0 & 1 & 0 \end{bmatrix}}_{C} \begin{bmatrix} \Delta\delta_k \\ \Delta\omega_k \\ \Delta P_{m_k} \end{bmatrix}$$

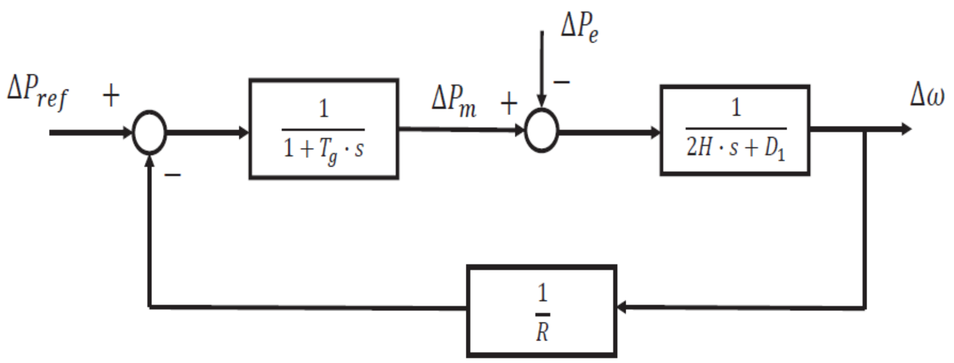


Fig. 1 Block diagram of synchronous generator with primary frequency droop control small signal model.

  - Input/output relationship on z-domain

$$\frac{y}{u} = C(zI - A)^{-1}B,$$
$$\Rightarrow A(z)y = B(z)u$$

  - ARX model's denominator and numerator

$$A(z) = 1 + \boxed{a_1}z^{-1} + \boxed{a_2}z^{-2}$$
$$B(z) = \boxed{b_1}z^{-1} + \boxed{b_2}z^{-2}$$

Input/output Identification Model

- System identification for generator parameters
  - Over-determined problem formulation

$$\underbrace{\begin{bmatrix} y(k+2) \\ \vdots \\ y(i) \\ \vdots \\ y(N) \end{bmatrix}}_{Y} = \underbrace{\begin{bmatrix} y(k+1) & y(k) & u(k+1) & u(k) \\ \vdots & \vdots & \vdots & \vdots \\ y(i-1) & y(i-2) & u(i-1) & u(i-2) \\ \vdots & \vdots & \vdots & \vdots \\ y(N-1) & y(N-2) & u(N-1) & u(N-2) \end{bmatrix}}_{\lambda} \cdot \underbrace{\begin{bmatrix} -a_1 \\ -a_2 \\ b_1 \\ b_2 \end{bmatrix}}_{X}$$

  - Solve the over-determined problem by LSE method

$$X = (\lambda^T \cdot \lambda)^{-1} \cdot \lambda^T \cdot Y$$

  - Parameters recovery from estimated ARX model coefficients

$$H = -\frac{h}{2 \cdot b_1} \qquad D_1 = -\frac{b_1 - b_2 + a_1 \cdot b_1}{b_1^2}$$

$$T_g = \frac{b_1 \cdot h}{b_1 + b_2} \qquad R = -\frac{b_1^2 \cdot (b_1 + b_2)}{a_2 \cdot b_1^2 - a_1 \cdot b_1 \cdot b_2 + b_2^2}$$

Input/output Identification Model

- Case study
  - IEEE 2 Area Test Case from Power System Toolbox by Dr. Joe Chow and Dr. Graham Rogers
  - Dynamic event is a three-phase fault on load bus 1.

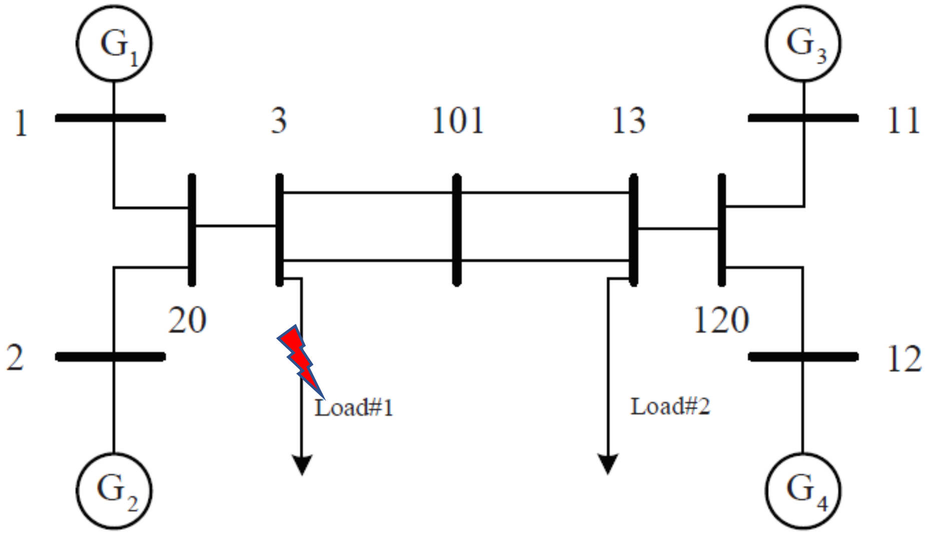
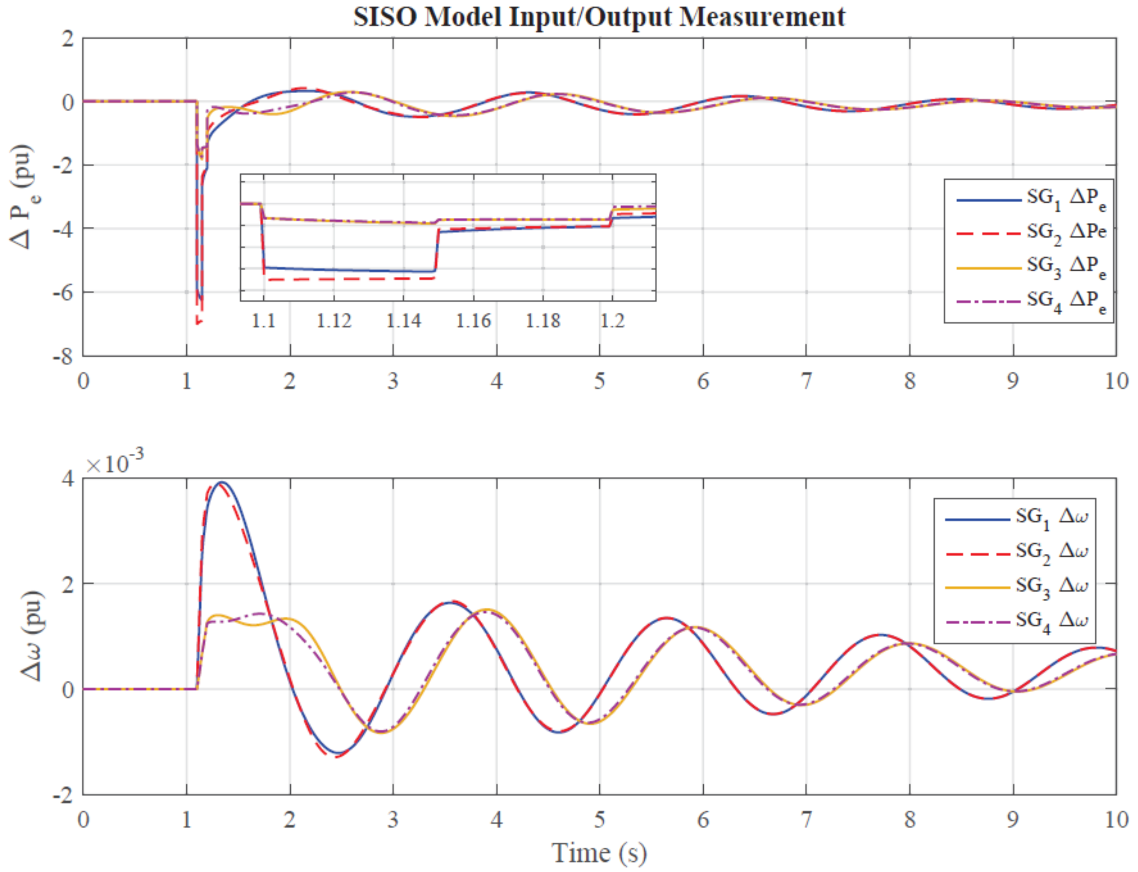


Fig. 2: 2 Area 4 Machine Dynamic Systems

Note: to ensure the quality of estimation, resampling of data is essential.



Input/output Identification Model

- Case study (Cont.)
  - Reference values of parameters and coefficients

Parameter	Reference Value	Parameter	Reference Value
H	58.5	D_1	54
T_g	0.25	R	0.004444

Coefficient	Reference Value	Coefficient	Reference Value
a_1	-1.995538	a_2	0.995548
b_1	-8.547009E-6	b_2	8.512821E-6

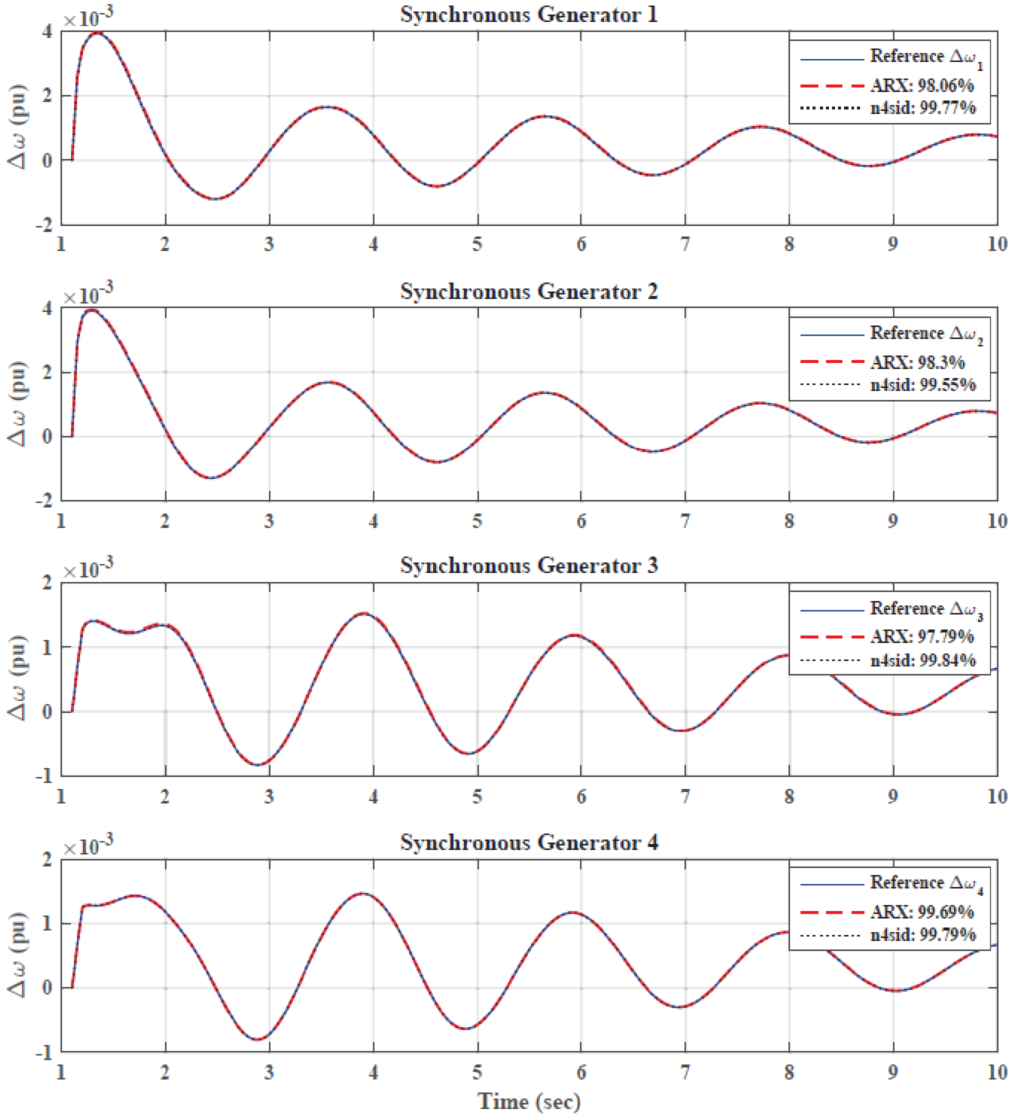
  - ARX-based LSE estimation VS. N4SID toolbox

		ARX-base LSE		*n4sid*	
Coefficient	Reference	Estimation	Error rate (%)	Estimation	Error rate (%)
a_1	-1.995538	-1.995535	0.00015	-1.995549	0.00055
a_2	0.995548	0.995545	0.00030	0.995559	0.00110
b_1	-8.5470E-6	-8.5879E-6	0.4774	-8.5792E-6	0.37674
b_2	8.5128E-6	8.5534E-6	0.4769	8.5452E-6	0.3806
Parameter	Reference	Estimation	Error rate (%)	Estimation	Error rate (%)
H	58.5	58.2212	0.4789	58.2805	0.3752
D_1	54	52.0740	3.5667	57.2394	5.9989
T_g	0.25	0.2489	0.4223	0.2520	0.8
R	0.004444	0.004535	1.9918	0.004578	3.0153

Input/output Identification Model

- Case study (Cont.)
  - Dynamic response replay
  - Both method estimated parameters are capable to accurately repeat the same dynamic behaviors of each generator in the event.

Note: it is important to ensure the scales of input/output signals are at the same level to have accurate estimation.



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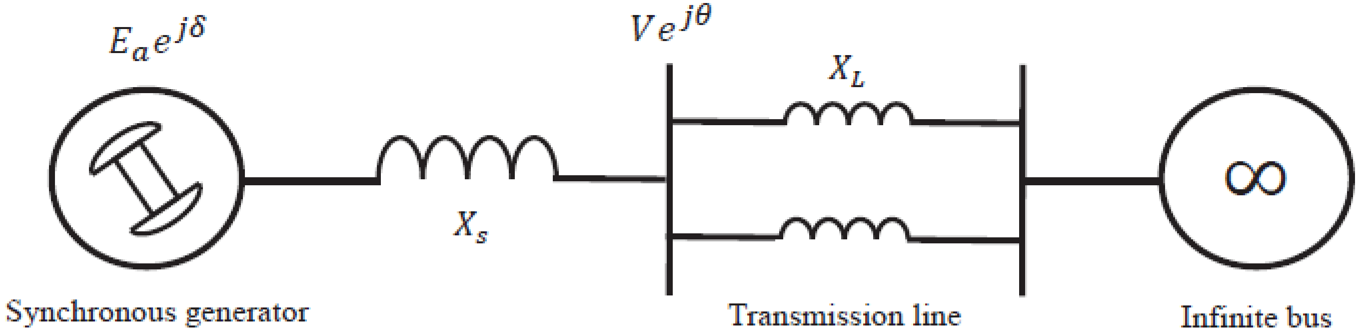
Output Only Identification Model

- Single generator to infinite bus model derivation



➢ Based on circuit analysis, the small signal model is derived as follows.

$$\begin{bmatrix}\Delta\delta_{k+1}\\ \Delta\omega_{k+1}\\ \Delta P_{m_{k+1}}\end{bmatrix} = \underbrace{\begin{bmatrix}1 & \omega_0 h & 0\\ -\frac{E_a h}{2H\tilde{X}}\cos(\delta) & 1-\frac{D_1 h}{2H} & \frac{h}{2H}\\ 0 & -\frac{h}{T_g R} & 1-\frac{h}{T_g}\end{bmatrix}}_{A'} \begin{bmatrix}\Delta\delta_k\\ \Delta\omega_k\\ \Delta P_{m_k}\end{bmatrix}$$

$$\Delta V_k^2 = \underbrace{\begin{bmatrix}-\frac{2X_s X_L E_a}{\tilde{X}^2}\sin(\delta) & 0 & 0\end{bmatrix}}_{C'} \begin{bmatrix}\Delta\delta_k\\ \Delta\omega_k\\ \Delta P_{m_k}\end{bmatrix}$$

Simplification

$$\begin{cases}\text{Par1}: & H_2 = \frac{1}{2H}\\ \text{Par2}: & DH_2 = \frac{D_1}{2H}\\ \text{Par3}: & T_{gr1} = \frac{1}{T_g R}\\ \text{Par4}: & T_{g1} = \frac{1}{T_g}\\ \text{Par7}: & E_a X = \frac{E_a}{\tilde{X}}\end{cases}$$

Output Only Identification Model

- Grey-box model building
  - To apply Grey-box toolbox for system identification, the state-space model structure formed by parameters is required.

```
A = [...
                        1,       w0*h,         0;
   -Par1*Par7*cos(Par8)*h,   1-Par2*h,     Par1*h;
                        0,    -Par3*h,  1-Par4*h];
C = [...
      -2*Par5*Par6*Par7*sin(Par8)/(Par5+Par6);
                  0;
                  0]';
```

  - Then, to inject data for parameter estimation, the system identification toolbox data management function is required to form the data in proper way.

```
data = iddata(y,[],h)
sys = idgrey(odefun,initials,fcntype);
sysest = greyest(data,sys),
```

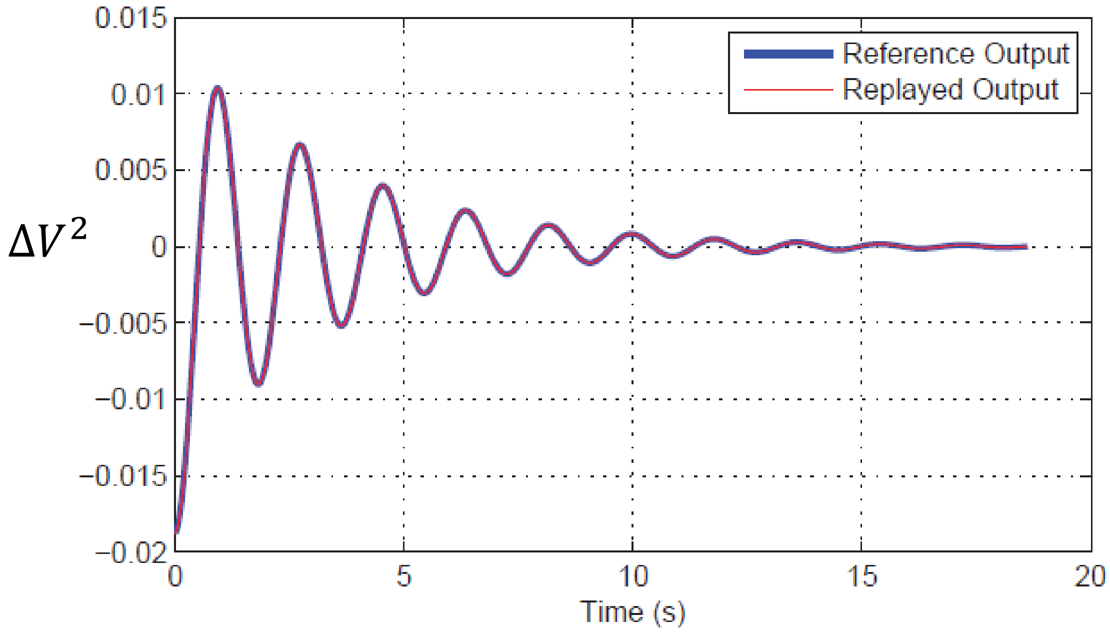
Output Only Identification Model

- Case Study
  - ➢ Without input signal, a set of initial values are assigned to the state variables to start running the derived small signal model.
  - ➢ With the output data collected from the model running, the parameter identification is performed via Grey-box estimation.

```
A =
              x1          x2          x3
x1             1       0.377           0
x2    -8.881e-06      0.9993   1.355e-05
x3             0       -0.45           1

C =
          x1        x2        x3
y1   -0.0429         0         0

Model parameters:
Par1 = 0.01355  |  Par5 = 0.002774
Par2 = 0.6847   |  Par6 = 0.09491
Par3 = 450      |  Par7 = 7.987
Par4 = 0        |  Par8 = 1.489

Sample time: 0.001 seconds
Status:
Estimated using GREYEST on time domain
 data "data".
Fit to estimation data: 94.49%
FPE: 3.884e-09, MSE: 3.877e-09
```

Output Only Identification Model

- Case Study (Cont.)
  - With estimated parameters obtained from Grey-box estimation, the dynamic response replay is performed. The plot below shows the comparisons between the original output data from running the state-space model and output signal data from running the model with estimated parameters.
  - Comparison shows great match, which means the parameter identification via Grey-box estimation method with output signal only is effective and accurate.



Q&A

Thank you !