System Identification of Reduced-Order Models of Power Systems from PMU Data

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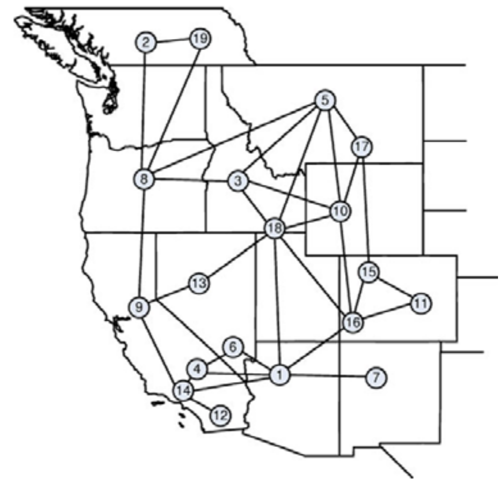
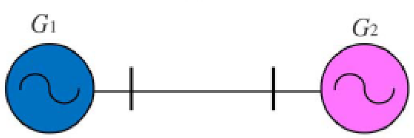
Introduction

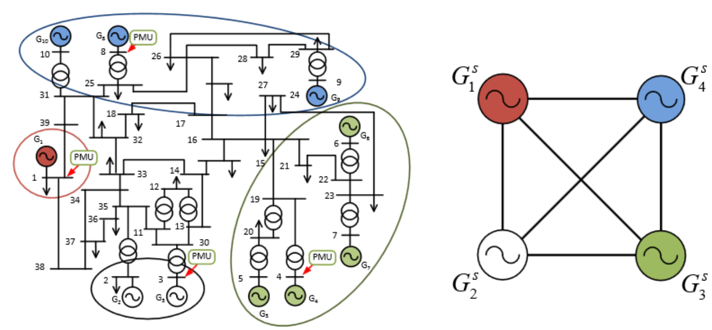
- Power systems dynamic model reduction has seen some 40 years of long and rich research history.
- Model-based methods:
  - Need the model of the power system,
  - Are computationally expensive,
  - Are based on idealistic assumption about system <u>structure</u> and <u>clustering</u>,
- With the recent increase in number of Phasor Measurement Units (PMUs) operators are gradually inclining more towards measurement based techniques for aggregation



Areas within WECC System (R. Podmore, 2013)



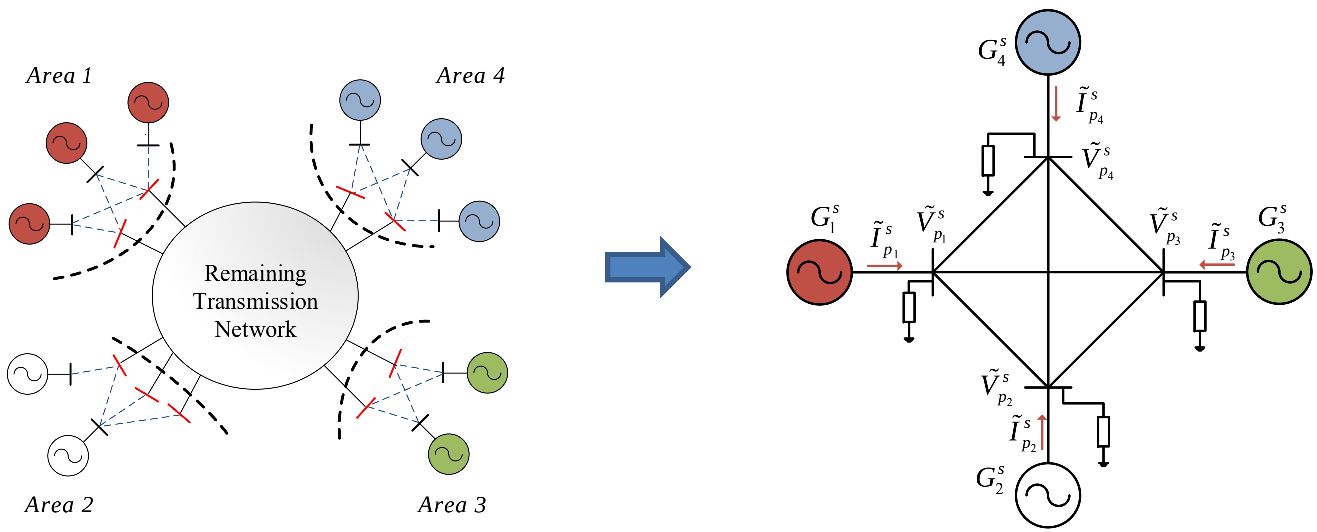
Dynamic equivalencing for a two-area test system (Chakrabortty et al. 2011)



Dynamic equivalencing for IEEE 39-Bus Model (S. Nabavi et al. 2013)

Proposed Dynamic Model Reduction

- Linear reduced-order models give the equivalent reduced-order model in the Kron's from.
  - No information about the equivalent machine parameters such as inertia and active power.
  - None of the reduced-order model components have any physical meaning
- We next propose an alternative method to identify the equivalent Differential-Algebraic (DAE) models.

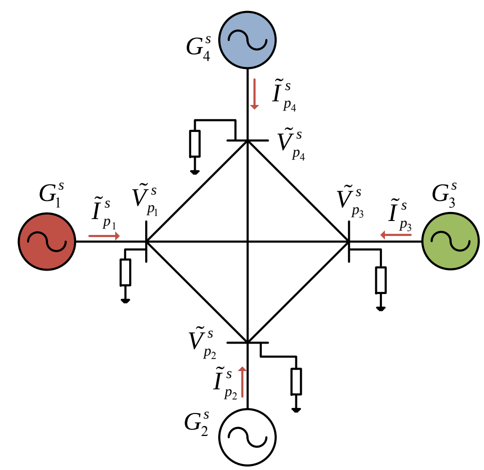


Problem Formulation

- **Assumptions:**
  - There are r coherent areas,
  - The area partitioning is given,
  - The boundary buses of area k, denoted by B_k, are equipped with PMUs or they are observable by PMUs
- **Objective:**
  - Finding the equivalent DAE model of a power system using a set of measurements $S_k, k = 1, \ldots, r$ where:

$$S_k = \{\tilde{V}_i(t) I_{i,j}(t)\} \qquad i \in B_k, j \in \mathcal{N}_i$$

- **Proposed Identification Steps**
  - Finding the equivalent pilot bus voltages and currents
  - Estimating the equivalent area impedances
  - Estimating the equivalent generator parameters
  - Estimating the inter-area impedances



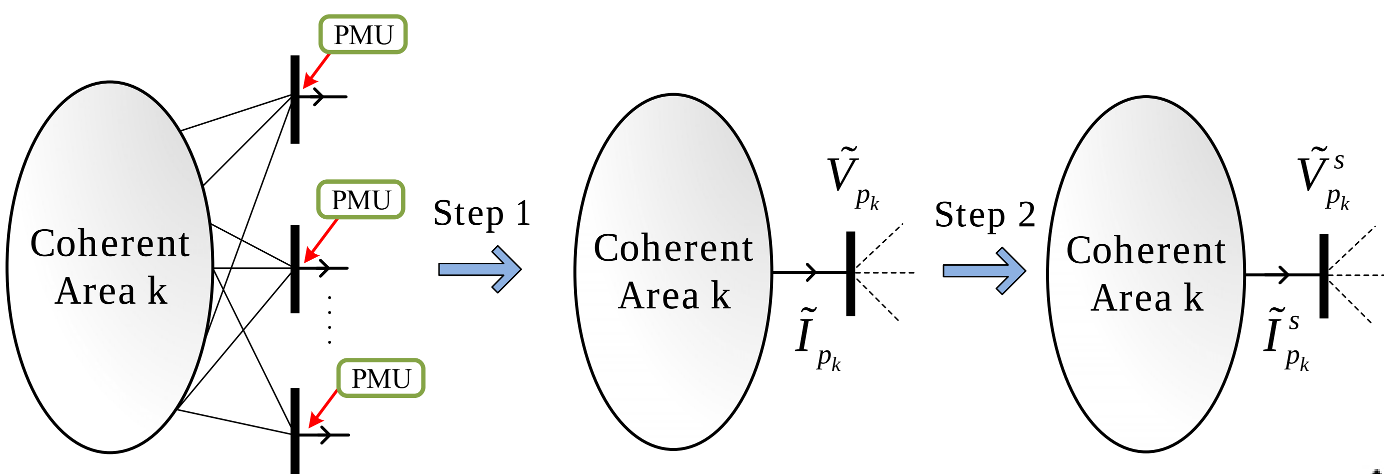
Equivalent Pilot Bus Voltage and Current Calculation

Step 1: Use S_k to calculate $\tilde{V}_{pk}(t)$ and $\tilde{I}_{pk}(t)$

$$\tilde{I}_{pk}(t) \triangleq \sum_{i \epsilon B_k} \tilde{I}_i(t),\ \tilde{V}_{pk}(t) \triangleq \frac{\sum_{i \epsilon B_k} \tilde{V}_i(t)\tilde{I}_i^*(t)}{\sum_{i \epsilon B_k} \tilde{I}_i^*(t)}$$

where

$$\tilde{I}_i(t) = \sum_{j \notin \text{Area k}} \tilde{I}_{i,j}(t)$$



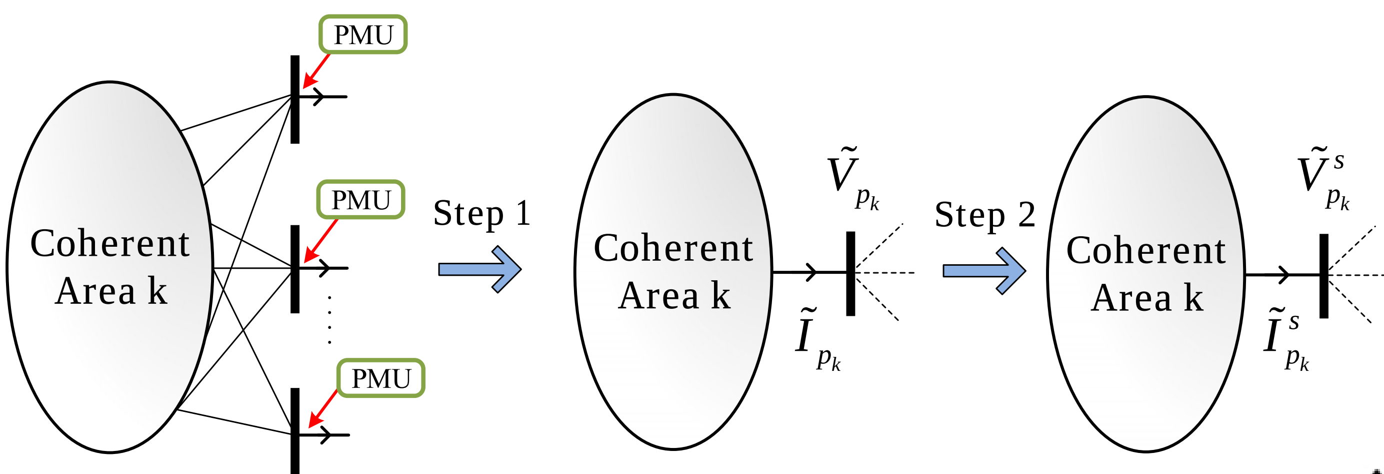
Equivalent Pilot Bus Voltage and Current Calculation

Step 2.1: Decompose $\tilde{V}_{pk}(t) \triangleq V_{pk}(t)\angle\theta_{pk}(t)$ and $\tilde{I}_{pk}(t) \triangleq I_{pk}(t)\angle\varphi_{pk}(t)$ into its slow and fast components using a modal decomposition technique such as Prony:

$$V_{pk}(t) \cong V_{pk}^{s}(t) + V_{pk}^{f}(t) \qquad \theta_{pk}(t) \cong \theta_{pk}^{s}(t) + \theta_{pk}^{f}(t)$$

$$I_{pk}(t) \cong I_{pk}^{s}(t) + I_{pk}^{f}(t) \qquad \varphi_{pk}(t) \cong \varphi_{pk}^{s}(t) + \varphi_{pk}^{f}(t)$$

Step 2.2: Form $\tilde{V}_{pk}^{s}(t) \triangleq V_{pk}^{s}(t)\angle\theta_{pk}^{s}(t)$ and $\tilde{I}_{pk}(t) \triangleq I_{pk}^{s}(t)\angle\varphi_{pk}^{s}(t)$



Equivalent Area Impedance Calculations

- KVL in the equivalent circuit:

$$E_k^s(t)\angle\delta_k^s(t) = \left(r_k^s + jx'^s_{dk}\right)\tilde{I}^s_{pk}(t) + \tilde{V}^s_{pk}(t)$$

- For time instance t_0 through t_m:

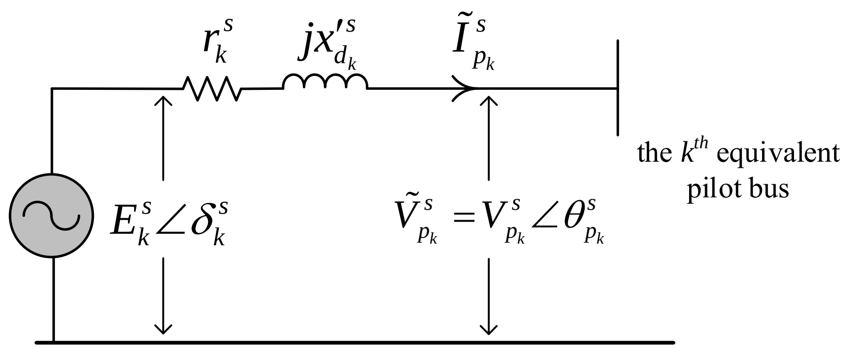
$$\Phi_0 \triangleq \left|\left(r_k^s + jx'^s_{dk}\right)\tilde{I}^s_{pk}(t_0) + \tilde{V}^s_{pk}(t_0)\right|$$

$$\vdots$$

$$\Phi_m \triangleq \left|\left(r_k^s + jx'^s_{dk}\right)\tilde{I}^s_{pk}(t_m) + \tilde{V}^s_{pk}(t_m)\right|$$

- The estimation of r_k^s and x'^s_{dk} for area k can be posed as the following NLS problem:

$$\min_{x'^s_{dk}, r_k^s} var(\Phi_0, \dots, \Phi_m)$$



Equivalent Area Generator Parameters

- Solve the following NLS problem

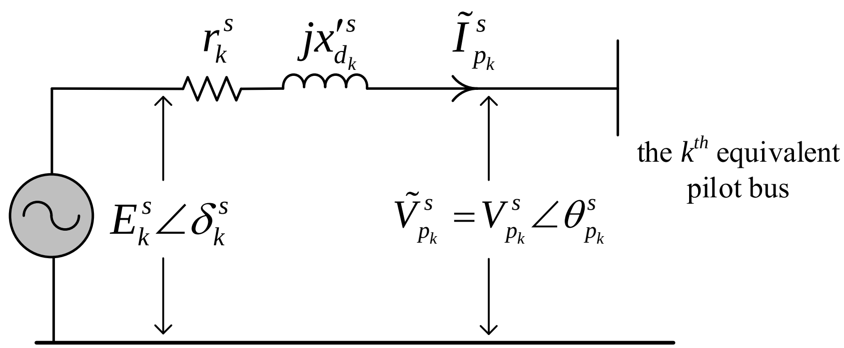
$$\min_{M_k^s, D_k^s, P_{mk}^s} \int_{t_0}^{t_m} |\hat{\delta}_k^s(t) - \delta_k^s(t, M_k^s, D_k^s, P_{mk}^s)|^2 dt$$

- Where

$$\dot{\delta}_k^s(t) = \omega_0(\omega_k^s(t) - 1)$$

$$M_k^s \dot{\omega}_k^s(t) = P_{mk}^s - \hat{P}_{ek}^s(t) - D_k^s(\omega_k^s(t) - 1)$$

$$\hat{P}_{ek}^s(t) = Re(\hat{E}_k^s \angle \hat{\delta}_k^s(t). \tilde{I}_{pk}^{s*}(t))$$



Inter-Area Impedance Calculations

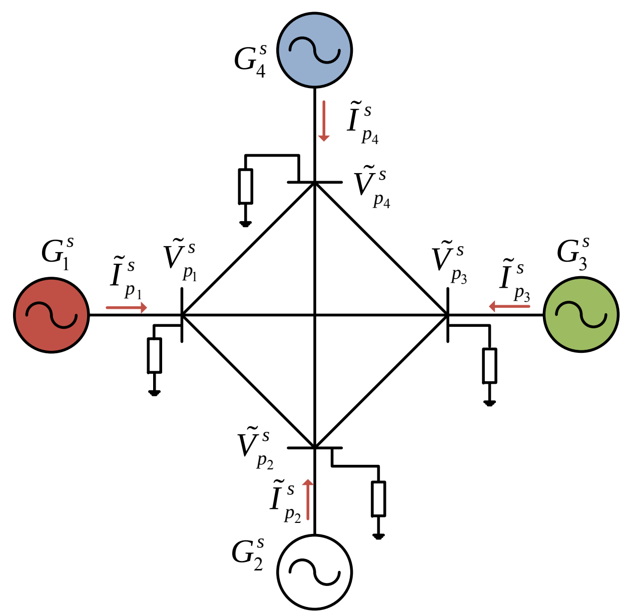
- KCL on equivalent pilot buses:

$$\underbrace{\begin{bmatrix} Y_{11}^s & \cdots & Y_{1r}^s \\ \vdots & \ddots & \vdots \\ Y_{r1}^s & \cdots & Y_{rr}^s \end{bmatrix}_{r\times r}}_{Y^s} \underbrace{\begin{bmatrix} V_1^s(t_0) & \cdots & V_1^s(t_m) \\ \vdots & \ddots & \vdots \\ V_r^s(t_0) & \cdots & V_r^s(t_m) \end{bmatrix}_{r\times m}}_{V^s} = \underbrace{\begin{bmatrix} I_1^s(t_0) & \cdots & I_1^s(t_m) \\ \vdots & \ddots & \vdots \\ I_r^s(t_0) & \cdots & I_r^s(t_m) \end{bmatrix}_{r\times m}}_{I^s}$$

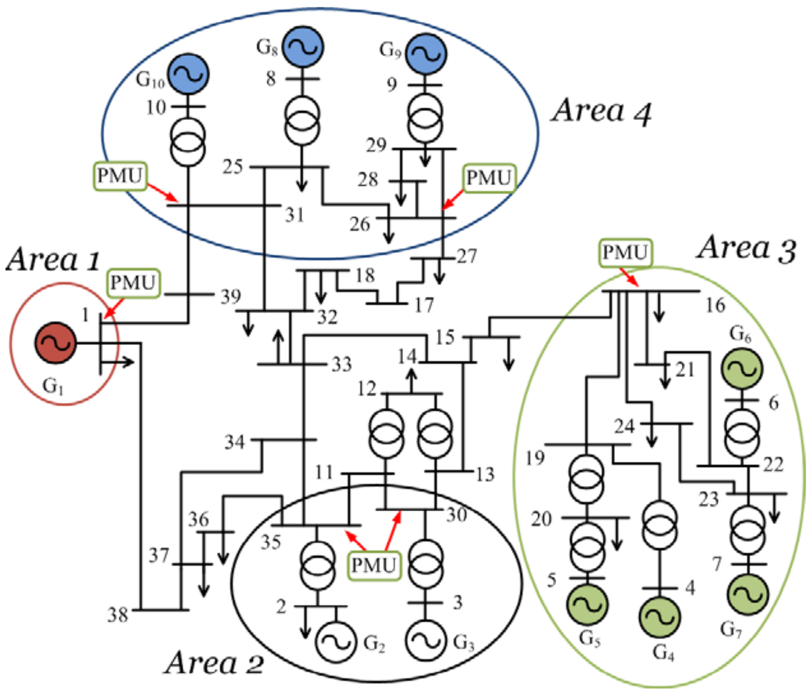
- Estimating Y^s by solving:

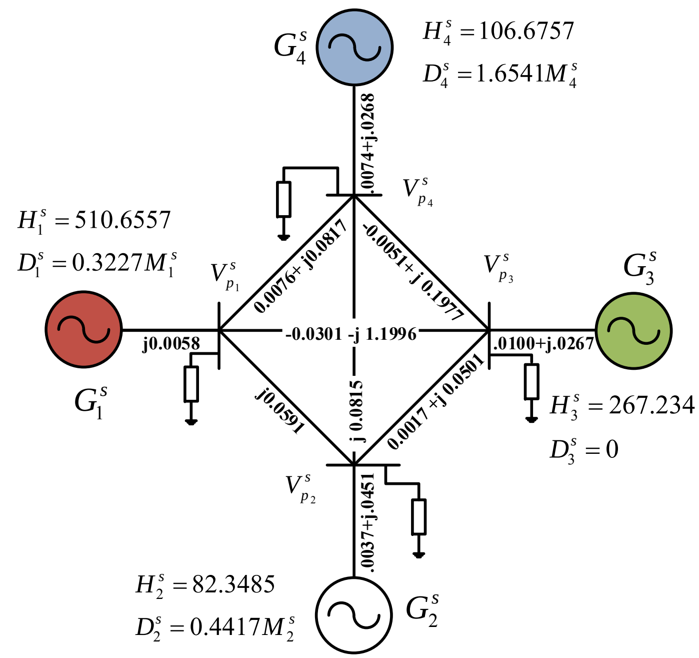
$$\min_{Y^s} \|Y^s V^s - I^s\|_F^2$$

$$\text{s.t. } Y^s = (Y^s)^T$$

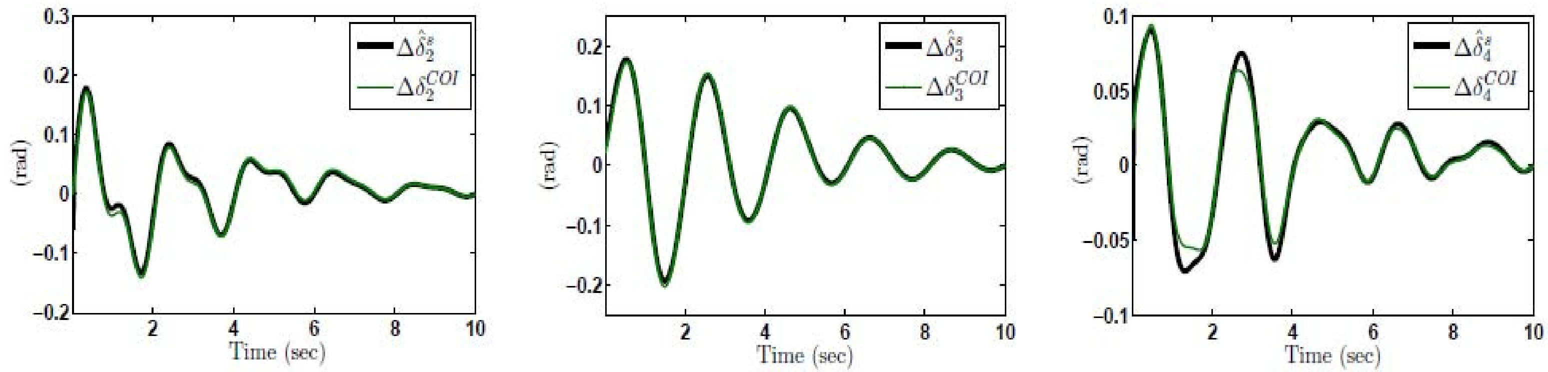


A Case Study: IEEE 39-Bus Model

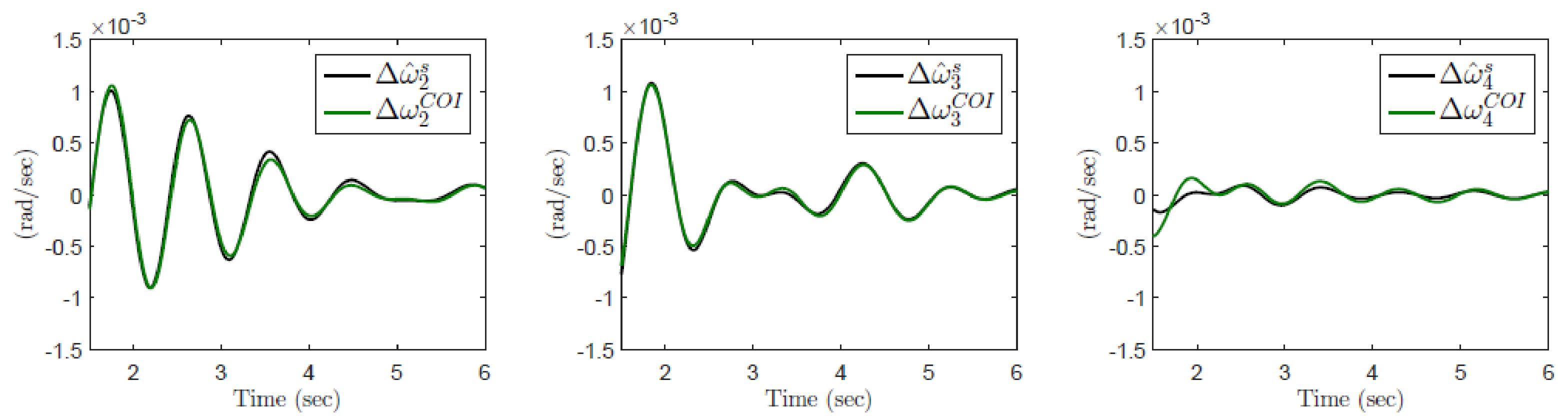




Predictive Capabilities of the Reduced-order Model



More contingencies:



Conclusion

- Coherency-based dynamic equivalencing has been a useful tool to assist utilities in reducing the running times associated with transient stability studies.
- We propose a new identification method to identify the equivalent dynamic models of large power system in DAE form using PMU measurements.
- Compared to the previous works, the proposed equivalent model provides more details about the equivalent generators such as their inertia, damping, produced active power, and transient impedance.
- One future extension of this method would be to include stochastic dynamic models of renewable generation and loads.