Interarea Model Estimation for Large-scale Electric Power Systems using Synchronized Phasor Measurements

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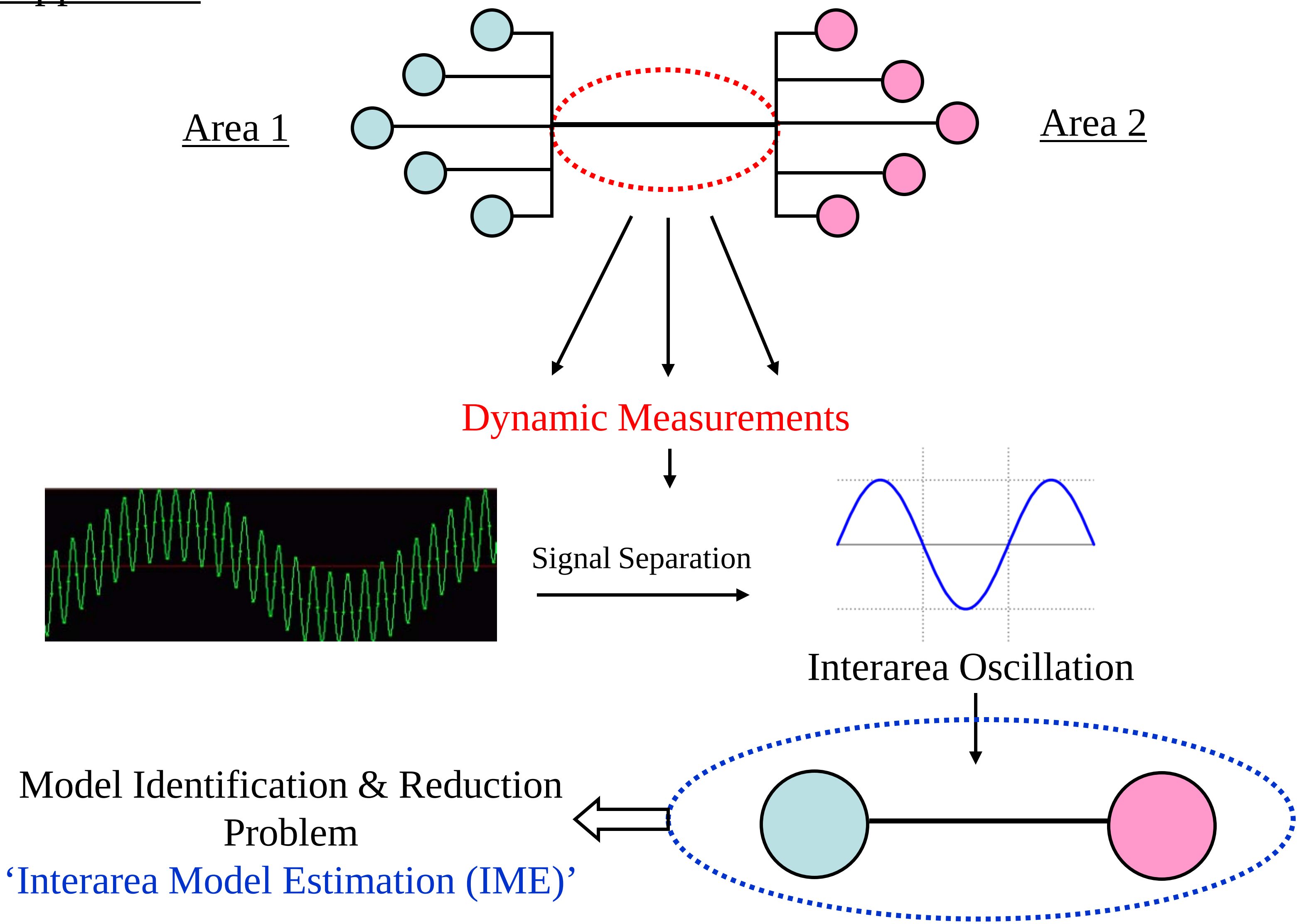
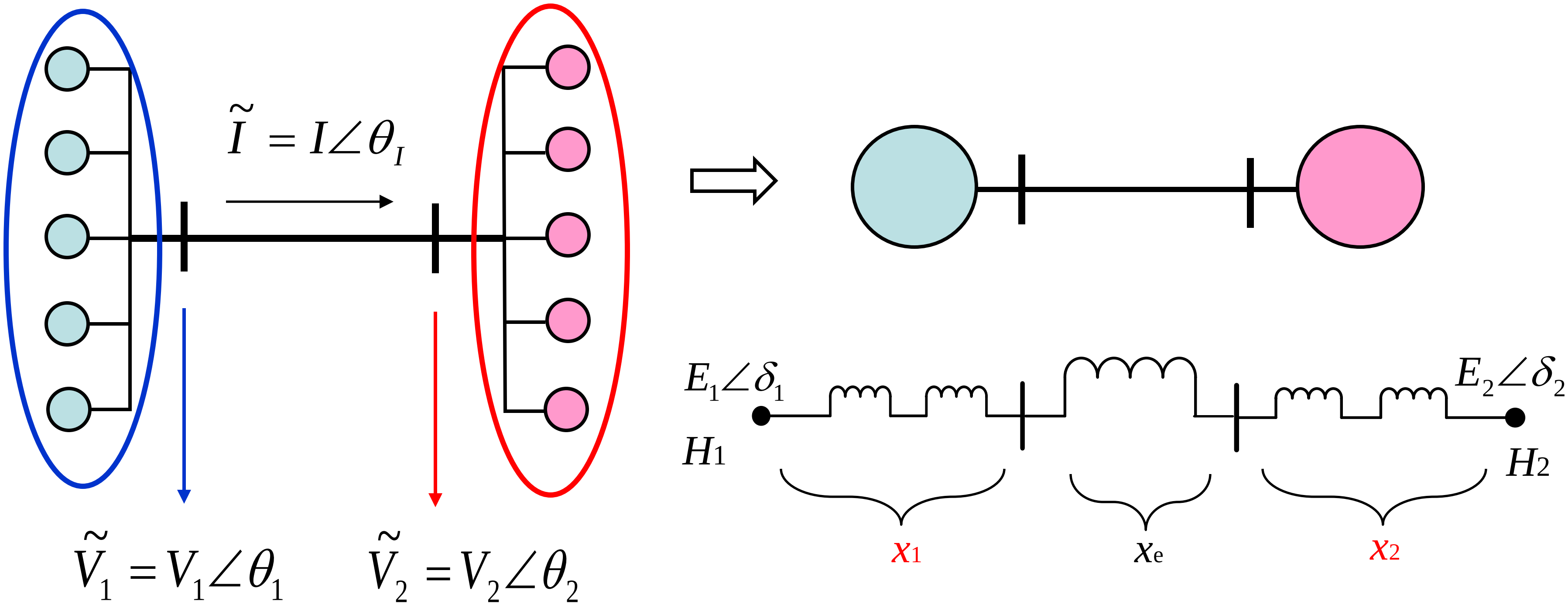
Two-machine Equivalents

Our Approach :



IME: Method



Problem:

How to estimate all parameters?

x_1, x_2, H_1, H_2

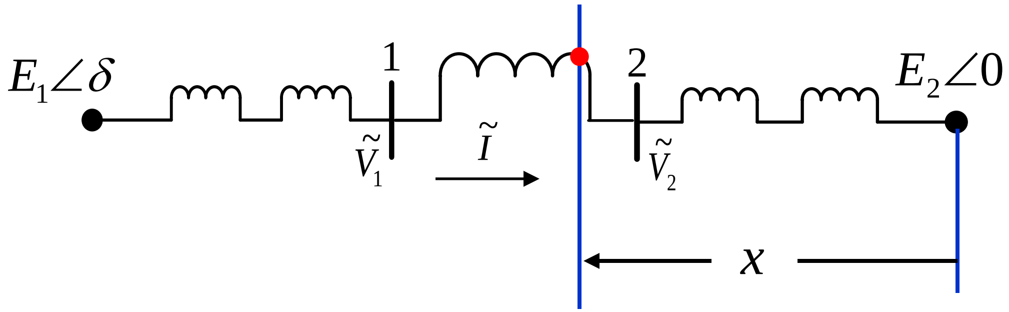
$$\dot{\delta} = \omega$$

$$2\frac{H_1 H_2}{H_1 + H_2}\dot{\omega} = \frac{H_2 P_{m1} - H_1 P_{m2}}{H_1 + H_2} - \frac{E_1 E_2}{(x_1 + x_e + x_2)}\sin\delta$$

Swing Equation

IME: Method *(Reactance Extrapolation)*

- **Key idea** : Amplitude of voltage oscillation at any point is a function of its electrical distance from the two fixed voltage sources.



$$\tilde{V}(x) = [E_2(1-a) + E_1 a\cos(\delta)] + j\,E_1 a\sin(\delta), \qquad a = \frac{x}{x_1 + x_e + x_2}$$

- Voltage magnitude : $V = |\tilde{V}(x)| = \sqrt{c + 2E_1E_2(a-a^2)\cos(\delta)}, \qquad c = (1-a)^2 E_2^{\,2} + a^2 E_1^{\,2}$

- Assume the system is initially in an equilibrium $(\delta_0, \omega_0 = 0, V_{ss})$:

$$\Delta V(x) = J(a,\delta_0)\Delta\delta$$

$$J(a,\delta_0) := \left.\frac{\partial V(a,\delta_0)}{\partial\delta}\right|_{\delta=\delta_0} = \frac{-E_1E_2}{V(a,\delta_0)}(a-a^2)\sin(\delta_0)$$

Reactance Extrapolation

$$\Delta V(x) = \frac{-E_1 E_2}{V(a,\delta_0)}(a - a^2)\sin(\delta_0)\Delta\delta$$

Reactance Extrapolation

$$\Delta V(x) = \frac{-E_1 E_2}{V(a,\delta_0)}(a-a^2)\sin(\delta_0)\Delta\delta$$

↓

$$\underbrace{\Delta V(x) V(a,\delta_0)}_{\text{can be computed from measurements}} = \underbrace{-E_1 E_2 \sin(\delta_0)}_{A}(a-a^2)\Delta\underbrace{\delta(t)}_{\text{solution of a linear differential equation}}$$

can be computed from measurements

A

solution of a linear differential equation

↓

$$V_n(x,t) = A(a-a^2)\Delta\delta(t)$$

Reactance Extrapolation

$$\Delta V(x) = \frac{-E_1E_2}{V(a,\delta_0)}(a-a^2)\sin(\delta_0)\Delta\delta$$

$$\underbrace{\Delta V(x)V(a,\delta_0)}_{} = \underbrace{-E_1E_2\sin(\delta_0)}_{A}(a-a^2)\underbrace{\Delta\delta(\mathbf{t})}_{}$$

can be computed from measurements

solution of a linear differential equation

$$V_n(x,t) = A(a-a^2)\Delta\delta(t)$$

Refer to as: *'Normalized voltage'*

Note: *Spatial* and *temporal* dependence are separated

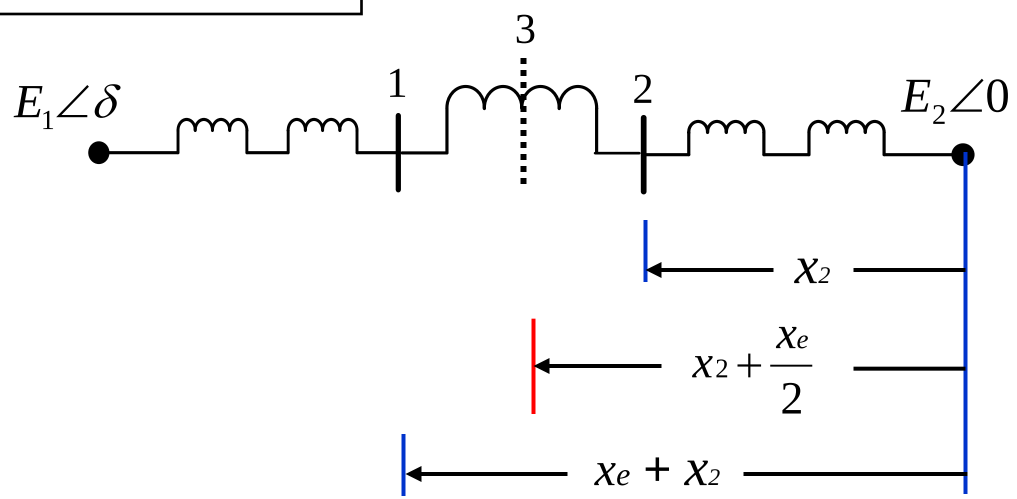
• Fix time: $t=t^*$

$$V_n(x,t^*) = A(a-a^2)\Delta\delta(t^*)$$

How can we use this relation to solve our problem?

Reactance Extrapolation

$$V_n(x,t^*) = A(a - a^2)\Delta\delta(t^*)$$



At Bus 2, $a_2 = \frac{x_2}{x_1 + x_e + x_2} \longrightarrow V_{n,\,Bus2} = A(a_2 - a_2^2)\Delta\delta(t^*)$

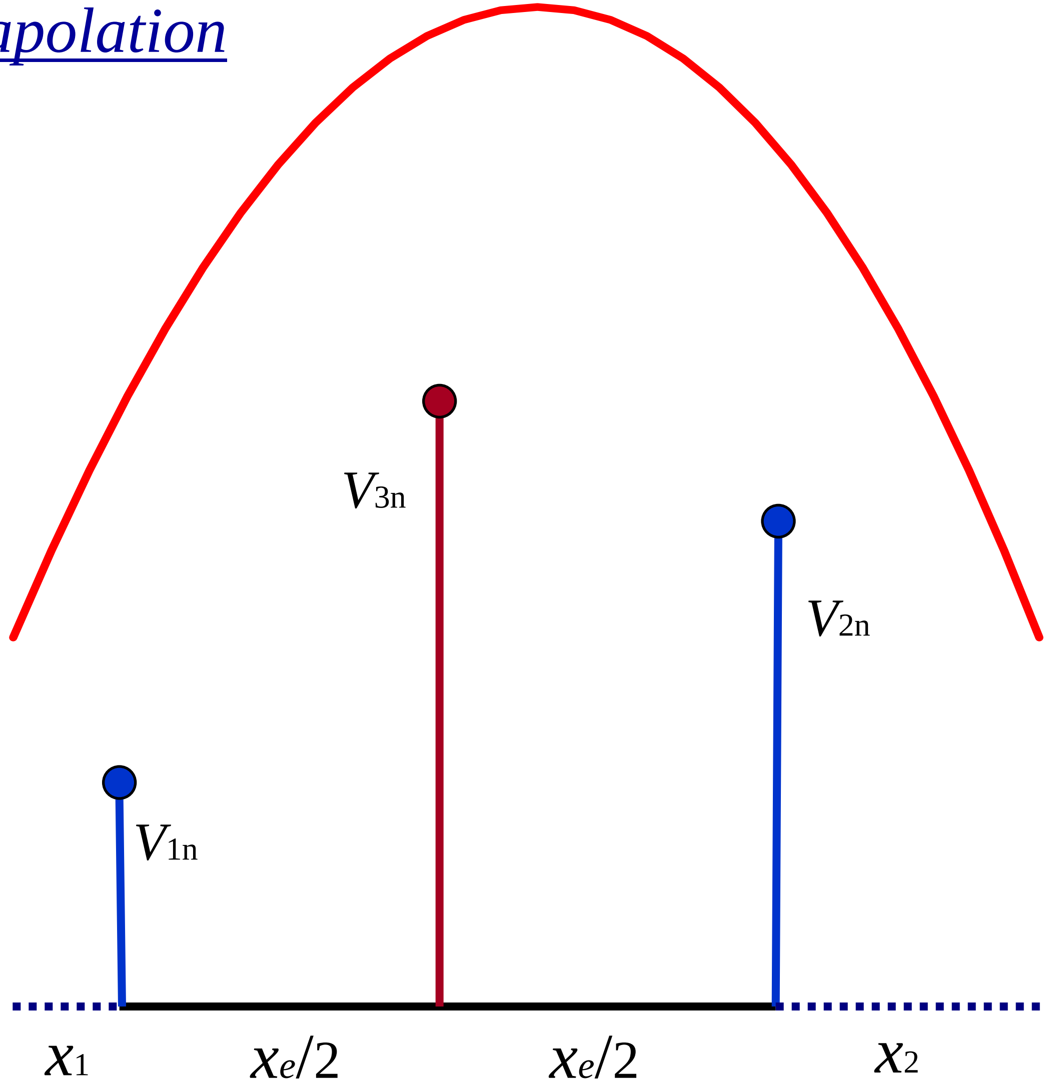
At Bus 1, $a_1 = \frac{x_e + x_2}{x_1 + x_e + x_2} \longrightarrow V_{n,\,Bus1} = A(a_1 - a_1^2)\Delta\delta(t^*)$

$$\frac{V_{n,\,Bus2}}{V_{n,\,Bus1}} = \frac{a_2(1-a_2)}{a_1(1-a_1)}$$

- Need one more equation
  - hence, need one more measurement at a known distance $\longrightarrow \frac{V_{n,\,Bus3}}{V_{n,\,Bus1}} = \frac{a_3(1-a_3)}{a_1(1-a_1)}$

Reactance Extrapolation

$V_n(a) = A\,a\,(1 - a)$



Key idea: Exploit the spatial variation of phasor outputs

IME: Method *(Inertia Estimation)*

- From linearized model

$$f_s = \frac{1}{2\pi}\sqrt{\frac{E_1 E_2 \cos(\delta_0)\Omega}{2H(x_e + x_1 + x_2)}}$$

where f_s is the measured swing frequency and $H = \frac{H_1 H_2}{H_1 + H_2}$

- For a second equation in H_1 and H_2, use *law of conservation of angular momentum*

$$2H_1\omega_1 + 2H_2\omega_2 = 2\int (H_1\dot{\omega}_1 + H_2\dot{\omega}_2)dt = \int (P_{m1} - P_{e1} + P_{m2} - P_{e2})\,dt = 0$$

$$\Rightarrow \boxed{\frac{H_1}{H_2} = -\frac{\omega_2}{\omega_1}}$$

- However, ω_1 and ω_2 are not available from PMU data,

→ Estimate ω_1 and ω_2 from the measured frequencies ξ_1 and ξ_2 at Buses 1 and 2

IME: Method *(Inertia Estimation)*

- Express *voltage angle θ* as a function of δ, and differentiate wrt time to obtain a relation between the machine speeds and bus frequencies:

$$\xi_1 = \frac{a_1\omega_1 + b_1(\omega_1 + \omega_2)\cos(\delta_1 - \delta_2) + c_1\omega_2}{a_1 + 2b_1\cos(\delta_1 - \delta_2) + c_1}$$

$$\xi_2 = \frac{a_2\omega_1 + b_2(\omega_1 + \omega_2)\cos(\delta_1 - \delta_2) + c_2\omega_2}{a_2 + 2b_2\cos(\delta_1 - \delta_2) + c_2}$$

where,

$$a_i = E_1^{\ 2}(1-r_i)^2, \quad b_i = E_1E_2r_i(1-r_i),$$

$$c_i = E_2^{\ 2}r_i^{\ 2}$$

- ξ_1 and ξ_2 are measured, and a_i, b_i, c_i are known from reactance extrapolation.

- Hence, we calculate ω_1/ω_2 to solve for H_1 and H_2 .

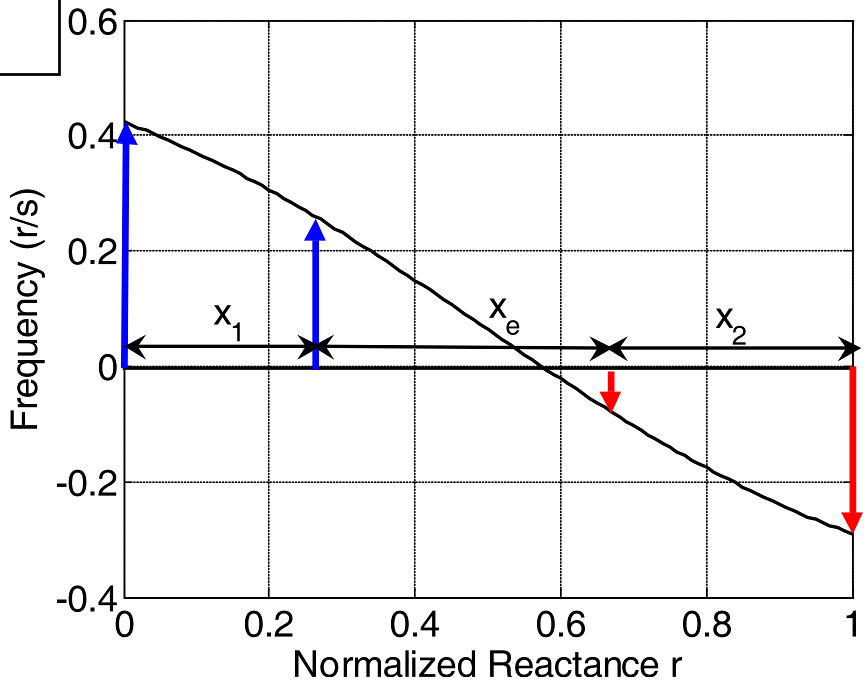
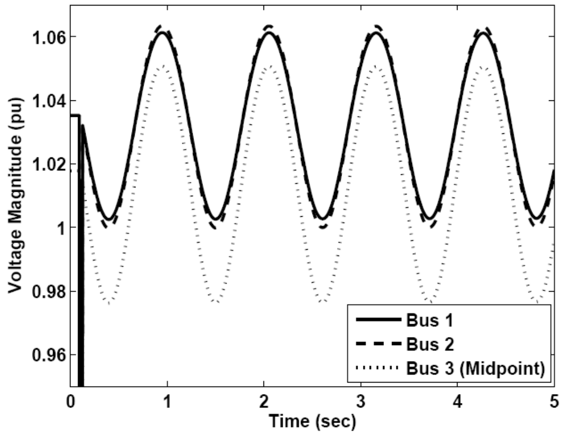


Illustration: 2-Machine Example

- Illustrate DME on classical 2-machine model
- Disturbance is applied to the system and the response simulated in MATLAB



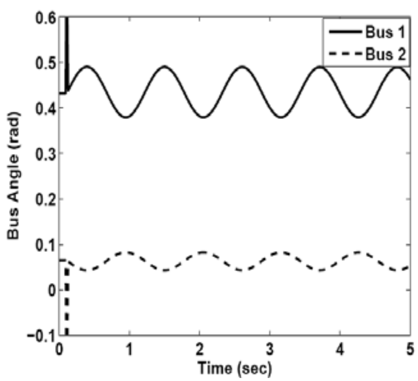
Voltage oscillations at 3 buses

$$V_{1m} = 0.0292 \quad V_{2m} = 0.0316 \quad V_{3m} = 0.0371$$
$$V_{1ss} = 1.0320 \quad V_{2ss} = 1.0317 \quad V_{3ss} = 1.0136$$
$$V_{1n} = 0.0301 \quad V_{2n} = 0.0326 \quad V_{3n} = 0.0376$$

DME Algorithm

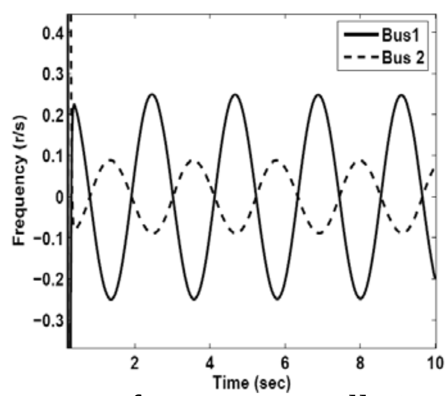
$x_1 = 0.3382$ pu
$x_2 = 0.3880$ pu

Exact values:
$x_1 = 0.34$ pu,
$x_2 = 0.39$ pu



Bus angle oscillations

$$G(s) = \frac{s}{sT+1}$$



Bus frequency oscillations

DME

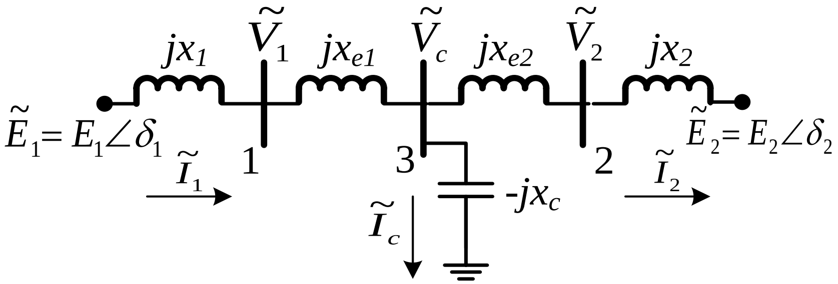
$H_1 = 6.48$ pu
$H_2 = 9.49$ pu

Exact values: $H_1 = 6.5$ pu,
$H_2 = 9.5$ pu

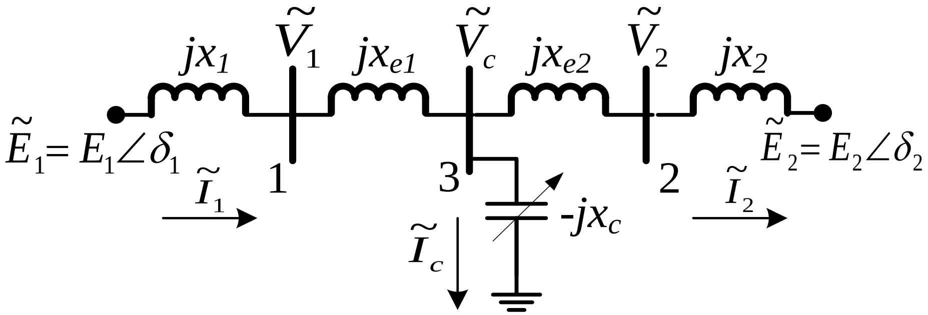
IME for Complex System Topologies

• Intermediate voltage support

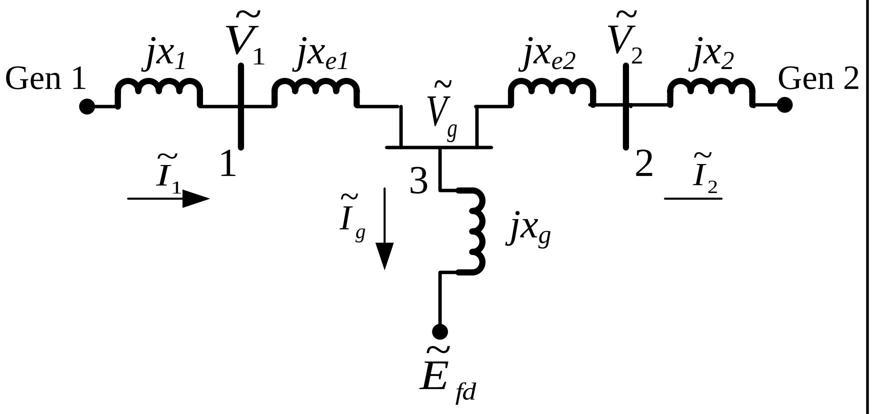
Shunt Capacitance



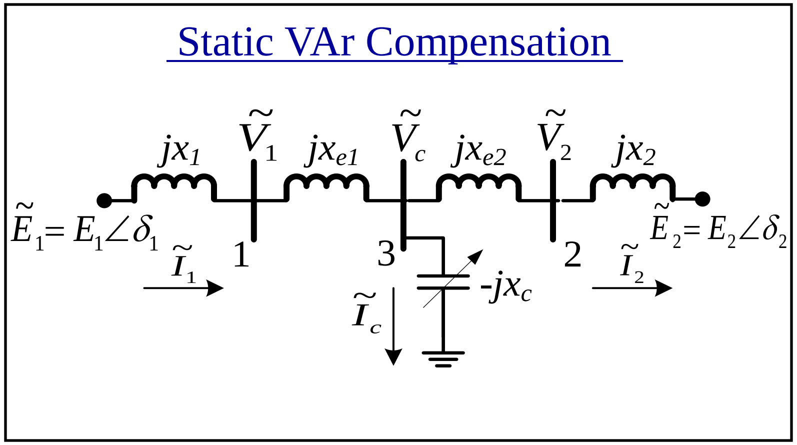
Static VAr Compensation



Generator Support



IME for Complex System Topologies

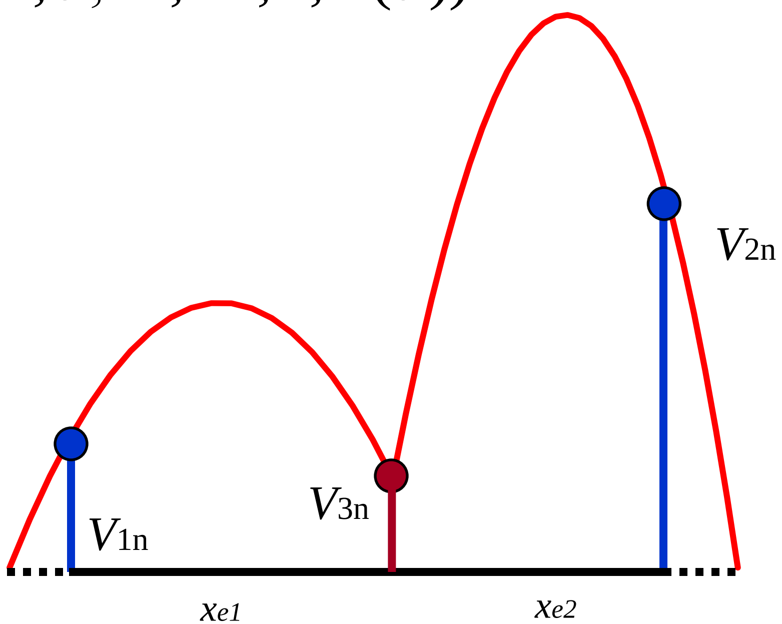


- $\dot{B} = -\frac{B}{\tau} + \frac{k}{\tau}(V_r - V_c), \qquad B = \frac{1}{x_c}$
- $B = k(V_r - V_c)$ (assuming τ is small)
- $\tilde{V}_c = f_3(E_1, E_2, \delta, x_{e1}, x_{e2}, x_c(V_c))$

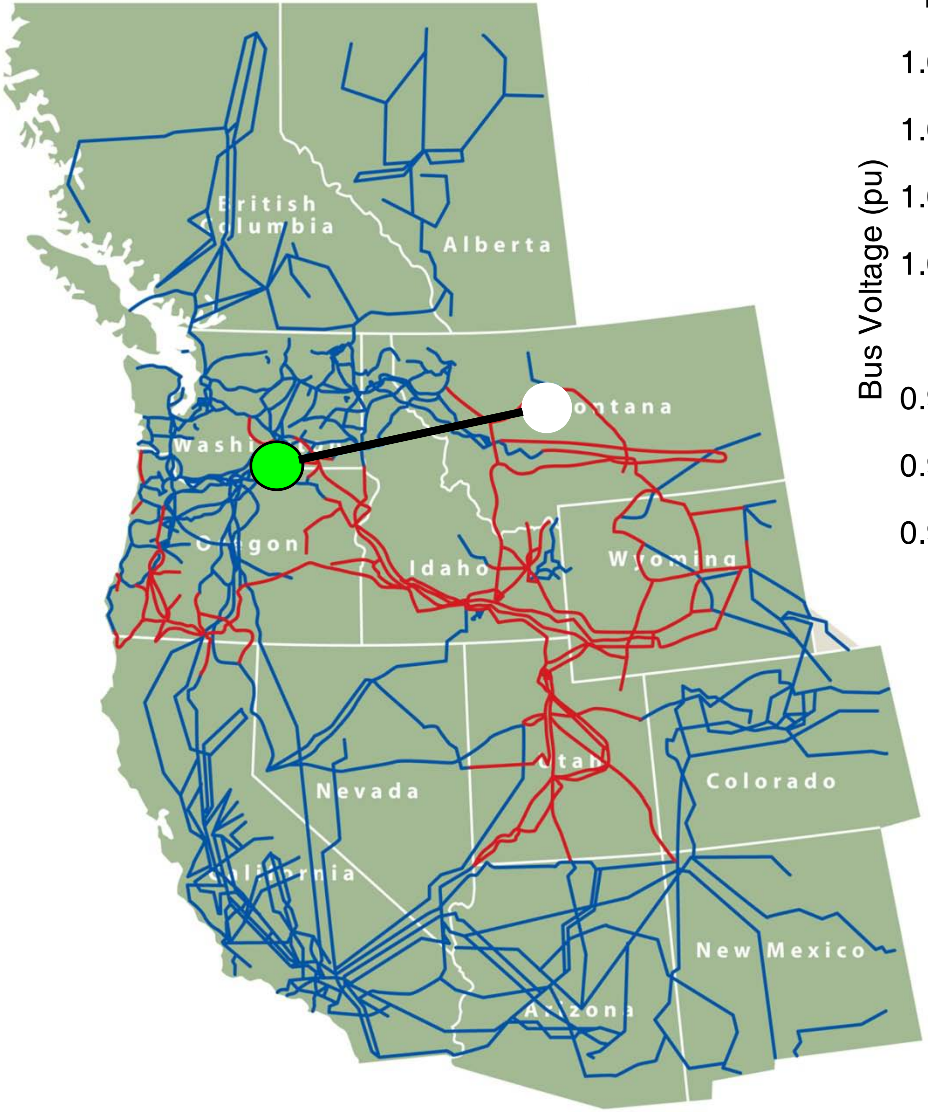
  → solve for a quadratic in $V_c(\delta)$

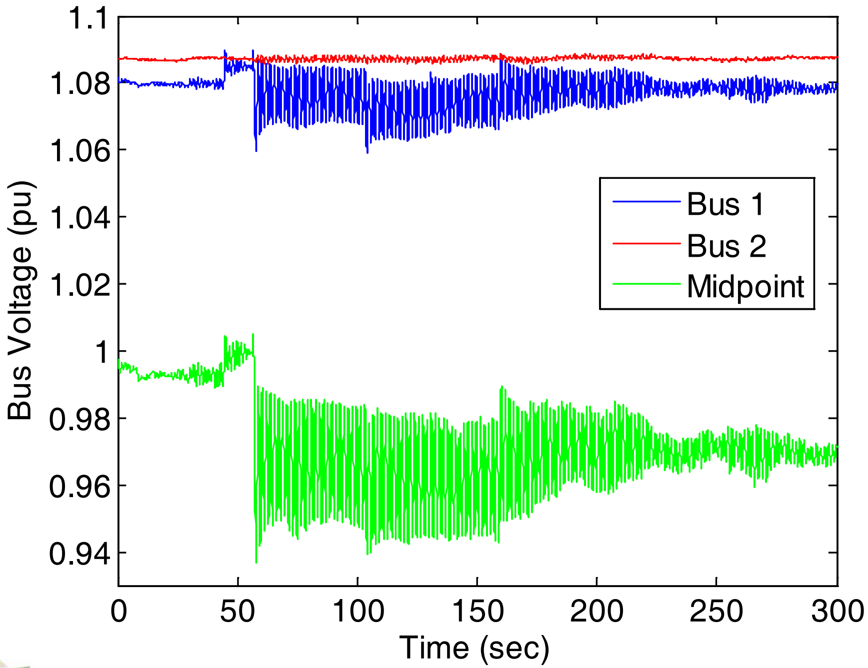
  → $B = k(V_r - V_c(\delta))$

- $\left|\tilde{V}(x)\right| = f_4(E_1, E_2, \delta, x_{e1}, x_{e2}, x, B(\delta))$ → extra terms in V_n



Application to WECC Data





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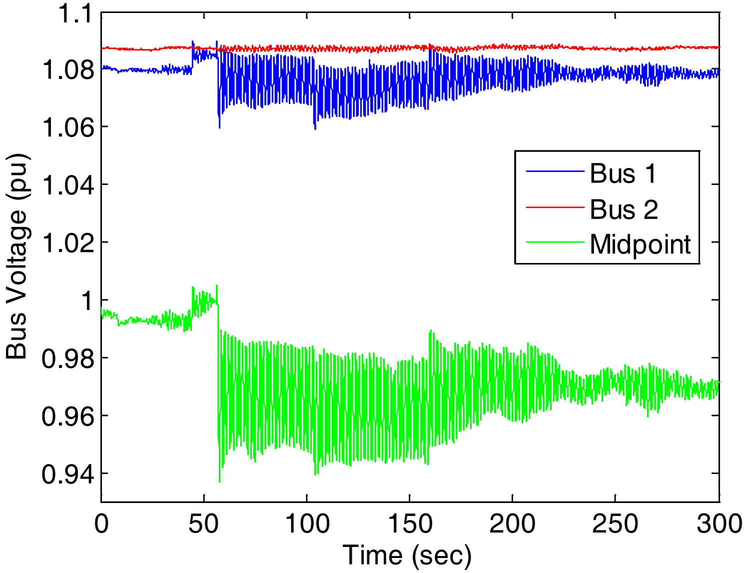
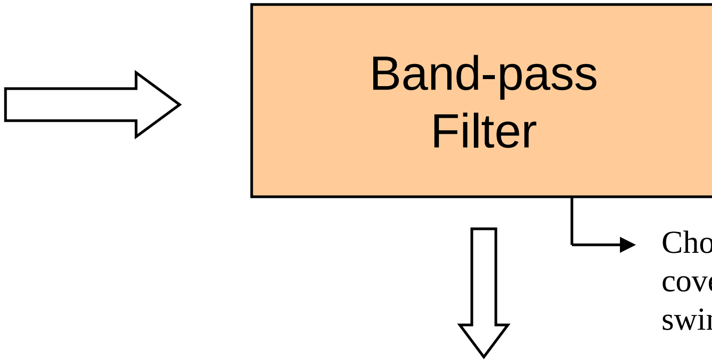
Needs processing to get usable data

- Sudden change/jump
- Oscillations
- Slowly varying steady-state (governer effects)

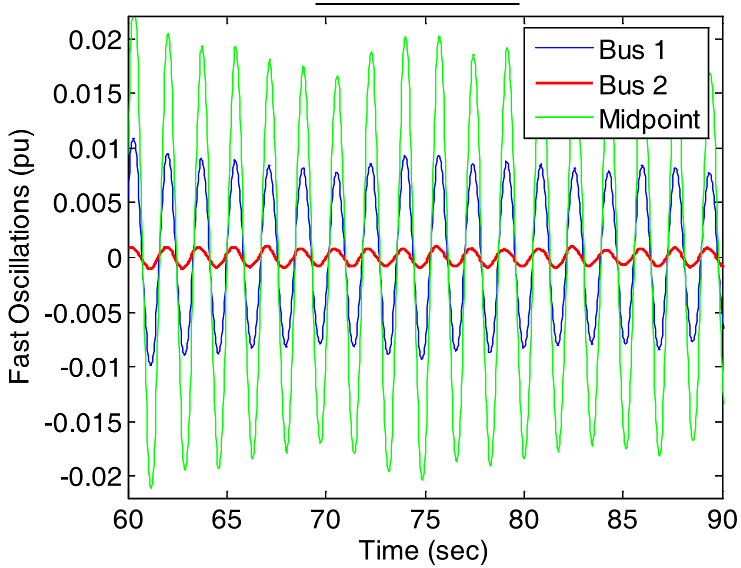
WECC Data





Choose pass-band covering typical swing mode range

Oscillations



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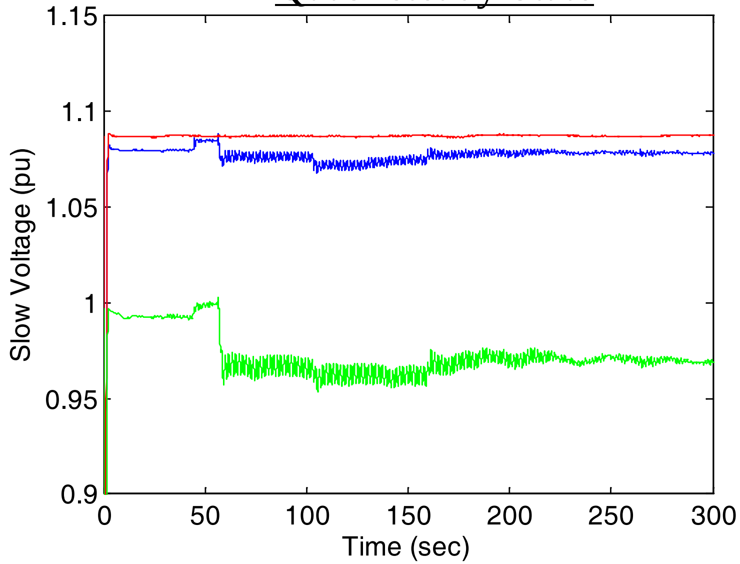
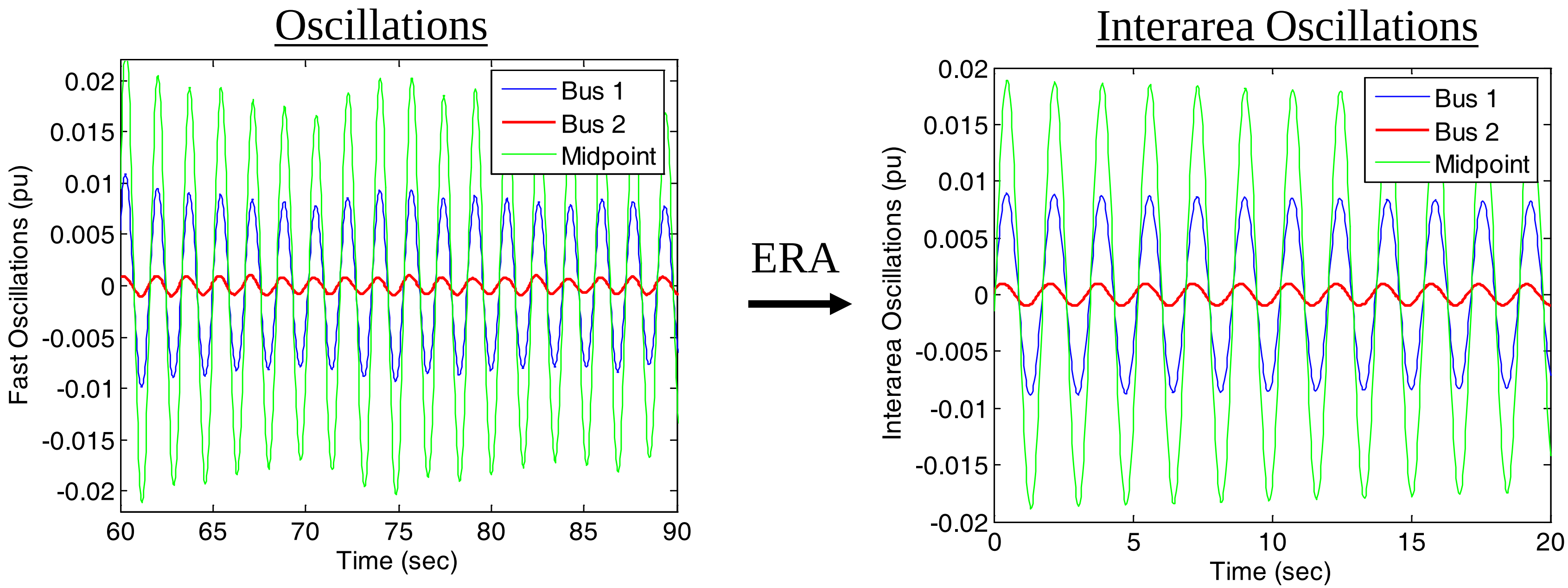
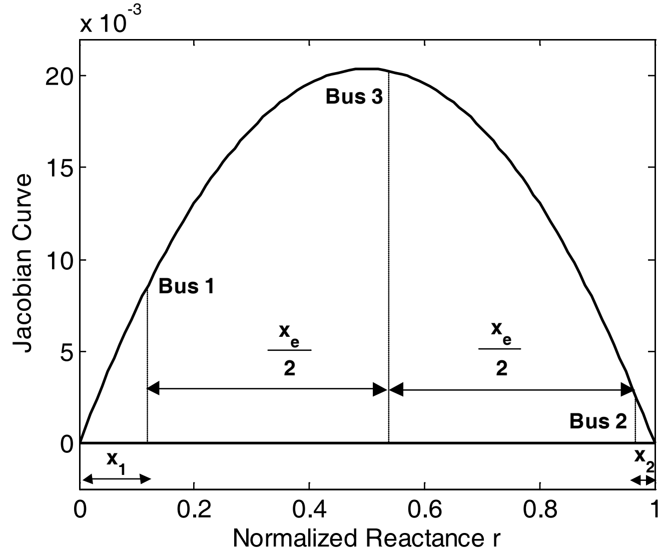
Quasi-steady State



WECC Data



- Can use modal identification methods such as: *ERA*, *Prony*, *Steiglitz-McBride*



Conclusions

- We developed novel methods for model identification and reduction of two-area power systems to represent interarea dynamics
  - spatial variation patterns of phasor variables are exploited

- Fast sampled *dynamic phasor measurements* are used for building these tools

- Both with and without voltage support cases are considered

- Appropriate signal processing tools are developed

- The method enables better estimation of energy margins, better estimation of wave speeds, easier design of PSS, etc.

Thank You