Estimation of electromechanical modes in power systems using system identification techniques

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The work has been carried in collaboration between:

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– Laboratoire Ampere UMR CNRS 5005: Xavier Bombois
– STATNETT SF: L. Vanfretti
Outline

- Electric power systems
- Electromechanical oscillations (modes)
- Basic principles of mode estimation
- Optimal probing signal design for mode estimation
- Optimal signal selection for ambient mode estimation
- Practical implementation
Electric power systems

”The largest and most complex machine ever built by humankind”

- Generation (Thermal and hydro power plants, renewables)
- Transmission (High voltage grid – electric power highways)
- Distribution (Medium and low voltage grid – local roads)
- Consumers
Electromechanical oscillations

Generators or rotating masses

Transmission grid or elastic shaft

System frequency
Oscillations
Need for the oscillation monitoring

February 19th 2011 – North-South Inter-Area Oscillation

Oscillations if lightly damped can lead to a system black-out.

Oscillations occupy transmission capacities and increase losses.

Continuously monitor frequency and damping.
Types of power system dynamic responses

$H(s) = k \frac{(s - z_1)(s - z_2)\ldots(s - z_m)}{(s - p_1)(s - p_2)\ldots(s - p_n)}$

$p_i$ (frequency and damping ratio)
Algorithms for measurement based mode estimation

- **Transient response:**
  - Prony, ERA, Pencil Matrix
  - Well established
  - Good accuracy
  - Not suitable for real-time monitoring

- **Ambient and probing:**
  - SysID and signal processing algorithms
  - Suitable for real-time monitoring
  - Lower accuracy
Ambient based mode estimation

• Assumptions:
  – The system operates in **quasi steady state** period
  – Behavior of the system is modeled by a **linear model**
  – System is excited only by **small load changes** modeled as **white noise**

- **Power System**
  - $H(j\omega)$

- **Measurements**

- **Load Changes**

- **The model of measured stochastic signal is determined by a model set and set of parameters. Most common model set is:**

$$H(z) = \frac{B(z)}{A(z)} = \frac{\sum_{k=0}^{q} b_k z^{-k}}{1 + \sum_{k=0}^{p} a_k z^{-k}}$$

$$\min_{\theta} \frac{1}{N} \sum_{t=1}^{N} \varepsilon(t, \theta)^2$$

$$\varepsilon(t, \theta) = y(t) - \hat{y}(t|t-1)$$
Probing based mode estimation

Power system

\[ \frac{dx}{dt} = Ax + Bu \]
\[ y = Cx + Du \]

Inputs
(lode noise)

Deterministic signal

Outputs
(PMUs)

Probing signals

- FACTS devices
- AVR
- Turbine governors

Exactly known excitation brings new information that can be used for improved mode identification
Difference between ambient and probing based mode estimation

• Model of the system determined as a solution of the optimization problem

\[
\min_{\theta} \frac{1}{N} \sum_{t=1}^{N} \varepsilon(t, \theta)^2 \quad \varepsilon(t, \theta) = y(t) - \hat{y}(t|t-1)
\]

• In case of probing, the model is:

\[
y(t) = \frac{B(z, \theta)u(t)}{A(z, \theta)} + \frac{C(z, \theta)}{D(z, \theta)}e(t)
\]

• ARMAX
• Box Jenkins
Parameter covariance matrix

- The goal is to identify the critical damping ratio of G(z)
- The critical damping ratio is a parameter of G(z) (element of θ)

\[
P^{-1}_θ = \left( \frac{N}{σ^2} \right) \left[ \frac{1}{2π} \int_{-π}^{π} F_u(ω, θ_0)F_u^*(ω, θ_0)Φ_u(ω)dω \right] + \left( \frac{N}{2π} \int_{-π}^{π} F_e(ω, θ_0)F_e^*(ω, θ_0)dω \right)
\]

**How should the probing signal look like??**

1) Length
2) Frequency spectrum
3) Time domain
Global algorithm (two steps)

- Spectrum calculation (LMI optimization)
- Time domain signal realization
  - FIR filter
  - Sample autocorrelation optimization
  - Multi-sine input signal
Requirements:
1) Control effort  2) System disturbance  3) Accuracy

Opt. criterion: \[ \min_{u(t)} J = \left( \frac{k_1}{2\pi} \int_{-\pi}^{\pi} \Phi_u(\omega) d\omega \right) + \left( \frac{k_2}{2\pi} \int_{-\pi}^{\pi} |G(s)|^2 \Phi_u(\omega) d\omega \right) \]

Spectrum parameterization:
1) \[ \Phi_u(\omega) = \sum_{r=-m}^{m} c_r e^{j\omega r} \]
2) \[ \Phi_u(\omega) = \frac{\pi}{2} \sum_{r=1}^{M} A_r^2 \delta(\omega - \omega_r) + A_r^2 \delta(\omega + \omega_r) \]

Constraint: \[ \text{var}(\zeta_i) = e_i^T P_{\theta} e_i < r \quad \text{r - tolerance} \]

Keeping in mind:
\[ P_{\theta}^{-1} = \left( \frac{N}{\sigma^2} \frac{1}{2\pi} \int_{-\pi}^{\pi} F_u(\omega, \theta_0) F_u^*(\omega, \theta_0) \Phi_u(\omega) d\omega \right) + \left( \frac{N}{2\pi} \int_{-\pi}^{\pi} F_e(\omega, \theta_0) F_e^*(\omega, \theta_0) d\omega \right) \]
Time domain signal realization

- Optimization based signal realization with constrained amplitude
- Multisine realization with crest factor minimization
- FIR filter signal realization (constant crest factor)
Signal realization with constrained magnitude

- **Power spectrum**
  \[ \Phi_u(\omega) = \sum_{r=-m}^{m} c_r e^{j\omega r} \]

- **Sample autocorrelation**
  \[ ACF_k(\tau) = \frac{1}{k} \sum_{i=\tau+1}^{k} u(i)u(i-\tau) \]

- **Optimization**
  \[ \min_{u(k)} \sum_{\tau=0}^{M+K} (ACF_k(\tau) - ACF_{des}(\tau))^2 \]

- **Efficient recursive algorithm**
  - Sample by sample
  - Every sample result of a simple optimization problem
Multisine signal realization

- Multisine signal:  \( u(t) = \sum_{r=1}^{M} A_r \cos(\omega_r t + \varphi_r) \)

- Two variables that describe multisine
  - Amplitude
  - Phase

- Crest factor:
  \[
  Cr\{u(t)\} = \frac{\max\{|u(t)|\}}{\text{rms}\{u(t)\}} = \frac{\max\{|u(t)|\}}{\sqrt{\frac{1}{2\pi} \int_{-\pi}^{\pi} \Phi_u d\omega}} = \frac{\max\{|u(t)|\}}{\sqrt{\text{var}\{u(t)\}}}
  \]

- Crest factor minimization algorithm

Diagram:
- Initial random phases
- Cut the peaks
- FFT
- Take the phases
- Construct the signal
- Crest improved
- Yes
- END
FIR signal realization

- $y(t) = h(t) * e(t)$ where $e(t)$ is a white noise
- Convenient realization- only random number generator required
- FIR filter determined by spectral factorization from autocorrelation coefficients

$$
\Phi_u(\omega) = \sum_{r=-m}^{m} c_r e^{j\omega r}
$$

Optimal probing signal design results

Input spectrum parameterization

<table>
<thead>
<tr>
<th></th>
<th>White noise</th>
<th>Multi-sine</th>
<th>FIR filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{var}{u(t)} )</td>
<td>10410.0</td>
<td>1441.58</td>
<td>1933.55</td>
</tr>
<tr>
<td>( \text{var}{y(t)} )</td>
<td>1.6761</td>
<td>1.598</td>
<td>1.5515</td>
</tr>
<tr>
<td>( \text{var}{uy(t)} )</td>
<td>6881.10</td>
<td>2318.81</td>
<td>2518.24</td>
</tr>
</tbody>
</table>
Optimal signal selection for mode estimation

- **Optimality criterion** is the variance of the estimate

\[ P_{\theta}^{-1} = \frac{NN}{2\pi^2} \int_{-\pi}^{\pi} \left( \phi_{\theta} F_e^*(\omega, \theta_0) \Phi_u(\omega) d\omega \right) + \frac{N}{2\pi} \int_{-\pi}^{\pi} F_e(\omega, \theta_0) F_e^*(\omega, \theta_0) d\omega \]

Compute asymptotic variance for each measured signal

Rank the signals

Select the top ones
Optimal signal selection results

Voltage magnitudes

Voltage angles
• Power system or real-time simulator
• Phasor measurement units (PMUs).
• Phasor data concentrator (PDC) - aggregator.
• Communication Network: composed by routers/switches, fiber optic links (or other medium)
• Software Development Kit (SDK)
Application example - ambient mode estimator

- Real-life data
- The critical mode is at 0.39 Hz with damping ratio 9% (in average)
- Other modes are observable at 0.2 Hz, 1 Hz and 1.4 Hz
- 0.5 Hz mode sporadically appears as a poorly damped mode
Conclusions

• Monitoring or electromechanical modes is important
• Staged experiments (probing) can provide good accuracy
• Probing signal has to be carefully designed
• In case of ambient mode estimation, signals used have to be carefully selected
• Testing of the mode estimation tools need to include others components of the system
Thank you!

Questions?

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