Forced oscillations identification from partial PMU coverage in high-voltage grids

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Delabays, Lokhov, MT, Vuffray, PRX Energy **2** (2), 023009 (2023).
MT, Lokhov, Vuffray, arXiv:2310.00458 (2023).

Modern power grids

Electric power grids

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- Thousands and thousands of components over thousands of kilometers.

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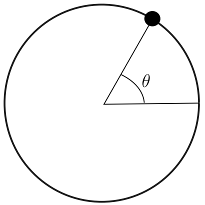
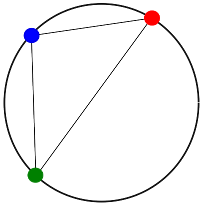
Collective state

Phase oscillators

Single phase oscillator: $\dot{\theta} = \omega$



Coupled phase oscillators: $\dot{\theta}_i = \omega_i - \sum_j a_{ij} f(\theta_i - \theta_j)$



Synchronization: phase-locked $\dot{\theta}_i(t) = \dot{\theta}_j(t)\,,\ \forall i,j\,.$

Coupled Oscillators: Power grids

Second order Kuramoto model

$$m_i\ddot{\theta}_i + d_i\dot{\theta}_i = P_i - \sum_j a_{ij}\sin(\theta_i - \theta_j) + \eta_i \quad , \; i = 1, ..., n.$$

$a_{ij} = a_{ji} \geq 0$.
P_i : natural frequencies.
m_i : inertia.
d_i : damping.

Electric Power Network (in the lossless line approximation)

P_i : injected/consumed power.
$m_i = 0$: loads.
$m_i \neq 0$: generators.
$a_{ij}\sin(\theta_i - \theta_j)$: power flow from i to j .

J. A. Acebrón, L. L. Bonilla, Conrad J. Pérez Vicente, F. Ritort, and R. Spigler, Rev. Mod. Phys. **77**, 137 (2005)
Power system control and stability PM Anderson, AA Fouad - 1977

Coupled Oscillators: Power grids

Second order Kuramoto model

$$m_i\ddot{\theta}_i + d_i\dot{\theta}_i = P_i - \sum_j a_{ij}\sin(\theta_i - \theta_j) + \eta_i \ \ , \ i = 1, ..., n.$$

→ power balance to maintain 50/60Hz
`https://fnetpublic.utk.edu/frequencymap.html`

Phasor mesurment units (PMU)

Second order Kuramoto model

$$m_i\ddot{\theta}_i + d_i\dot{\theta}_i = P_i - \sum_j a_{ij}\sin(\theta_i - \theta_j) + \eta_i \;\;,\;\; i = 1, ..., n.$$

Phase and frequency at generators and some other buses

$$\dot{\theta}_i, \theta_i.$$

Forced oscillations

More than 20 large-scale events in the past 30 years. Expected to be more frequent in the future with renewable, inverter-based, and microgrid generation

- Major issue 1: excitation of normal modes can create oscillations far away from source.
  - January 11, 2019 event: faulty turbine in Florida created amplitude of 200 MW at the source, power swings of about 50 MW observed as far as the New England.
  - November 29, 2005 Western American Oscillation event: 20MW forcing in Alberta led to 200 MW oscillations registered on the California-Oregon Interface, thousands of miles away
- Major issue 2: system parameters are unknown to independent system operators beyond their area of responsibility and may also drift over time

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`https://www.eecs.utk.edu/eastern-interconnection-frequency-oscillation-observed/`

Forced oscillations

Second order Kuramoto model

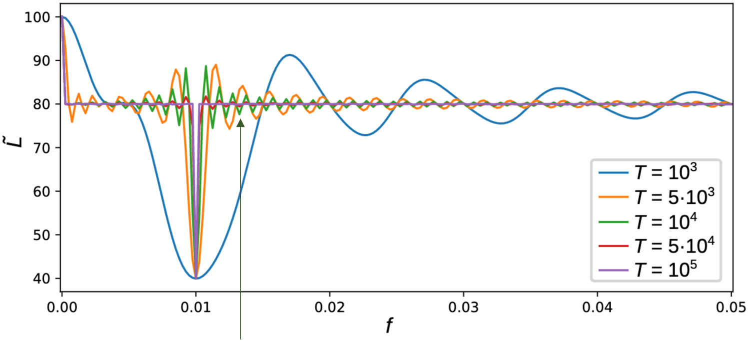
$$m_i\ddot{\theta}_i + d_i\dot{\theta}_i = P_i - \sum_j a_{ij}\sin(\theta_i - \theta_j) \ \ , \ i = 1, ..., n.$$

$\rightarrow$ P_i has a periodic input signal $\gamma \mathbf{e_l} \cos(2\pi(ft+\phi))$.

Forced oscillations

SALO: System-Agnostic Localization of Oscillations

$$\widetilde{L}\left(\boldsymbol{A},\gamma,l,f,\phi \mid \{\boldsymbol{X}_{t_j}\}_{j=1}^{N}\right) = \frac{1}{N}\sum_{j=0}^{N-1}\left\|\boldsymbol{\Delta}_{t_j} - \boldsymbol{A}\boldsymbol{X}_{t_j} - \gamma\boldsymbol{e}_l\cos(2\pi i(ft_j+\phi))\right\|^2$$



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SALO: System-Agnostic Localization of Oscillations

$$\widetilde{L}\left(\boldsymbol{A},\gamma,l,f,\phi \mid \{\boldsymbol{X}_{t_j}\}_{j=1}^{N}\right)$$ → Hard to optimize over f

↓ finite resolution in frequencies

$$L\left(\boldsymbol{A},\gamma,l,k,\phi \mid \{\boldsymbol{X}_{t_j}\}_{j=1}^{N}\right)$$ → Many local minima for each k

↓ optimization over ϕ

$$L_{SALO}\left(\boldsymbol{A},\gamma,l,k \mid \{\boldsymbol{X}_{t_j}\}_{j=0}^{N-1}\right)$$ → Single minimum for each k

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SALO: System-Agnostic Localization of Oscillations

$$\frac{1}{N}\sum_{j=0}^{N-1}\left\|\boldsymbol{\Delta}_{t_j}-\boldsymbol{A}\boldsymbol{X}_{t_j}-\gamma\boldsymbol{e}_l\cos(2\pi i(ft_j+\phi))\right\|^2$$

→ Hard to optimize over f

↓ finite resolution in frequencies

$$\frac{1}{N}\sum_{j=0}^{N-1}\left\|\boldsymbol{\Delta}_{t_j}-\boldsymbol{A}\boldsymbol{X}_{t_j}-\gamma\boldsymbol{e}_l\mathrm{Re}\left(e^{2\pi i(\frac{k}{N}j+\phi)}\right)\right\|^2$$

→ Many local minima for each k

↓ optimization over ϕ

$$\mathrm{Tr}(\boldsymbol{A}^\top\boldsymbol{A}\Sigma_0)-2\mathrm{Tr}(\boldsymbol{A}\Sigma_1)+\frac{1}{2}\gamma^2-\frac{2\gamma}{\sqrt{N}}\sqrt{\mathrm{Tr}\left(\boldsymbol{A}_{l,\cdot}^\top\boldsymbol{A}_{l,\cdot}F(k)\right)-2f_l(k)\boldsymbol{A}_{l,\cdot}+g_l(k)}$$

→ Single minimum for each k

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Forced oscillations

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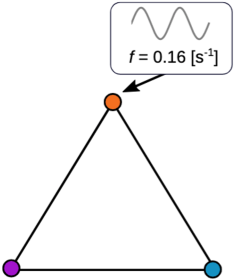

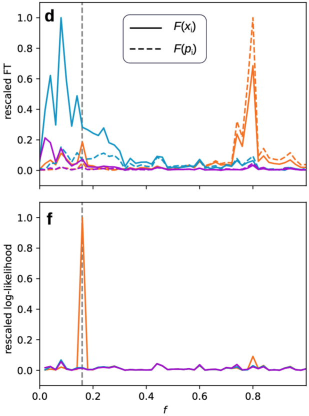

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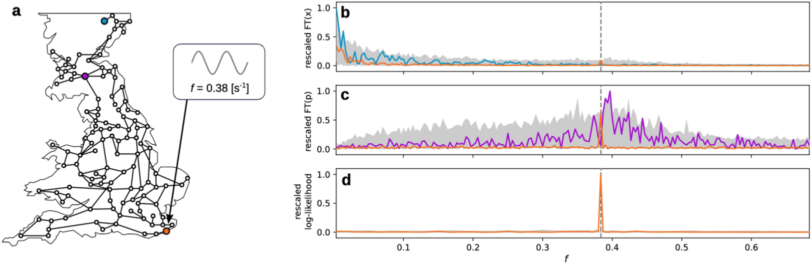

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Reduced dynamics

Differential and algebraic equations:

$$m_i\ddot{\theta}_i + d_i\dot{\theta}_i = P_i - \sum_j a_{ij}(\theta_i - \theta_j) + \eta_i^g \,, i \in \mathcal{G} \quad (1)$$

$$0 = P_i - \sum_j a_{ij}(\theta_i - \theta_j) + \eta_i^l \,, i \in \mathcal{L} \,, \quad (2)$$

$\eta_i^{g,l}$: i.i.d. Gaussian.

MT, Lokhov, Vuffray, arXiv:2310.00458 (2023).

Reduced dynamics

Laplacian matrix:

$$L_{ij} = \begin{cases} -a_{ij} & i \neq j \\ \sum_k a_{ik} & i = j \end{cases} \tag{3}$$

$$\mathbf{L} = \begin{bmatrix} \mathbf{L}^{gg} & \mathbf{L}^{gl} \\ \mathbf{L}^{lg} & \mathbf{L}^{ll} \end{bmatrix} . \tag{4}$$

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Kron reduction:

$$\mathbf{L}^{r} = \mathbf{L}^{gg} - \mathbf{L}^{gl}(\mathbf{L}^{ll})^{-1}\mathbf{L}^{lg} . \tag{5}$$

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Noise:

$$\eta^{gl} = \eta^{g} - \mathbf{L}^{gl}(\mathbf{L}^{ll})^{-1}\eta^{l} . \tag{6}$$

Reduced dynamics

Generators dynamics

$$\begin{bmatrix} \dot{\theta}^g \\ \ddot{\theta}^g \end{bmatrix} = \begin{bmatrix} 0 & \mathbf{I} \\ \mathbf{M}^{-1}\mathbf{L}^r & \mathbf{M}^{-1}\mathbf{D} \end{bmatrix} \begin{bmatrix} \theta^g \\ \dot{\theta}^g \end{bmatrix} + \begin{bmatrix} 0 \\ \eta^{gl} \end{bmatrix} + \begin{bmatrix} 0 \\ \mathbf{F} \end{bmatrix} \tag{7}$$

$\mathbf{F} = \gamma\, \mathbf{e}_l \cos(2\pi(ft + \phi))$ with $l \in \mathcal{G}$

$\mathbf{F} = -\gamma\, \mathbf{L}^{gl}\mathbf{L}^{ll^{-1}}\mathbf{e}_l \cos(2\pi(ft + \phi))$ with $l \in \mathcal{L}$.

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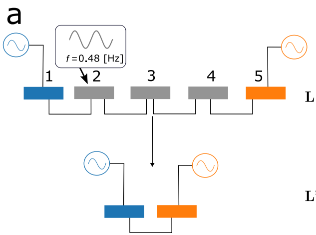
$$\tilde{L}\left(\mathbf{M},\mathbf{D},\gamma,l,k,\phi \mid \{X_{t_j}\}_{j=1}^N,\mathbf{L}^r\right) = -\frac{1}{N}\sum_{j=0}^{N-1}\mathbf{v}_{t_j}^\top\mathbf{\Sigma}^{-1}\mathbf{v}_{t_j}\,, \tag{8}$$

with

$$\mathbf{v}_{t_j} = \mathbf{\Delta}_{t_j} - \mathbf{A}\mathbf{X}_{t_j} - \begin{bmatrix}0\\ \mathbf{F}(k)\end{bmatrix}\,, \tag{9}$$

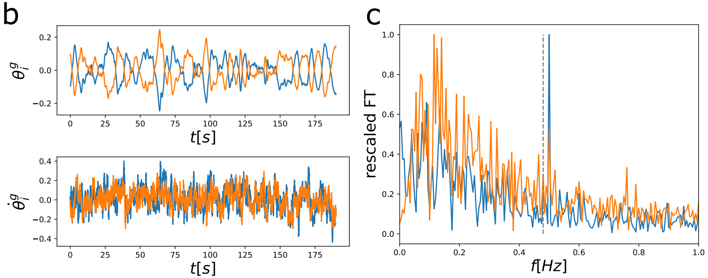
$$\mathbf{\Sigma}^{-1} = \begin{bmatrix}\mathbf{I} & 0\\ 0 & (\sigma^2\left[\mathbf{I} + \mathbf{L}^{gl}(\mathbf{L}^{ll})^{-2}\mathbf{L}^{lg}\right])^{-1}\end{bmatrix}\,. \tag{10}$$

Toy example



$$\mathbf{L} = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 2 & 1 & 1 & 0 \\ 0 & -1 & 2 & -1 & 0 \\ 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

$$\mathbf{L}^r = \frac{1}{4}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$$



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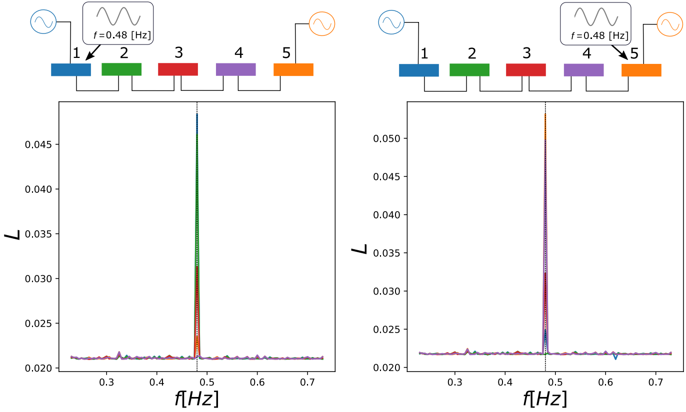

f = 0.48 [Hz]
1
2
3
4
5
L
0.045
0.040
0.035
0.030
0.025
0.020
0.3
0.4
0.5
0.6
0.7
f[Hz]
f = 0.48 [Hz]
1
2
3
4
5
L
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0.035
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0.4
0.5
0.6
0.7
f[Hz]

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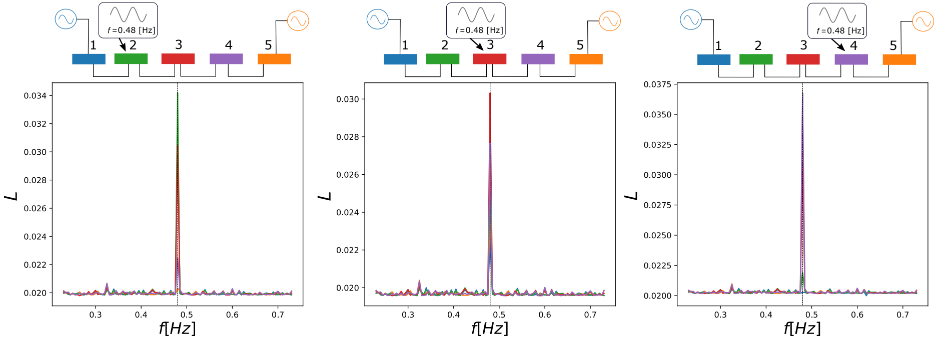
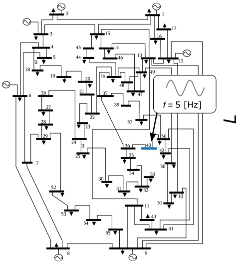
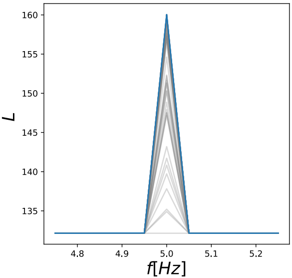
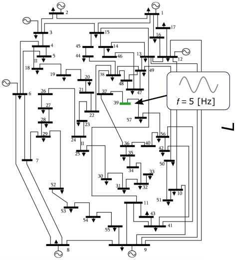
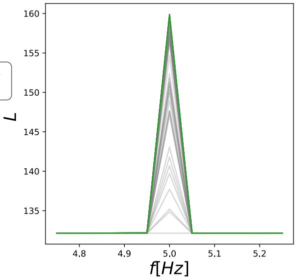


IEEE-57 bus test case









Conclusion and future work

So far

- Identification of forced oscillations in high-voltage grids.

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Conclusion and future work

So far

- Identification of forced oscillations in high-voltage grids.

Ongoing and future

- Other types of perturbations or attacks.
- Reconstruction of grid paramters from partial observation.
- Sensor valuation.

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