

A Complex LASSO-Approach for Localizing Forced Oscillations in Power Systems

A brief reiteration

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Introduction

Forced Oscillations in Power Systems

Natural Oscillations	Forced Oscillations
natural	forced
natural	forced
natural	forced



Theory

State Space Representation

Express Power System Dynamics in State Space:

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \underset{n \times 1}{\mathbf{A}} \underset{n \times n}{\mathbf{x}}(t) + \underset{n \times m}{\mathbf{B}} \underset{m \times 1}{\mathbf{u}}(t) \\ \mathbf{y}(t) &= \underset{b \times 1}{\mathbf{C}} \underset{b \times n}{\mathbf{x}}(t) \\ \forall t &\geq 0\end{aligned}\tag{1}$$

$\mathbf{x}(t)$: internal state variables + controller variables vector
 $n \times 1$

$\mathbf{u}(t)$: forced oscillation vector
 $m \times 1$



Forced Oscillation Vector

Express Forced Oscillations based on locations of origin and signal composition:

$$\underset{m \times 1}{\mathbf{u}(t)} = \underset{m \times 1}{\begin{bmatrix} u_1(t) \\ u_2(t) \\ \vdots \\ u_m(t) \end{bmatrix}} = \underset{m \times 1}{\begin{bmatrix} \sum_{l=1}^{M_1} a_{1,l} \sin(\omega_{1,l}t + \phi_{1,l}) \\ \sum_{l=2}^{M_2} a_{2,l} \sin(\omega_{2,l}t + \phi_{2,l}) \\ \vdots \\ \sum_{l=m}^{M_m} a_{m,l} \sin(\omega_{m,l}t + \phi_{m,l}) \end{bmatrix}} \quad (2)$$

$$a_{r,l} \geq 0$$

$$\omega_{r,l} = 2\pi f \geq 0$$

(r, l) refer to the l^{th} sinusoid at the r^{th} location



Sparsity Assumption

Let $\mathbf{a}_r(t)$ be the vector representation of the sinusoids at the r^{th} location.

$$\underset{1 \times M_r}{\mathbf{a}_r(t)} = \left[\underset{1 \times M_r}{a_{r,1} \sin(\omega_{r,1}t + \phi_{r,1})} \quad \dots \quad a_{r,M_r} \sin(\omega_{r,M_r}t + \phi_{r,M_r}) \right]$$

Assumption 1: Both $\mathbf{u}(t)$ and $\mathbf{a}_r(t)$ are sparse vectors. That implies most locations are FO free and for the locations that do have FO, the number of distinct sinusoidal components of the local FO is small.



Discrete State Space Representation

Most PMUs sample at 30Hz or 60Hz. So the sampling time period is $T = 1/30\text{s}$ or $1/60\text{s}$.

Let $\underset{n \times n}{\mathbf{A}_d} = \exp(\mathbf{A}T)$ and $\underset{n \times m}{\mathbf{B}_d} = \{\int_0^T \exp(\mathbf{A}(T-s))ds\}\mathbf{B}$.

Let $k = 0, 1, \dots$ and define $\mathbf{x}[k] \triangleq \mathbf{x}(kT)$, $\mathbf{u}[k] \triangleq \mathbf{u}(kT)$ and $\mathbf{y}[k] \triangleq \mathbf{y}(kT)$. Suppose that $\mathbf{u}(t)$ is piece-wise constant during $kT \leq t \leq (k+1)T$. Then

$$\begin{aligned} \underset{n \times 1}{\mathbf{x}[k+1]} &= \underset{n \times n}{\mathbf{A}_d} \underset{n \times 1}{\mathbf{x}[k]} + \underset{n \times m}{\mathbf{B}_d} \underset{m \times 1}{\mathbf{u}[k]} \\ \underset{b \times 1}{\mathbf{y}[k]} &= \underset{b \times n}{\mathbf{C}} \underset{n \times 1}{\mathbf{x}[k]} \end{aligned} \tag{3}$$

We assume $\mathbf{x}[0] = 0$ as our focus is only on inputs triggered by FOs.



Introduction to My Work

Transient vs Steady State Stability

Transient Stability

A sudden, out-of-trend, high magnitude change in a state variable(s) causes blackouts.

Chief parameters of concern are ROCOF, frequency nadir, steady-state frequency deviation.

Inertia is a fundamental parameter here.

Steady State Stability

Accumulation of several seemingly minor trends in state variables over time, ultimately leading to a **critical point** where a small change could cause blackouts.

Autocorrelation and covariance are some of the commonly used parameters for prognosis.

Inertia plays a minor role here.



Bifurcations and Critical Slowing Down

Bifurcation: A qualitative change in the 'motion' of a dynamical System due to a quantitative change in one of its parameters. Serious bifurcations, called **Critical Bifurcations**, cause the system to become unstable from stable.



Bifurcations and Critical Slowing Down

Critical Slowing Down: Dynamical Systems exhibit early statistical warning signs before collapsing:

- Increased recovery times from perturbations.
- Increased signal variance from the mean trajectory.
- Increased flicker and asymmetry in the signal

The above three properties can be identified by increasing variance and autocorrelation in time-series measurements taken from the system.



Procedure

- Accessed a bunch of real-world frequency time-series data and plotted their:
 - bulk distribution (pdf)
 - auto-correlation curves
- Obtained explanation for the *signature dynamics* of each grid.



Results

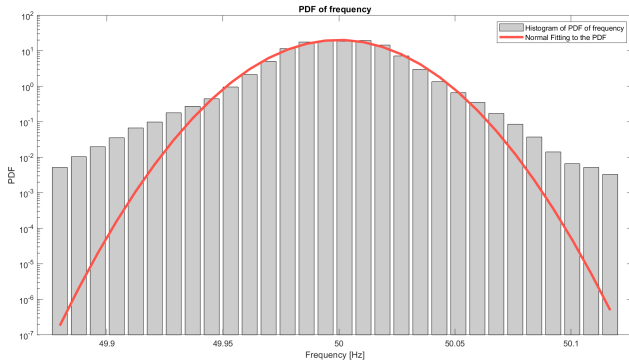


Figure 1: Continental European Grid frequency PDF: Heavier tails than a Gaussian Distribution.



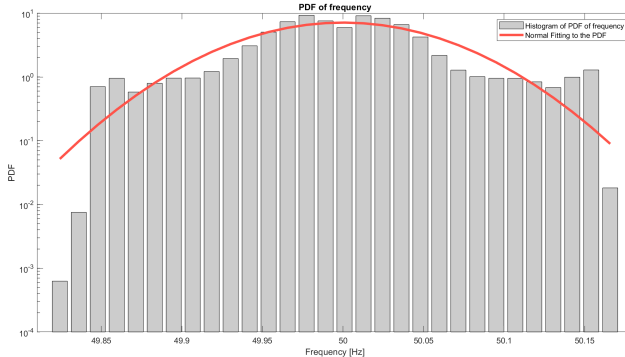


Figure 2: Mallorca (an islanded Spanish grid) frequency pdf



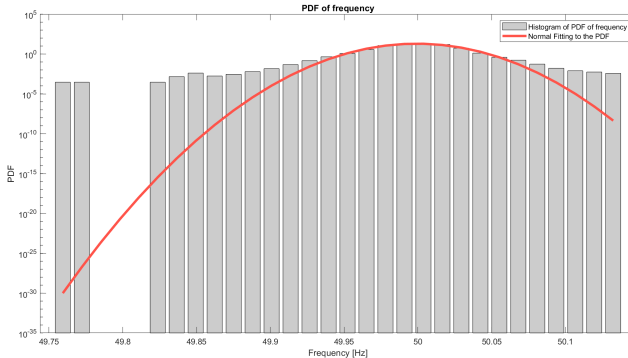


Figure 3: French grid frequency pdf including a blackout



Results

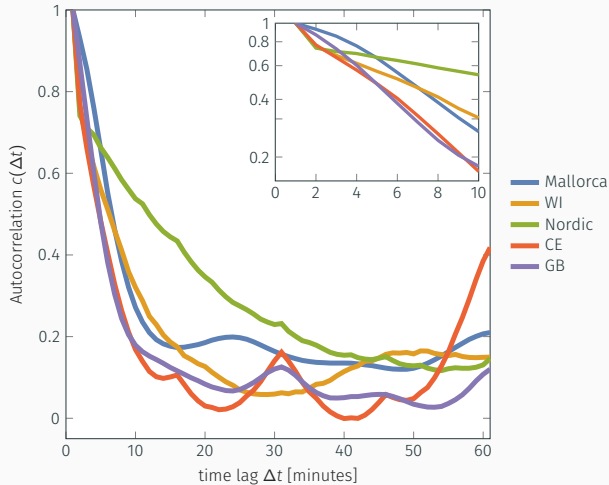


Figure 4: Autocorrelation decay of different synchronous regions.



Table 1: Inverse-correlation values for different grids

Grid name	Inverse-correlation value T^{-1} [min^{-1}]
Mallorca	0.0654
Western Interconnection	0.0498
Nordic	0.0235
Continental Europe	0.0829
Great Britain	0.0879

Figure 5: Inverse correlation time is proportional to the damping constant of the grid.

