HOCHSCHULE FÜR ANGEWANDTE WISSENSCHAFTEN MÜNCHEN

Internal model based grid state estimation

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Outline I

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Introduction

Motivation: The future low-inertia power system—A likely guess [1]

- more distributed generation / renewable energy systems
- diminishing mechanical inertia
- hybrid grid and transmission topologies (e.g. AC & DC)
- more unbalanced faults ($> 75\%$ of faults already today)
- more loosely-coupled & unbalanced micro-grids
- more power electronics

$\Longrightarrow$ Faster dynamics/transients, more harmonics & weaker overall grid!

$\Longrightarrow$ Grid state estimation in real time crucial

$\Longrightarrow$ ... for balancing, harmonics suppression, frequency/voltage support!

Introduction

Problem statement

For measured grid signal (voltage, current or power), given by

$$y(t) := a_0 + \sum_{\nu\in\mathbb{H}_n} \underbrace{a_\nu(t)\cos\big(\phi_\nu(t)\big)}_{=:y_\nu(t)} \quad \text{where} \quad \begin{cases} \mathbb{H}_n := \{1, \nu_2, \ldots, \nu_n\} \subset \mathbb{Q}_{>0} \\ \phi_\nu(t) := \int_0^t \nu\omega(\tau)\,\mathrm{d}\tau + \phi_{\nu,0}, \end{cases} \tag{1}$$

the **main goals** are

(i) signal estimation after *prescribed settling time* $t_{\mathrm{set}} > 0\,\mathrm{s}$ for some $\varepsilon_y > 0$, i.e.

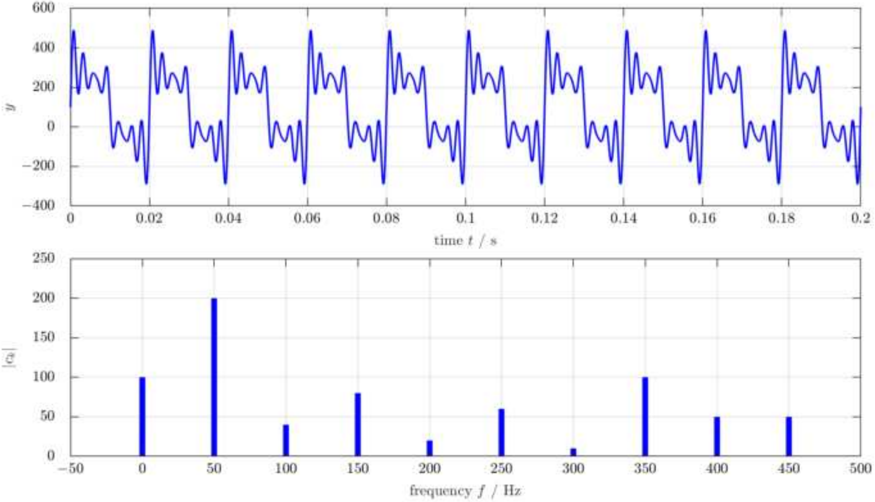
$$\forall t \geqslant t_{\mathrm{set}}: \ |y(t) - \hat{y}(t)| \leqslant \varepsilon_y \quad \text{with} \quad \hat{y}(t) := \hat{a}_0 + \sum_{\nu\in\mathbb{H}_n} \underbrace{\hat{a}_\nu(t)\cos\big(\hat{\phi}_\nu(t)\big)}_{=:\hat{y}_\nu(t)}; \tag{2}$$

(ii) amplitude estimation, i.e. $\hat{a}_0 \to a_0$ and $\hat{a}_\nu \to a_\nu$ for all $\nu \in \mathbb{H}_n$; and

(iii) frequency and angle estimation, i.e. $\hat{\omega} \to \omega$ and $\hat{\phi}_\nu \to \phi_\nu$ for all $\nu \in \mathbb{H}_n$.

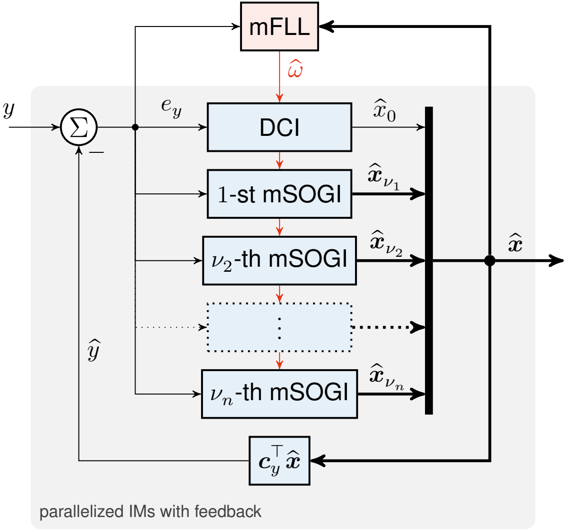
Introduction

Problem statement (illustration)



Introduction

Proposed solution: **Nonlinear observer** consisting of ...



- **DC-integrator (DCI)** for DC offset estimation
- **modified Second-Order-Generalized-Integrators (mSOGIs)** for harmonics estimation
- **modified frequency-locked loop (mFLL)** for frequency estimation

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Internal model principle

Motivation

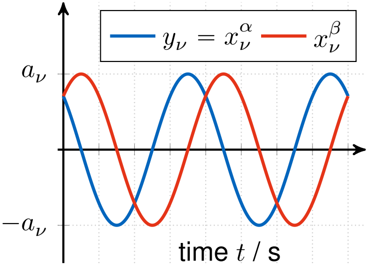
Walter M. Wonham (1985):
"Every good regulator [or observer] must incorporate a model of the outside world being capable to reduplicate the dynamic structure of the exogenous signals which the regulator [or observer] is required to process." [2]

Internal model principle

Example: Sinusoidal signal reduplication of the ν-th harmonic where $\nu \in \mathbb{H}_n$

sinusoidal IM (with initial values)

$$\boldsymbol{x}_{\nu,0} = a_\nu \begin{pmatrix} \cos(\phi_{\nu,0}) \\ \sin(\phi_{\nu,0}) \end{pmatrix} \longrightarrow \boxed{\nu\text{-th IM}_{\mathrm{sin}}} \xleftarrow{\;\omega\;} \quad \boxed{\nu\text{-th IM}_{\mathrm{sin}}} \longrightarrow \boldsymbol{x}_\nu = \begin{pmatrix} x_\nu^\alpha \\ x_\nu^\beta \end{pmatrix}$$

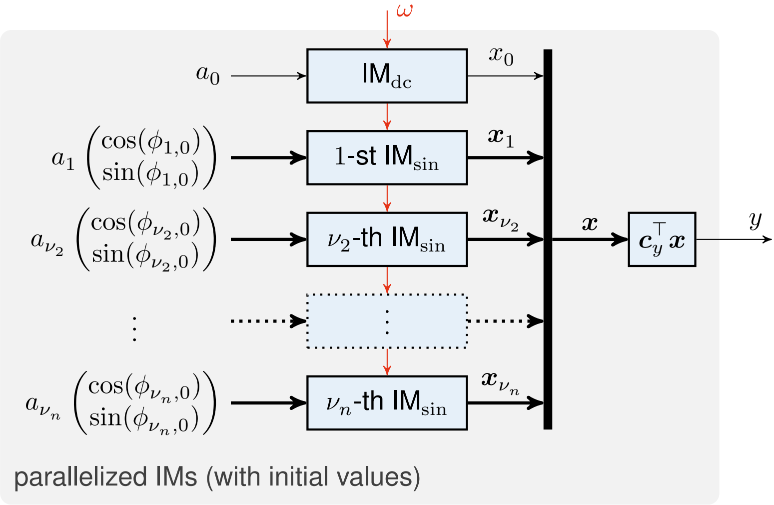


$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}_\nu = \omega(t) \begin{bmatrix} 0 & -\nu \\ \nu & 0 \end{bmatrix} \boldsymbol{x}_\nu, \quad \boldsymbol{x}_\nu(0) = \boldsymbol{x}_{\nu,0}$$

$$y_\nu = \begin{pmatrix} 1, & 0 \end{pmatrix} \boldsymbol{x}_\nu$$

Internal model principle

Overall signal reduplication by parallelization of IMs



Internal model principle

Dynamics of parallelized IMs

$$\frac{\mathrm{d}}{\mathrm{d}t}\overbrace{\begin{pmatrix} x_0 \\ \begin{pmatrix} x_1^\alpha \\ x_1^\beta \end{pmatrix} \\ \begin{pmatrix} x_{\nu_2}^\alpha \\ x_{\nu_2}^\beta \end{pmatrix} \\ \vdots \\ \begin{pmatrix} x_{\nu_n}^\alpha \\ x_{\nu_n}^\beta \end{pmatrix} \end{pmatrix}}^{=:\boldsymbol{x}\in\mathbb{R}^{2n+1}} = \omega(t) \overbrace{\begin{bmatrix} 0 & & & & \\ & \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} & & & \\ & & \nu_2 \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} & & \\ & & & \ddots & \\ & & & & \nu_n \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \end{bmatrix}}^{=:\boldsymbol{A}\in\mathbb{R}^{(2n+1)\times(2n+1)}} \boldsymbol{x}, \quad \boldsymbol{x}(0) = \boldsymbol{x}_0$$

$$y = \underbrace{\begin{pmatrix} 1, & (1, & 0), & (1, & 0), & \dots & (1, & 0) \end{pmatrix}}_{=:\boldsymbol{c}_y^\top\in\mathbb{R}^{1\times(2n+1)}} \boldsymbol{x}$$

$\Longrightarrow$ Observation problem of an **observable** system $\Longrightarrow$ **Observer design**

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Observer design

Overall observer and pole placement: parallelized internal models with **feedback**

For $\boldsymbol{J} := \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ and $\boldsymbol{l}_\nu := \nu \begin{pmatrix} k_\nu \\ g_\nu \end{pmatrix}$, define the observer dynamics

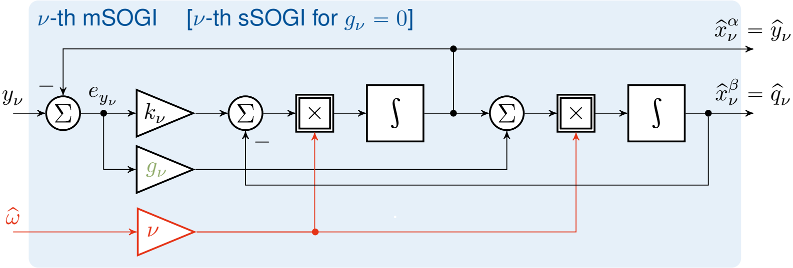
$$\frac{\mathrm{d}}{\mathrm{d}t} \overbrace{\begin{pmatrix} \widehat{x}_0 \\ \widehat{\boldsymbol{x}}_1 \\ \widehat{\boldsymbol{x}}_{\nu_2} \\ \vdots \\ \widehat{\boldsymbol{x}}_{\nu_n} \end{pmatrix}}^{=:\widehat{\boldsymbol{x}} \in \mathbb{R}^{2n+1}} = \widehat{\omega}(t) \overbrace{\left[\begin{bmatrix} 0 & & & & \\ & \boldsymbol{J} & & & \\ & & \nu_2 \boldsymbol{J} & & \\ & & & \ddots & \\ & & & & \nu_n \boldsymbol{J} \end{bmatrix} - \begin{pmatrix} l_0 \\ \boldsymbol{l}_1 \\ \boldsymbol{l}_{\nu_2} \\ \vdots \\ \boldsymbol{l}_{\nu_n} \end{pmatrix} \boldsymbol{c}_y^\top \right]}^{= \boldsymbol{A} - \boldsymbol{l} \boldsymbol{c}_y^\top =: \boldsymbol{H}} \widehat{\boldsymbol{x}} - \widehat{\omega}(t) \boldsymbol{l}\, y, \quad \widehat{\boldsymbol{x}}(0) = \widehat{\boldsymbol{x}}_0$$

$$\widehat{y} = \underbrace{\big(1, \quad (1, \quad 0), \quad (1, \quad 0), \quad \ldots \quad (1, \quad 0)\big)}_{=:\boldsymbol{c}_y^\top \in \mathbb{R}^{1 \times (2n+1)}} \widehat{\boldsymbol{x}}$$

- Recall: $(\boldsymbol{c}_y^\top, \boldsymbol{A})$ observable $\Longrightarrow \exists \boldsymbol{l} \in \mathbb{R}^{2n+1}$: $\boldsymbol{H} := \boldsymbol{A} - \boldsymbol{l} \boldsymbol{c}_y^\top$ Hurwitz!
- Pole placement: $\boldsymbol{l} = \boldsymbol{S} \boldsymbol{p}_{\boldsymbol{H}}^* \Longrightarrow s_0^* = -p_0^* \wedge \forall \nu \in \mathbb{H}_n: \; s_{\nu,1/2}^* = -p_\nu^* \pm \jmath \nu$

Observer design

Modified SOGI (mSOGI) for ν-th harmonic estimation: ν-th IM$_{\sin}$ **with** extended **feedback**

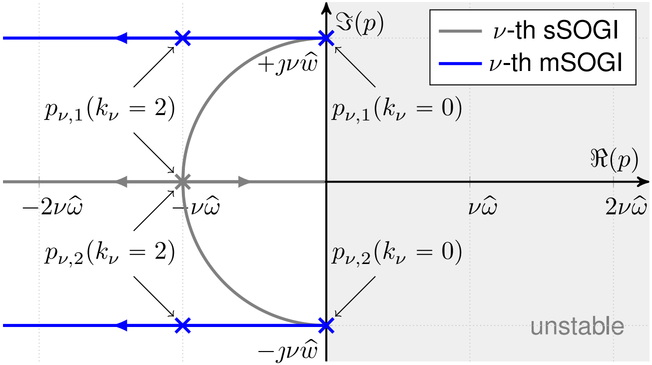


$$\frac{\mathrm{d}}{\mathrm{d}t}\widehat{\boldsymbol{x}}_\nu(t) = \widehat{\omega}(t)\underbrace{\begin{bmatrix} -\nu k_\nu & -\nu \\ \nu - \nu g_\nu & 0 \end{bmatrix}}_{=:\boldsymbol{A}_\nu - \boldsymbol{l}_\nu(k_\nu, g_\nu)\boldsymbol{c}_y^\top}\widehat{\boldsymbol{x}}_\nu(t) + \widehat{\omega}(t)\underbrace{\begin{pmatrix} \nu k_\nu \\ \nu g_\nu \end{pmatrix}}_{=:\boldsymbol{l}_\nu(k_\nu, g_\nu)} y_\nu(t), \quad \widehat{\boldsymbol{x}}_\nu(0) = \widehat{\boldsymbol{x}}_{\nu,0}$$

$$\widehat{y}_\nu(t) = \boldsymbol{c}_\nu^\top \widehat{\boldsymbol{x}}_\nu(t)$$

Observer design

Comparison of root loci of ν-th sSOGI and mSOGI



sSOGI

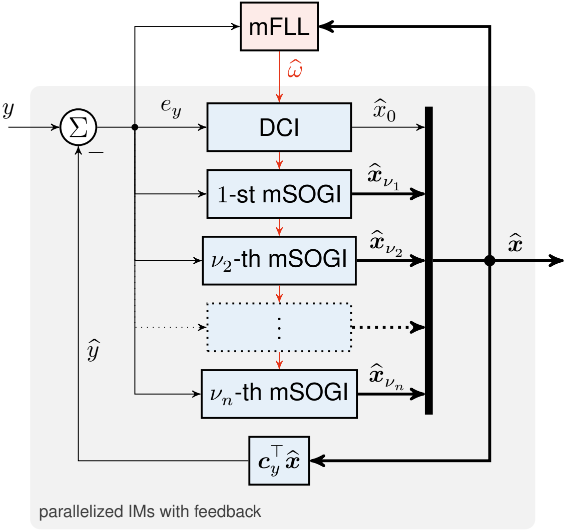
$$p_{\nu,1/2} = -\frac{\nu\widehat{\omega}k_\nu}{2}\left(1 \pm \sqrt{1 - \frac{4}{k_\nu^2}}\right)$$

mSOGI (for $g_\nu = -\frac{k_\nu^2}{4}$)

$$p_{\nu,1/2} = -\frac{\nu\widehat{\omega}k_\nu}{2} \pm \jmath\nu\widehat{\omega}\,.$$

Observer design

Overall observer structure



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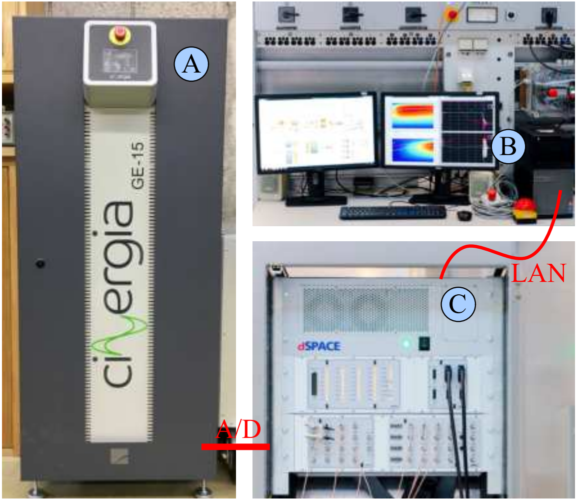
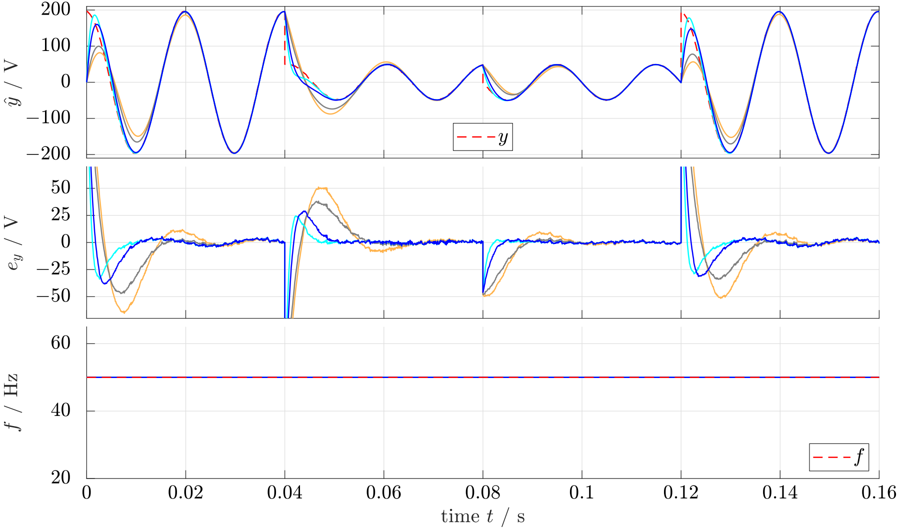
Implementation

Laboratory setup: (A) Grid emulator, (B) Host-PC and (C) Real-time system



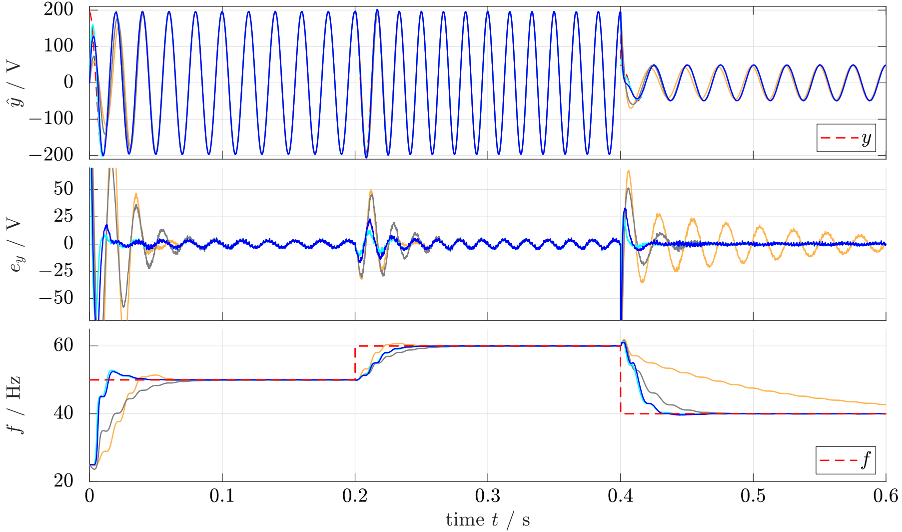
Implementation

Measurements **w/o** FLL ($\nu = 1$): mSOGI, $\text{mSOGI}_{\text{fast}}$, sSOGI & ANF



Implementation

Measurements **with** FLL ($\nu = 1$): mSOGI, mSOGI$_{\text{fast}}$, sSOGI & ANF



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Conclusion

Summary and outlook

To take home

- **unified theory** for grid state estimation, based on
  - **internal model principle** and **parallelization** $\Longrightarrow$ observation problem;
  - **parallelized internal models** with **feedback** (mSOGIs) $\Longrightarrow$ modular structure;
  - **pole placement** $\Longrightarrow$ prescribed settling time
  - **modified** frequency-locked loop (FLL) with sign-correct anti-windup and rate limitation
- **real-time estimation**
- **positive, negative** and **zero sequence extraction** for each harmonic (also possible)

Future work

- Frequency Locked-Loop weakest component $\Longrightarrow$ further improvement
- Reduction of noise sensitivity $\Longrightarrow$ (extended) Kalman filter design or pre-filtering?
- three-phase implementation, validation and test in laboratory