Grid state estimation: An internal model based approach

Habilitationsvortrag im Rahmen der Schlussbewertung

Christoph Hackl

15.02.2019

Technical University of Munich

Outline I

1. Teaching and research activities

2. Grid state estimation: An internal model based approach

Outline I

1 Teaching and research activities
- Teaching
- Research group
- Research projects
- Publications

Outline I

1 Teaching and research activities
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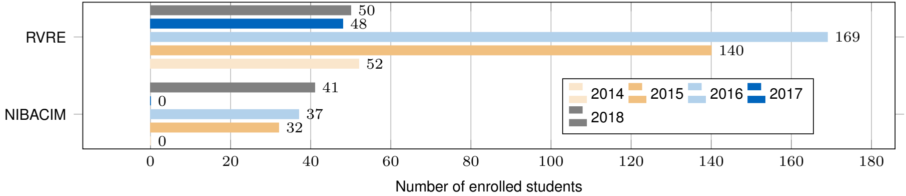
- Publications

Teaching and research activities (2014-2018)

Teaching: Lectures, tutorials, practical courses and miscellaneous (3-6 SWS per semester)



- Lectures, tutorials, practical courses & student projects
  - “**R**egelung **v**on **r**egenerativen **E**nergiesystemen” (WS, 3SWS with PhD students)
  - “**N**on-**i**dentifier **b**ased **a**daptive **c**ontrol in **m**echatronics” (SS, 4SWS)
  - “Projektstudium Antriebstechnik” [1–3] (Umsetzung EOF Lehrpreis, WS1415): **13**
  - Supervised student projects: $>$**30** (master & bachelor thesis, seminars, internships)
  - 3 lectures and 2 practical courses at Munich University of Applied Sciences: $>$**100**
- Miscellaneous (e.g.)
  - Winter School “Holistic Modeling & Control of Energy Systems”: **47** (w. Dörfler & Jokić)
  - H2020 ITN Workshop “Electrical Drives and Predictive Control”: **15** (with M. Diehl)
  - Industrial training on “Optimal feedforward torque control of anisotropic synchronous machines”, Volkswagen, Salzgitter: **8**
  - Invited lecture on “Modeling and control of renewable energy systems” and seminar on “Selected topics in energy research”, CREATE, Singapore (May-July 2017): **10-20**

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Teaching and research activities (2014-2018)

Research group: 9 PhD candidates, 1 Post-Doc, several PhD collaborations@EAL&NES


H. Eldeeb, M.Sc.
(CRES, 09/2015)


C. Dirscherl, M.Sc.
(CRES, 01/2014)


C. Hackl, Dr.-Ing.
(CRES, 01/2014)


J. Kullick, M.Sc.
(CRES, 10/2015)


K. Schechner, M.Sc.
(CRES, 01/2014)


C. Ladisla, M.Sc.
(CRES, 01/2018)

External PhD students


M. Landerer, M.Sc.
(CRES, 06/2016)


Z. Zhang, Dr.-Ing.
(CRES/EAL,07/2015)


K. Bär, M.Sc.
(THI, 07/2017)


A. Birda, M.Sc.
(BMW, 04/2016)


S. Krüner, M.Sc.
(SINNPower,11/2015)

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1 Teaching and research activities
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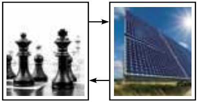
Teaching and research activities (2014-2018)

Research projects with focus on **modeling**, **simulation**, **control**, **efficiency** and **reliability**
(funding: > 2.2 million €; e.g. DAAD, Bavaria, BMBF, BMWi, DFG, EU)

Large-scale WTS

Small-scale WTS

MPC for RES



AWE systems

Geothermal energy

Wave energy (SinnPower)

Electric vehicles (BMW)

Power systems

Biogas power plants

Multi-level converters

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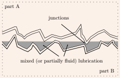
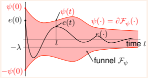
Teaching and research activities (2014-2018)

Publications (1 monograph, 6 chapters, 21 articles & 49 conference papers; all peer-reviewed)

System identification [12–16]



Friction [17, 18]



Non-identifier based adaptive control [17, 19–30], [31–34]

Paper coating maschines [7–11]

Teaching [117, 118],[1–3, 34, 119–121, 121, 122]

Robotics & Mechatronics [17, 35–44],[18, 34, 45]

Mechatronic & renewable energy systems

Electro-active polymers [4–6]

Power electronics [46, 47], [48–56],[57–63],[34, 64–69],[70–75],[76]

Renewable energy systems [47],[16, 31, 33, 34, 48, 51, 55, 56, 58–60, 62, 64, 70, 75, 76, 81–83, 86, 88, 95, 100–116]

Electrical drives (motors/generators) [17, 19, 21, 22, 40, 44, 77–80], [16, 32, 34, 57, 65, 70, 72, 75, 81–99]

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2 Grid state estimation: An internal model based approach
- Introduction
- Internal model principle
- Observer design
- Frequency estimation
- Harmonic sequence extraction
- Conclusion

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Introduction

Motivation: The future power system—A likely guess

- 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.

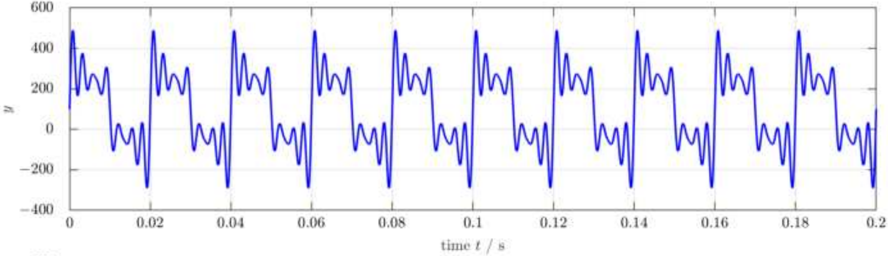
$$\forall t \geqslant t_{\mathrm{set}}: \ |y(t) - \hat{y}(t)| \leqslant \varepsilon_y \ \text{ with } \ \hat{y}(t) := \hat{a}_0 + \sum_{\nu \in \mathbb{H}_n} \underbrace{\hat{a}_\nu(t) \cos\big(\hat{\phi}_\nu(t)\big)}_{=: \hat{y}_\nu(t)}; \tag{2}$$

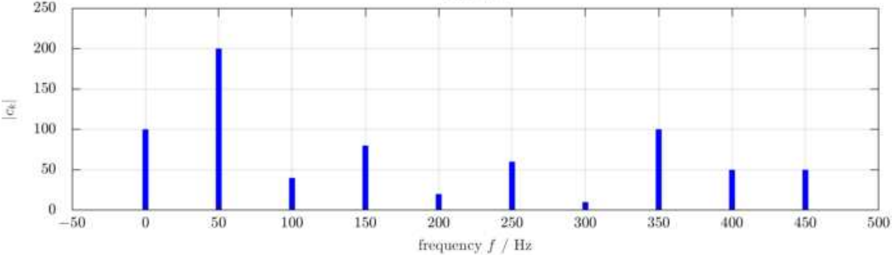
(ii) amplitude estimation, i.e. $\hat{a}_0 \to a_0$ and $\hat{a}_\nu \to a_\nu$ for all $\nu \in \mathbb{H}_n$; and

(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

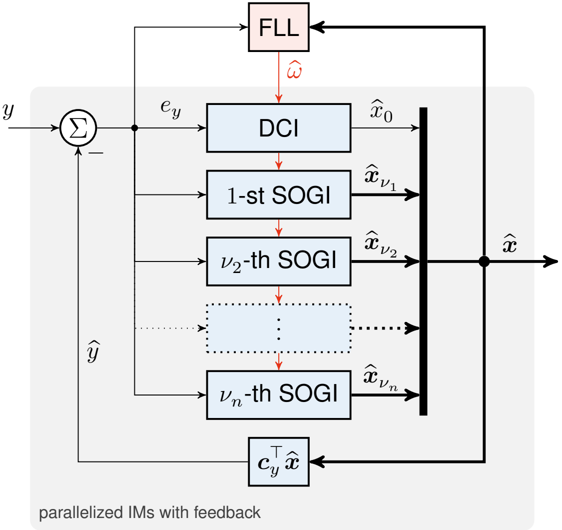
Problem statement (illustration)





Introduction

Proposed solution: Time-varying observer consisting of parallelized IMs with feedback and FLL



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Internal model principle

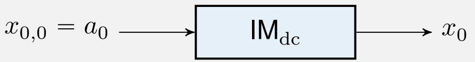
Motivation

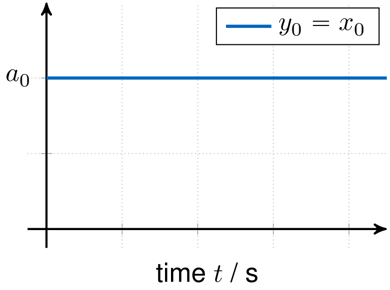
Francis Wonham (1985):
"Every good regulator [or observer] must incorporate a model of the outside world being capable to reduplicate the dynamic structure of the exogenous signals which the regulator [or observer] is required to process." [123]

Internal model principle

Constant signal reduplication

constant IM (with initial value)





$$\frac{\mathrm{d}}{\mathrm{d}t} x_0 = 0, \quad x_0(0) = x_{0,0}$$

$$y_0 = x_0$$

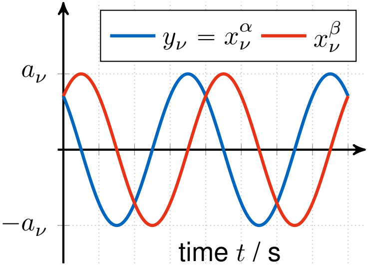
Internal model principle

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

sinusoidal IM (with initial values)

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

ω

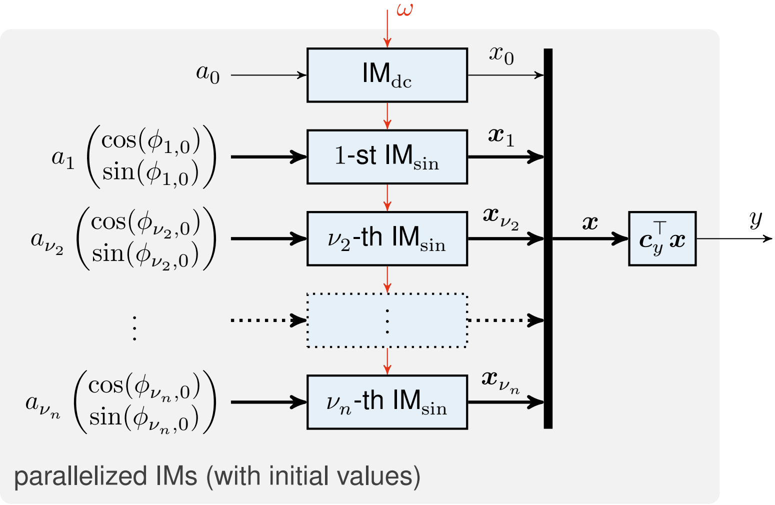


$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}_\nu = \omega(t) \begin{bmatrix} 0 & -\nu \\ \nu & 0 \end{bmatrix} \boldsymbol{x}_\nu, \quad \boldsymbol{x}_\nu(0) = \boldsymbol{x}_{\nu,0}$$

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

Internal model principle

Overall signal reduplication by parallelization of IMs



Internal model principle

Dynamics of parallelized IMs

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

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

$\Longrightarrow$ Observation problem of a dynamical system ... if observable!

Internal model principle

Observability of parallelized IMs (for constant $\omega > 0$)

$$\operatorname{rank}\begin{bmatrix} \boldsymbol{c}_y^\top \\ \boldsymbol{c}_y^\top \boldsymbol{A} \\ \boldsymbol{c}_y^\top \boldsymbol{A}^2 \\ \boldsymbol{c}_y^\top \boldsymbol{A}^3 \\ \boldsymbol{c}_y^\top \boldsymbol{A}^4 \\ \vdots \\ \boldsymbol{c}_y^\top \boldsymbol{A}^{2n-1} \\ \boldsymbol{c}_y^\top \boldsymbol{A}^{2n} \end{bmatrix} =$$

$$\operatorname{rank}\begin{bmatrix} 1 & 1 & 0 & 1 & 0 & \cdots & 1 & 0 \\ 0 & 0 & -1 & 0 & -\nu_2 & \cdots & 0 & -\nu_n \\ 0 & -1 & 0 & -\nu_2^2 & 0 & \cdots & -\nu_n^2 & 0 \\ 0 & 0 & 1 & 0 & \nu_2^3 & \cdots & 0 & \nu_n^3 \\ 0 & 1 & 0 & \nu_2^4 & 0 & \cdots & \nu_n^4 & 0 \\ 0 & \vdots & & & \vdots & & & \vdots \\ 0 & 0 & (-1)^n & 0 & (-1)^n \nu_2^{2n-1} & \cdots & 0 & (-1)^n \nu_n^{2n-1} \\ 0 & (-1)^n & 0 & (-1)^n \nu_2^{2n} & 0 & \cdots & (-1)^n \nu_n^{2n} & 0 \end{bmatrix}$$

$= \boxed{2n+1 \quad \Longleftarrow \quad \nu_i \neq \nu_j \text{ for all } i,j \in \{1,\ldots,n\}}$

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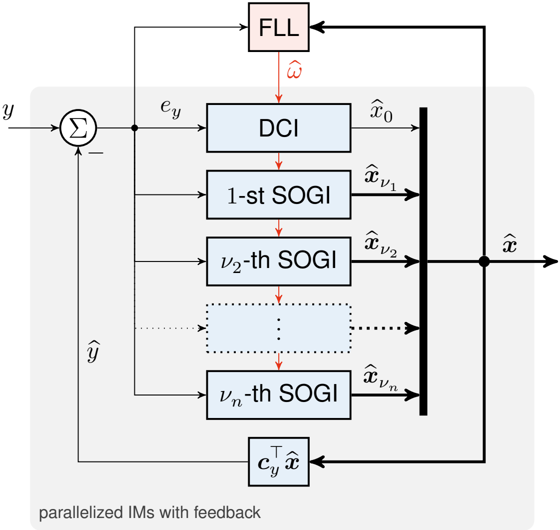
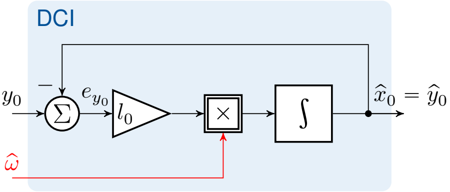
Observer design

Overall observer structure



Observer design

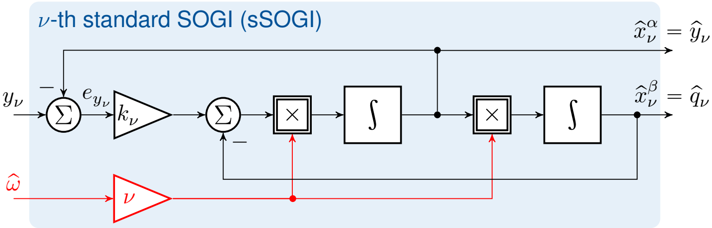
DC-Integrator (DCI) for constant signal estimation: $\mathrm{IM}_{\mathrm{dc}}$ with **feedback**



$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}\widehat{x}_0 &= -\widehat{\omega}(t) l_0\,\widehat{x}_0 + \widehat{\omega}(t) l_0 y_0, \qquad \widehat{x}_0(0) = 0 \\ \widehat{y}_0 &= \widehat{x}_0 \end{aligned}$$

Observer design

Standard SOGI (sSOGI) for ν-th harmonic estimation: ν-th $\mathrm{IM}_{\sin}$ with **feedback**

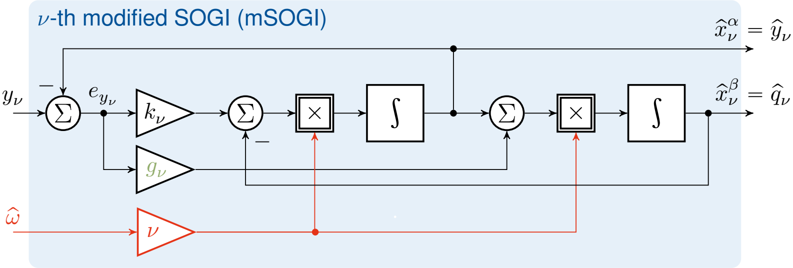


$$\frac{\mathrm{d}}{\mathrm{d}t}\overbrace{\begin{pmatrix}\widehat{x}_\nu^\alpha(t)\\ \widehat{x}_\nu^\beta(t)\end{pmatrix}}^{=:\widehat{\boldsymbol{x}}_\nu(t)\in\mathbb{R}^2} = \widehat{\omega}(t)\overbrace{\begin{bmatrix}0 & -\nu\\ \nu & 0\end{bmatrix}}^{=:\boldsymbol{A}_\nu - \boldsymbol{l}_\nu(k_\nu)\boldsymbol{c}_y^\top}\widehat{\boldsymbol{x}}_\nu(t) + \widehat{\omega}(t)\overbrace{\begin{pmatrix}\nu k_\nu\\ 0\end{pmatrix}}^{=:\boldsymbol{l}_\nu(k_\nu)} y_\nu(t), \quad \widehat{\boldsymbol{x}}_\nu(0) = \widehat{\boldsymbol{x}}_{\nu,0}$$

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

Observer design

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

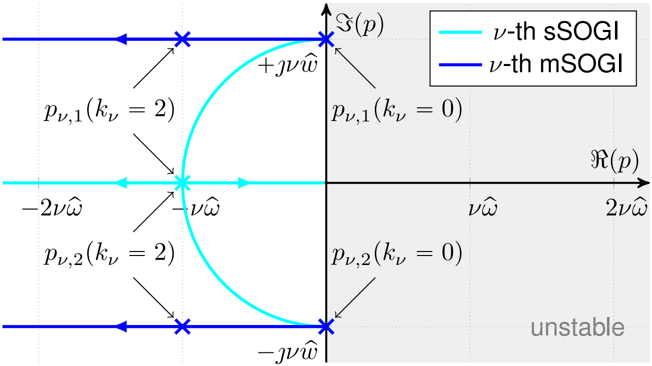


$$\frac{\mathrm{d}}{\mathrm{d}t}\widehat{\boldsymbol{x}}_\nu(t) = \widehat{\omega}(t)\overbrace{\begin{bmatrix} -\nu k_\nu & -\nu \\ \nu - \nu g_\nu & 0 \end{bmatrix}}^{=:\boldsymbol{A}_\nu - \boldsymbol{l}_\nu(k_\nu)\boldsymbol{c}_y^\top}\widehat{\boldsymbol{x}}_\nu(t) + \widehat{\omega}(t)\overbrace{\begin{pmatrix}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

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

Observer design

Comparison of root loci of ν-th sSOGI and mSOGI



sSOGI

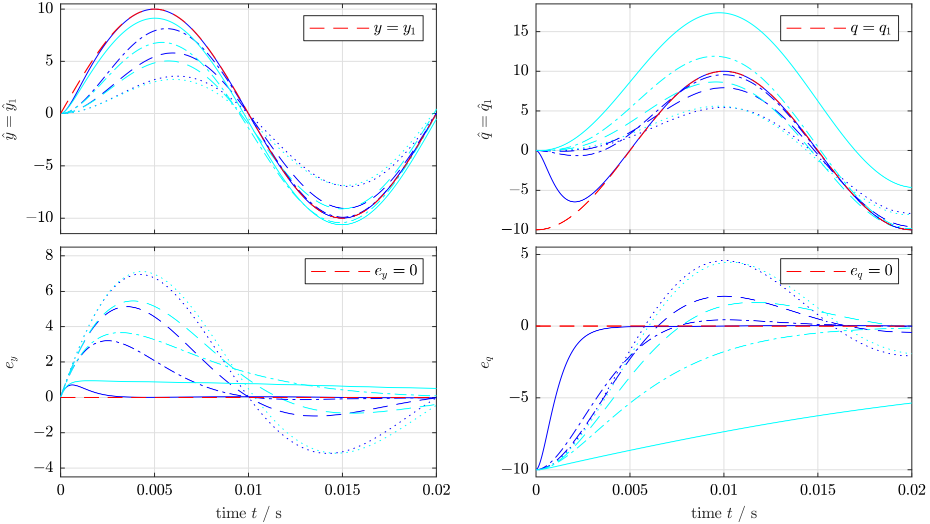
$$p_{\nu,1/2} = -\frac{\nu\widehat{\omega}k_\nu}{2}\left(1 \pm \sqrt{1 - \frac{4}{k_\nu^2}}\right)$$

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

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

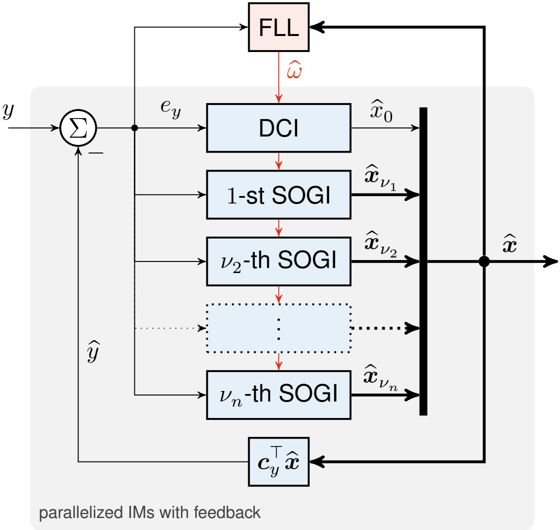
Observer design

Estimation performances of sSOGI (———) and mSOGI (———) for different $k_1 \in \{0.5, 1, 2, 10\}$



Observer design

Pole placement for overall observer



Observer design

Pole placement for overall observer: parallelized internal models with **feedback**

For $\boldsymbol{J} := \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ and $\boldsymbol{l}_\nu := \nu \binom{k_\nu}{g_\nu}$, 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

Stability analysis for $\omega(\cdot) \in \mathcal{PC} \cap \mathcal{L}^\infty(\mathbb{R}_{\geqslant 0}; \mathbb{R}_{\geqslant \varepsilon})$ and $\hat{\omega}(\cdot) \in \mathcal{C}^1 \cap \mathcal{L}^\infty(\mathbb{R}_{\geqslant 0}; \mathbb{R}_{\geqslant \varepsilon})$

- **Error dynamics** $\boldsymbol{e}_x := \boldsymbol{x} - \hat{\boldsymbol{x}}$ and $e_\omega := \omega - \hat{\omega}$ $\Longrightarrow$ $\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{e}_x = \boldsymbol{f}(\boldsymbol{e}_x, e_\omega, \dots)$
- **Lyapunov candidate** $V(\boldsymbol{e}_x) := \boldsymbol{e}_x^\top \boldsymbol{P} \boldsymbol{e}_x$ and using
  - $\boldsymbol{H} := \boldsymbol{A} - \boldsymbol{l}\boldsymbol{c}_y^\top$ Hurwitz $\Longrightarrow$ $\forall \boldsymbol{Q} = \boldsymbol{Q}^\top > 0 \, \exists \boldsymbol{P} = \boldsymbol{P}^\top > 0\colon \; \boldsymbol{H}^\top \boldsymbol{P} + \boldsymbol{P}\boldsymbol{H} = -\boldsymbol{Q} < 0$ [124, Cor. 3.3.47]
  - $\forall a, b, m \in \mathbb{R}\colon \; 2\,a\,b = \frac{a^2}{m} + mb^2 - \left(\frac{a}{\sqrt{m}} - \sqrt{m}\,b\right)^2 \leqslant \frac{a^2}{m} + m\,b^2$

$\Longrightarrow$ $\frac{\mathrm{d}}{\mathrm{d}t} V(\boldsymbol{e}_x) = \cdots \leqslant -\mu_V V(\boldsymbol{e}_x) + c_\omega e_\omega^2$ with $e_\omega(\cdot) \in \mathcal{L}^\infty(\mathbb{R}_{\geqslant 0}; \mathbb{R})$

  - Bellmann-Gronwall Lemma [34, Lemma 5.50]

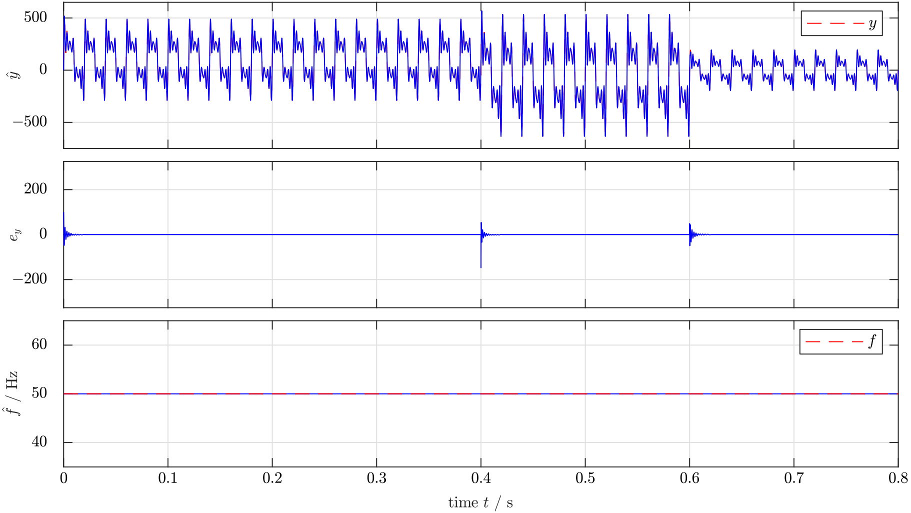
$\Longrightarrow$ $\forall t \geqslant t_i\colon \; V(\boldsymbol{e}_x(t)) \leqslant V(\boldsymbol{e}_x(t_i))\mathrm{e}^{-\mu_V (t - t_i)} + c_\omega \int_{t_i}^{t} e_\omega(\tau)^2 \mathrm{e}^{-\mu_V (t-\tau)} \, \mathrm{d}\tau$

- **Error bound** by invoking $\lambda_{\min}(\boldsymbol{P})\|\boldsymbol{e}_x\|^2 \leqslant V(\boldsymbol{e}_x) = \boldsymbol{e}_x^\top \boldsymbol{P} \boldsymbol{e}_x \leqslant \lambda_{\max}(\boldsymbol{P})\|\boldsymbol{e}_x\|^2$

$\Longrightarrow$ $\forall t \geqslant t_i\colon \; \|\boldsymbol{e}_x(t)\|^2 \leqslant c_{\boldsymbol{P}} \|\boldsymbol{e}_x(t_i)\|^2 \mathrm{e}^{-\mu_V (t - t_i)} + c'_\omega \int_{t_i}^{t} e_\omega(\tau)^2 \mathrm{e}^{-\mu_V (t-\tau)} \, \mathrm{d}\tau$

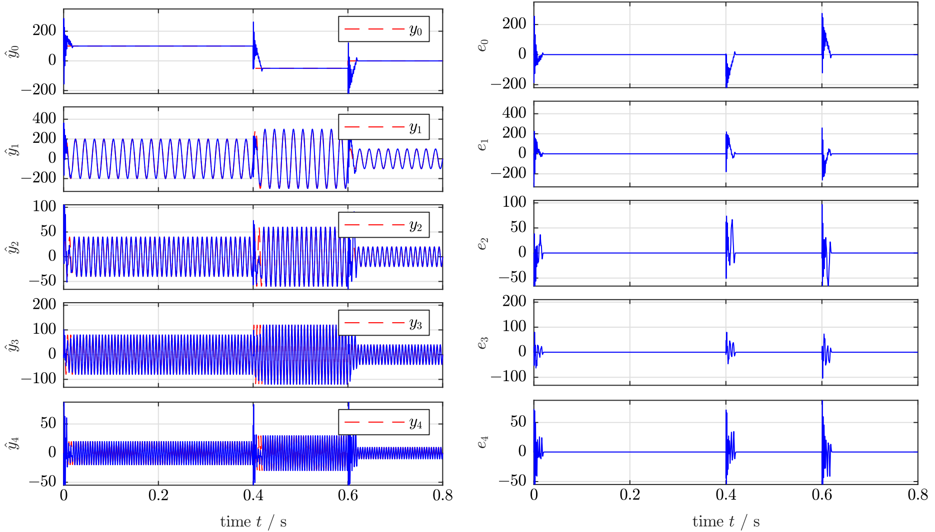
Observer design

Simulation results: Estimate $\hat{y}$, estimation error $e_y = y - \hat{y}$ and estimated frequency $\hat{f} = \frac{\hat{\omega}}{2\pi}$



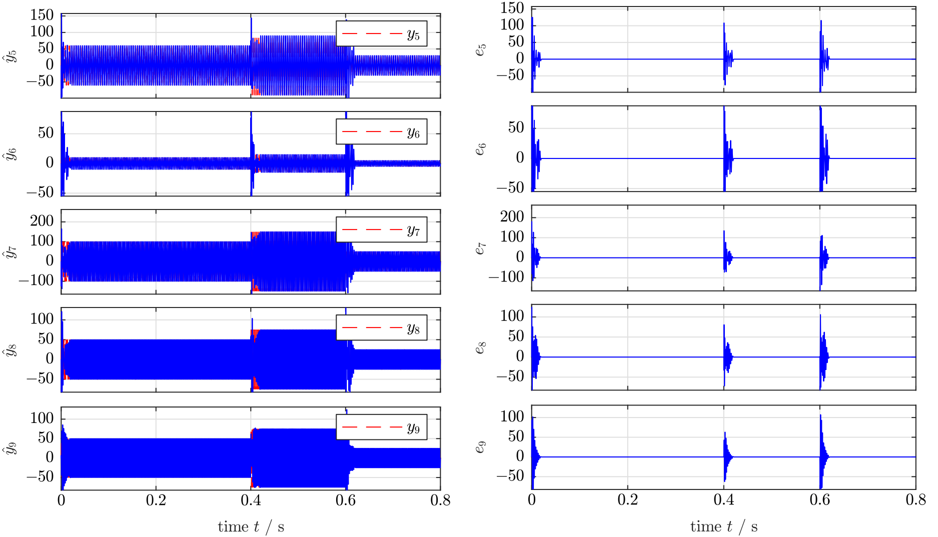
Observer design

Simulation results: Estimate $\widehat{y}_\nu$ (left) and estimation error $e_\nu = y_\nu - \widehat{y}_\nu$ (right)



Observer design

Simulation results: Estimate $\hat{y}_\nu$ (left) and estimation error $e_\nu = y_\nu - \hat{y}_\nu$ (right)



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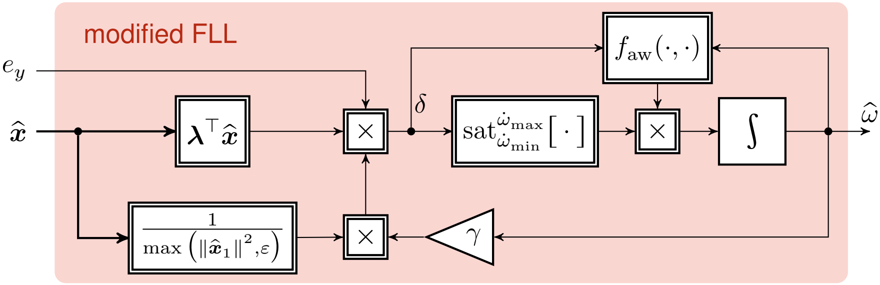
Frequency estimation

Modified Frequency Locked Loop (mFLL) with sign-correct anti-windup and rate limitation

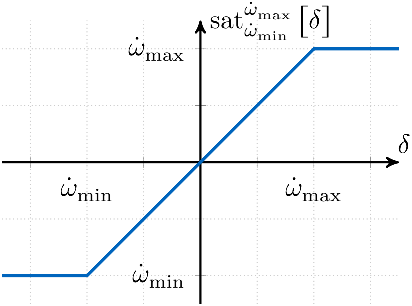


$$\frac{\mathrm{d}}{\mathrm{d}t}\widehat{\omega} = f_{\mathrm{aw}}(\widehat{\omega},\delta)\cdot \mathrm{sat}_{\dot{\omega}_{\min}}^{\dot{\omega}_{\max}}\Bigg[\underbrace{\frac{\gamma\,\widehat{\omega}\,e_y\,\boldsymbol{\lambda}^\top\widehat{\boldsymbol{x}}}{\max\left(\|\widehat{\boldsymbol{x}_1}\|^2,\varepsilon\right)}}_{=:\delta}\Bigg] = \begin{cases} > 0, & \widehat{\omega} < \omega \wedge e_y \neq 0 \\ < 0, & ,\widehat{\omega} > \omega \wedge e_y \neq 0 \end{cases}$$

$$\Longleftarrow \quad \boldsymbol{\lambda} := \mathrm{blockdiag}\left(0, \boldsymbol{J}^{-1}, \boldsymbol{O}_{2\times 2}, \ldots, \boldsymbol{O}_{2\times 2}\right)\boldsymbol{l} \qquad \text{(mFLL)}$$

Frequency estimation

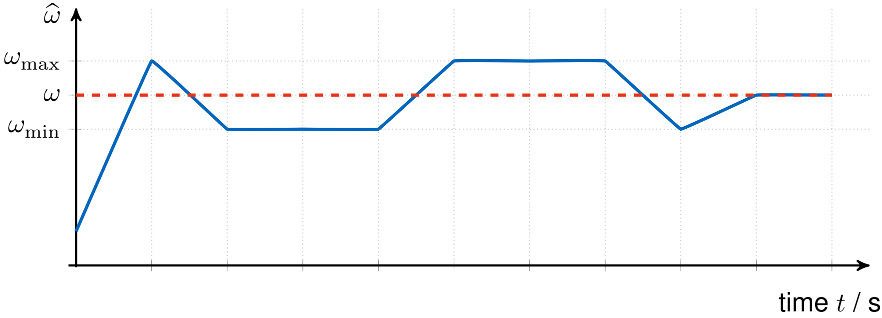
Modified FLL: Saturation of derivative of angular frequency estimate (rate limitation)



$$\mathrm{sat}_{\dot{\omega}_{\min}}^{\dot{\omega}_{\max}}[\delta] = \begin{cases} \dot{\omega}_{\max} & , \delta > \dot{\omega}_{\max} \\ \delta & , \dot{\omega}_{\min} \leqslant \delta \leqslant \dot{\omega}_{\max} \\ \dot{\omega}_{\min} & , \delta < \dot{\omega}_{\min} \end{cases}$$

Frequency estimation

Modified FLL: Sign-correct anti-windup

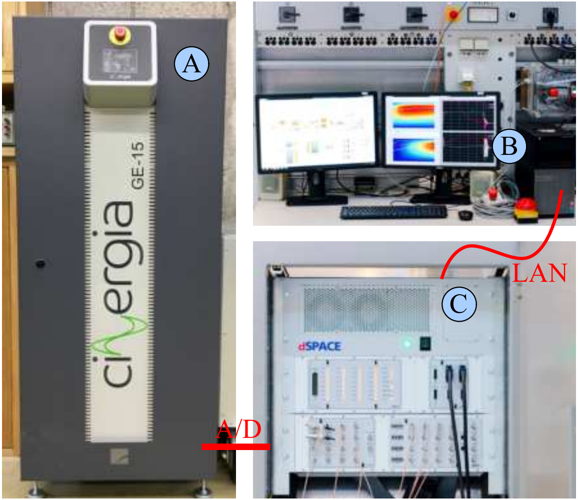


$$f_{\mathrm{aw}}\left(\widehat{\omega}, \tfrac{\mathrm{d}}{\mathrm{d}t}\widehat{\omega}\right) := \begin{cases} 0, & \text{for } \left(\widehat{\omega} \geqslant \omega_{\max} \wedge \tfrac{\mathrm{d}}{\mathrm{d}t}\widehat{\omega} > 0\right) \vee \left(\widehat{\omega} \leqslant \omega_{\min} \wedge \tfrac{\mathrm{d}}{\mathrm{d}t}\widehat{\omega} < 0\right) \\ 1, & \text{else} \end{cases}$$

$$\Longrightarrow \; \forall t \geqslant 0\colon \; \widehat{\omega}(t) \in \left[\min(\omega_{\min}, \widehat{\omega}_0), \min(\omega_{\max}, \widehat{\omega}_0)\right] \; \Longrightarrow \; \widehat{\omega}(\cdot) \in \mathcal{L}^{\infty}(\mathbb{R}_{\geqslant 0}; \mathbb{R}_{>0})$$

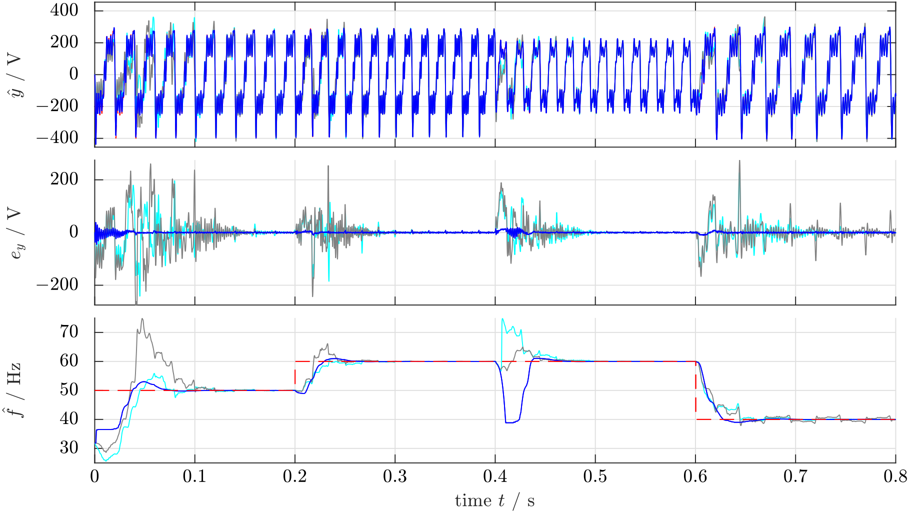
Frequency estimation

Measurement results in laboratory: (A) Grid emulator, (B) Host-PC and (C) Real-time system



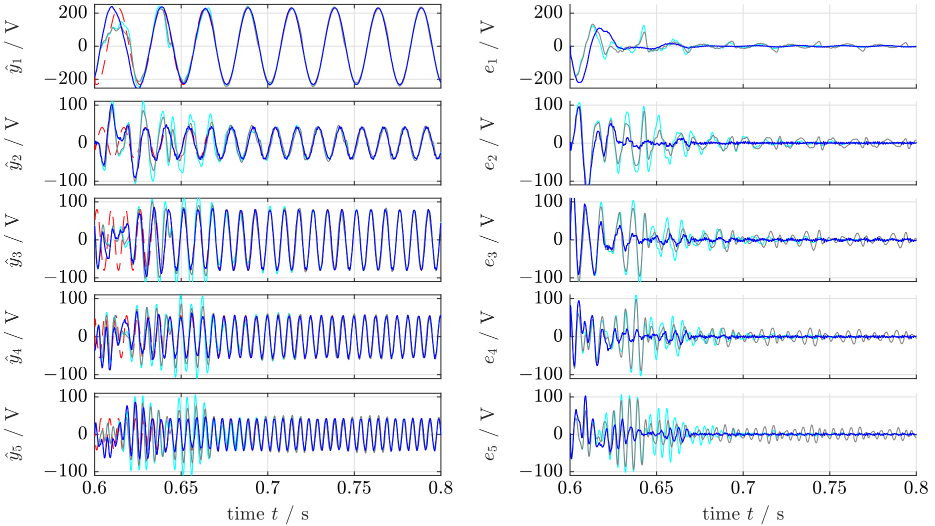
Frequency estimation

Measurement results with FLL: mSOGI, sSOGI, ANF, y, f



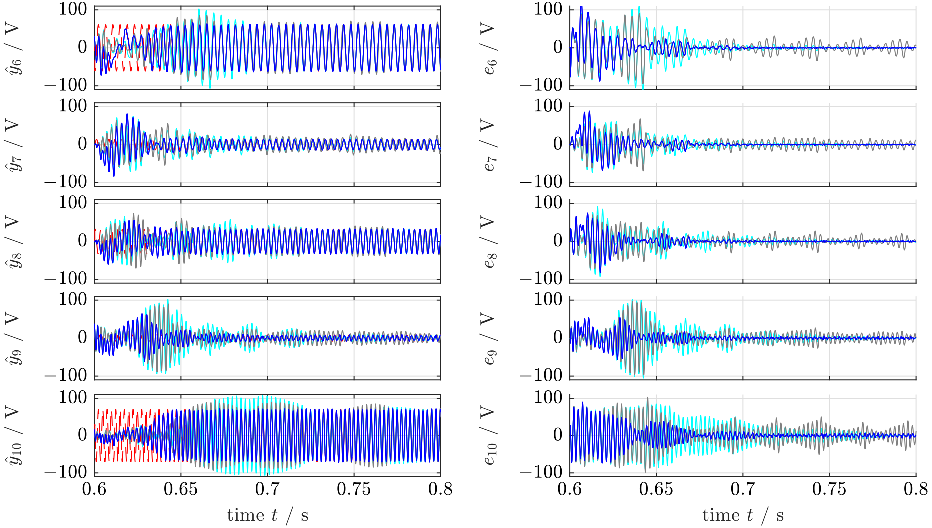
Frequency estimation

Measurement results with FLL [Zoom]: mSOGI, sSOGI, ANF, y_ν (left)



Frequency estimation

Measurement results with FLL [Zoom]: mSOGI, sSOGI, ANF, y_ν (left)



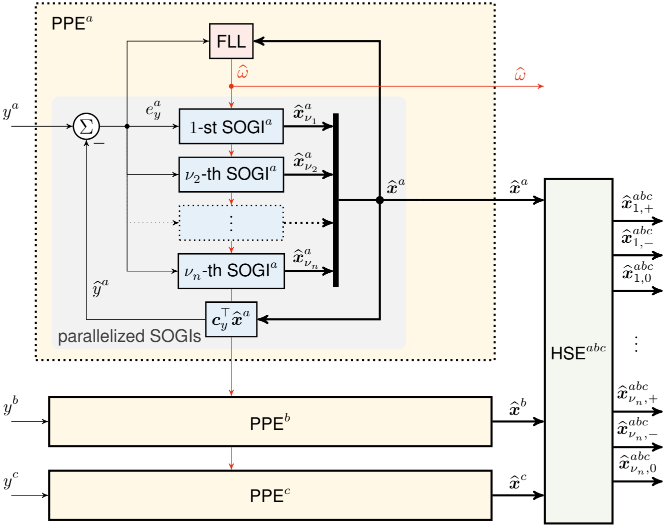
Outline I

2 Grid state estimation: An internal model based approach

- Introduction
- Internal model principle
- Observer design
- Frequency estimation
- **Harmonic sequence extraction**
- Conclusion

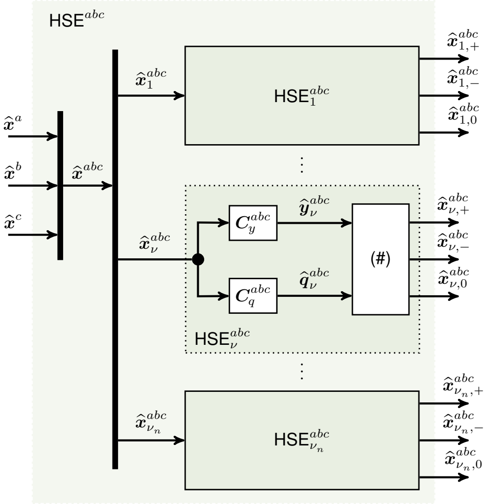
Harmonic sequence extraction

Overview: Phase parameter estimation (PPE) and Harmonic sequence extraction (HSE)



Harmonic sequence extraction

Harmonic sequence extraction (HSE) for the three phases a, b, c



Harmonic sequence extraction

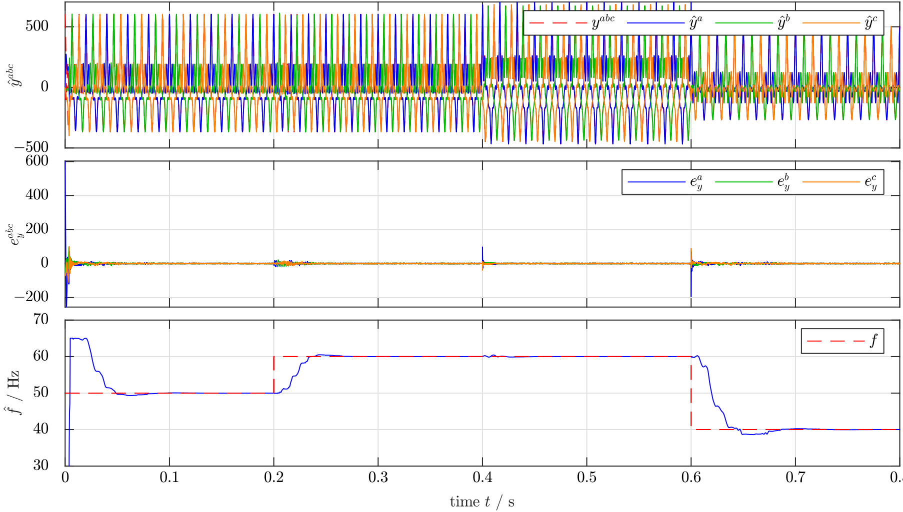
Positive, negative and zero sequence estimation of ν-th harmonic

Let $\nu \in \mathbb{H}_n$, $\boldsymbol{J}_1 := \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ and $\boldsymbol{T}_\mathrm{c} := \kappa \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$, $\kappa \in \{\frac{2}{3}, \sqrt{\frac{2}{3}}\}$, define

$$
\left.
\begin{aligned}
\boldsymbol{y}_\nu^{abc}(t) = {} & \underbrace{\tfrac{1}{2}\boldsymbol{T}_\mathrm{c}^{-1} \overbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}}^{=:\boldsymbol{D}_{12}} \boldsymbol{T}_\mathrm{c} \widehat{\boldsymbol{y}}_\nu^{abc}(t) + \tfrac{1}{2}\boldsymbol{T}_\mathrm{c}^{-1}\boldsymbol{J}_1\boldsymbol{D}_{12}\boldsymbol{T}_\mathrm{c}\widehat{\boldsymbol{q}}_\nu^{abc}(t)}_{=:\widehat{\boldsymbol{x}}_{\nu,+}^{abc}(t) \text{ [positive sequence]}} \\
& + \underbrace{\tfrac{1}{2}\boldsymbol{T}_\mathrm{c}^{-1}\boldsymbol{D}_{12}\boldsymbol{T}_\mathrm{c}\widehat{\boldsymbol{y}}_\nu^{abc}(t) - \tfrac{1}{2}\boldsymbol{T}_\mathrm{c}^{-1}\boldsymbol{J}_1\boldsymbol{D}_{12}\boldsymbol{T}_\mathrm{c}\,\widehat{\boldsymbol{q}}_\nu^{abc}(t)}_{=:\widehat{\boldsymbol{x}}_{\nu,-}^{abc}(t) \text{ [negative sequence]}} \\
& + \underbrace{\boldsymbol{T}_\mathrm{c}^{-1} \overbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}}^{=:\boldsymbol{D}_3} \boldsymbol{T}_\mathrm{c}\,\widehat{\boldsymbol{y}}_\nu^{abc}(t)}_{=:\widehat{\boldsymbol{x}}_{\nu,0}^{abc}(t) \text{ [zero sequence]}}
\end{aligned}
\right\} \qquad (\#)
$$

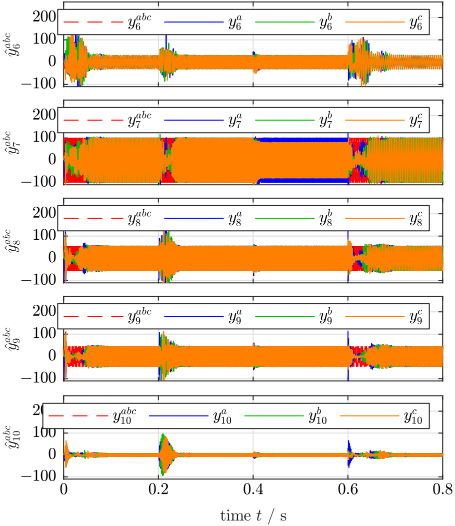
Harmonic sequence extraction

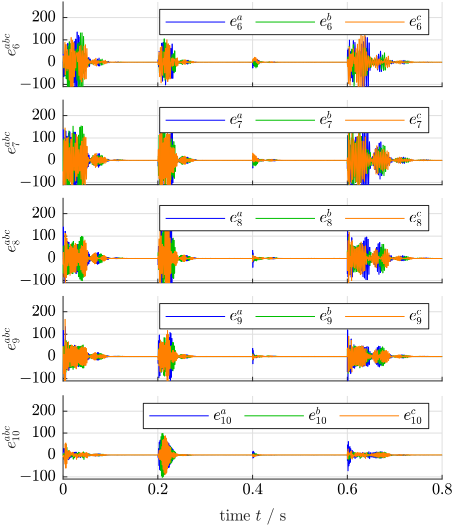
Simulation results: Estimate $\hat{\boldsymbol{y}}^{abc}$, estimation error $\boldsymbol{e}^{abc} = \boldsymbol{y}^{abc} - \hat{\boldsymbol{y}}^{abc}$ & estimated frequency $\hat{f}$



Harmonic sequence extraction

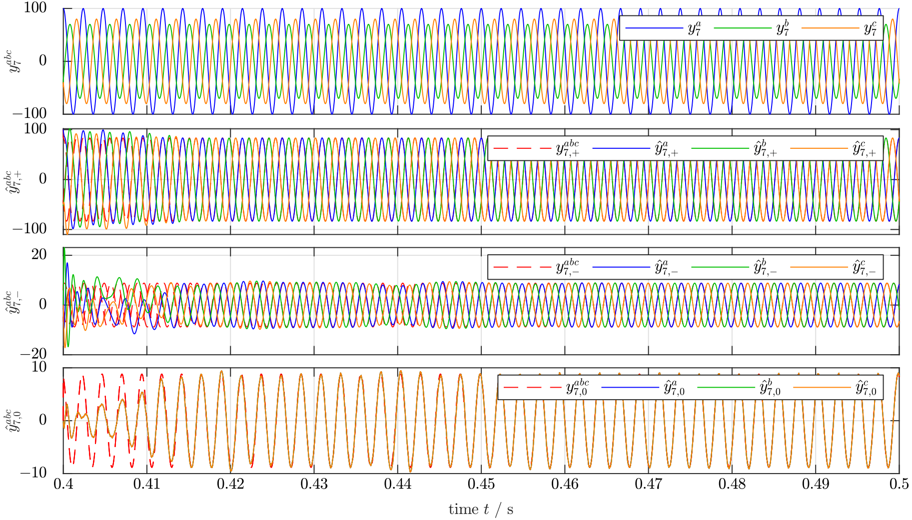
Simulation results: Estimate $\widehat{y}_\nu$ (left) and estimation error $e_\nu = y_\nu - \widehat{y}_\nu$ (right)





Harmonic sequence extraction

Simulation results: Harmonic $\boldsymbol{y}_7^{abc}$, positive $\hat{\boldsymbol{y}}_{7,+}^{abc}$, negative $\hat{\boldsymbol{y}}_{7,-}^{abc}$ & zero $\hat{\boldsymbol{y}}_{7,0}^{abc}$ sequence



Outline I

2 Grid state estimation: An internal model based approach
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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

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

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