Hochschule München (HM) University of Applied Sciences

Laboratory for Mechatronic and Renewable Energy Systems (LMRES)

# On Phase-locked loops and frequency-adaptive observers

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# Outline

# Introduction: HM research environment

HM (www.hm.edu), ISES (ises.hm.edu) and LMRES (lmres.ee.hm.edu)


**HM – Munich University of Applied Sciences**

- 14 departmens
- >18.000 students
- ~480 professors
- 3 campuses

**ISES – Institute for Sustainable Energy Systems**

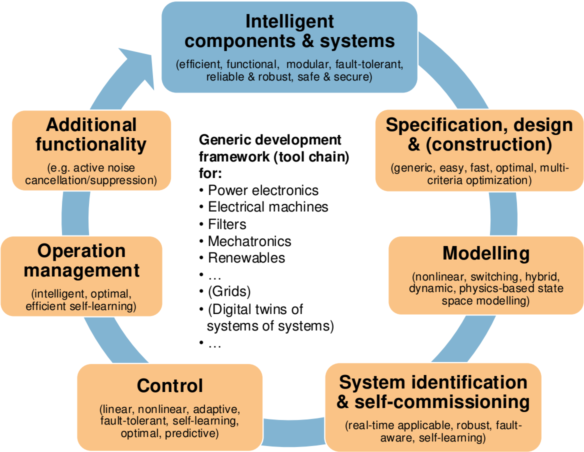
- 8 research labs (8 professors)
- 34 PhD candidates

**LMRES – Laboratory for Mechatronic and Renewable Energy Systems**

- International team
- 15 PhD candidates (status 2024)
- >150 publications / >8.3 Mio. € raised

# Introduction: LMRES research activities

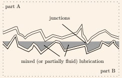
Research projects and research goals (funding: $> 9.2$ million €; e.g. DAAD, Bavaria, BMBF, BMWi, DFG, EU)

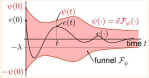
# Introduction: LMRES research interests

## Interdisciplinary expertise & publications

**System identification** [9–26]




**Fric-tion** [27–29]




**Non-identifier based adaptive control** [14, 27, 30–46]

**Paper coating machines** [4–8]

**Supervision & teaching** (Award) [157–163]


**Mechatronics & robotics** [27, 28, 40, 46–58]

**Mechatronic and renewable energy systems**

**Electro-active polymers** [1–3]

**Power electronics** [19–21, 46, 58–88]

**Wind energy, renewables & smart grid** [13–15, 44, 46, 57, 58, 60, 61, 67, 68, 70–72, 74, 79, 85, 93–95, 98, 100, 107, 112, 120, 132, 136, 139–156]

**Electrical machines & drives** [13, 15, 17, 23–27, 30, 32, 33, 45, 46, 51, 55, 57, 69, 77, 78, 80, 89–138]

# Introduction: LMRES selected research results

## Smart grid/renewables/power systems (grid synchronisation) [16]

energies

MDPI

*Article*

### A Unified Method for Online Detection of Phase Variables and Symmetrical Components of Unbalanced Three-Phase Systems with Harmonic Distortion

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**Abstract:** This paper presents a method for online detection of symmetrical components of arbitrarily distorted and biased three-phase input signals. This method is based on *Second-Order Generalized Integrators* (SOGIs), for which a new tuning based on a gradient search is presented to achieve the fastest possible estimation. Frequency estimation is achieved by a *Frequency Locked Loop* (FLL) with *Gain Normalization* (GN) for which an *Output Saturation* (OS) is applied; this OS guarantees stability of the overall system. Offset detection is implemented by a combination of *High-Pass Filter* (HPF) and HPF-*Amplitude Phase Correction* ($\mathrm{APC}_{\mathrm{HPF}}$); the HPF filters out any offset, where the APC reconstructs the original offset-free signal. An identical method ($\mathrm{APC}_{\mathrm{LPF}}$) can be used for the implemented *Low-Pass Filter* (LPF) used for noise filtering. The resulting estimates are then used for *Harmonic Sequence Detection* (HSD) of each harmonic. For the overall system, stability is proven. The estimation performances of the proposed overall system are verified by simulation results. The improvements in tuning and offset detection are compared to standard approaches.

**Keywords:** second-order generalized integrator; symmetrical components; real Fortescue transformation; frequency locked-loop; DC-offset detection; frequency detection; amplitude detection; stability analysis; convergence analysis

- an *Amplitude Phase Correction* ($\mathrm{APC}^p_{\mathrm{x}}$ with $\mathrm{x} \in \{\mathrm{LPF}, \mathrm{HPF}\}$) to mitigate for amplitude damping and phase shift introduced by $\mathrm{LPF}^p$ and $\mathrm{HPF}^p$, resp.: The merged estimated signal vector $\hat{\vec{x}}^p_{\mathrm{HPF}}$ of the parallelized SOGIs is fed into the $\mathrm{APC}^p_{\mathrm{HPF}}$. The $\mathrm{APC}^p_{\mathrm{HPF}}$ output vector

$$\hat{\vec{x}}^p_{\mathrm{LPF}} = \Big( \underbrace{(\hat{y}^p_{\mathrm{LPF},1}, \hat{q}^p_{\mathrm{LPF},1})^\top}_{=:(\hat{\vec{x}}^p_{\mathrm{LPF},1})^\top}, \underbrace{(\hat{y}^p_{\mathrm{LPF},\nu_2}, \hat{q}^p_{\mathrm{LPF},\nu_2})^\top}_{=:(\hat{\vec{x}}^p_{\mathrm{LPF},\nu_2})^\top}, \dots, \underbrace{(\hat{y}^p_{\mathrm{LPF},\nu_n}, \hat{q}^p_{\mathrm{LPF},\nu_n})^\top}_{=:(\hat{\vec{x}}^p_{\mathrm{LPF},\nu_n})^\top} \Big)^\top \in \mathbb{R}^{2n} \tag{5}$$

comprises all amplitude-correct and phase-correct direct and quadrature estimates of the low-pass filtered signal $y^p_{\mathrm{LPF}}$ (see Figure 1). The signal vector $\hat{\vec{x}}^p_{\mathrm{LPF}}$ is fed into the $\mathrm{APC}^p_{\mathrm{LPF}}$ to reconstruct amplitude-correct and phase-correct direct and quadrature estimates of the original signal $y^p$ (see Figure 1). The output vector of the $\mathrm{APC}^p_{\mathrm{LPF}}$ is given by

$$\hat{\vec{x}}^p = \Big( \underbrace{(\hat{y}^p_1, \hat{q}^p_1)^\top}_{=:(\hat{\vec{x}}^p_1)^\top}, \underbrace{(\hat{y}^p_{\nu_2}, \hat{q}^p_{\nu_2})^\top}_{=:(\hat{\vec{x}}^p_{\nu_2})^\top}, \dots, \underbrace{(\hat{y}^p_{\nu_n}, \hat{q}^p_{\nu_n})^\top}_{=:(\hat{\vec{x}}^p_{\nu_n})^\top} \Big)^\top \in \mathbb{R}^{2n}. \tag{6}$$

- A *DC-offset detection* to obtain an estimate $\hat{a}^p_0$ of the DC-offset $a^p_0$ in the original signal $y^p$ (see Figure 1).

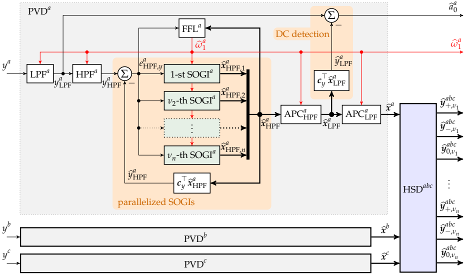



**Figure 1.** Overall block diagram of Phase Variables Detection (PVD) for the three phases $a, b, c$ and Harmonic Sequence Detection (HSD).

# Introduction: LMRES selected research results

## Smart grid/renewables/power systems (grid synchronisation) [22]



### Modified Second-Order Generalized Integrators With Modified Frequency Locked Loop for Fast Harmonics Estimation of Distorted Single-Phase Signals

Christoph M. Hackl, *Senior Member, IEEE*, and Markus Landerer

***Abstract*—This article proposes *modified second-order generalized integrators* (mSOGIs) for a fast estimation of all harmonic components of arbitrarily distorted single-phase signals, such as voltages or currents in power systems. The estimation is based on the internal model principle leading to an overall observer consisting of parallelized mSOGIs. The observer is tuned by pole placement. For a constant fundamental frequency, the observer is capable of estimating all harmonic components with prescribed settling time by choosing the observer poles appropriately. For time-varying fundamental frequencies, the harmonic estimation is combined with a *modified frequency locked loop* (mFLL) with gain normalization, sign-correct antiwindup, and rate limitation. The estimation performances of the proposed parallelized mSOGIs with and without mFLL are illustrated and validated by measurement results. The results are compared to standard approaches such as parallelized standard SOGIs (sSOGIs) and adaptive notch filters (ANFs).**

***Index Terms*—Amplitude estimation, frequency estimation, frequency-locked loop (FLL), phase estimation, second-order generalized integrator (SOGI).**

*Notation*

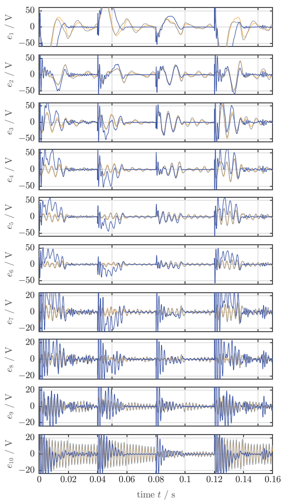
$\mathbb{N}, \mathbb{R}, \mathbb{C}, \mathbb{Q}$: natural, real, complex and rational numbers. For the following, let $n, m \in \mathbb{N}$. $\boldsymbol{x} := (x_1, \ldots, x_n)^\top \in \mathbb{R}^n$: column vector (where $:=$ means "is defined as" and $^\top$ means "transposed"). $\boldsymbol{0}_n := (0, 0, \ldots, 0)^\top \in \mathbb{R}^n$: zero vector. $\|\boldsymbol{x}\| := \sqrt{\boldsymbol{x}^\top \boldsymbol{x}}$: Euclidean norm of $\boldsymbol{x}$. $\boldsymbol{A} \in \mathbb{R}^{n \times m}$: real (non-square) matrix. $\mathrm{diag}(\boldsymbol{a}) \in \mathbb{R}^{n \times n}$: diagonal matrix with

#### I. Introduction

*A. Motivation and Literature Review*

In view of the increasing number of decentralized generation units with power electronics-based grid connection and the decreasing number of large-scale generators, the overall inertia in the grid is diminishing. This results in faster and more abrupt frequency fluctuations and significant harmonic distortion of physical quantities (such as currents or voltages) of the power system [1]. Fast frequency fluctuations endanger stability of the power grid. Significant harmonic distortions of voltages and currents can degrade power quality and lead to damage or even destruction of grid components. To be capable of taking appropriate countermeasures such as 1) improving system stability and power quality and 2) compensating for such deteriorated operation conditions, it is crucial to detect and estimate fundamental and higher harmonic components of the considered quantities in real time as fast and accurate as possible. Modern power electronic devices (e.g., flexible ac transmission systems or grid-connected converters of decentralized renewable energy systems) can then be used to implement such countermeasures. That is why, grid state estimation became of particular interest to the research community in the past years and has been studied extensively (see e.g., [2]–[24] to name a few).

It is well known that a signal with significant harmonic



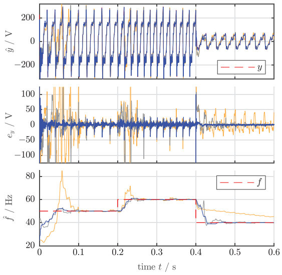




Fig. 11. Measurement results for Scenario ($S_4$): Comparison of the estimation performances of *parallelized* mSOGIs (——), sSOGIs (——), and ANFs (——) *without* FLL. Signals shown from top to bottom are: Harmonic signals $y_1$ to $y_{10}$ (- - -) and their estimates $\widehat{y}_1$ to $\widehat{y}_{10}$ and harmonic estimation errors $e_1 = y_1 - \widehat{y}_1$ to $e_{10} = y_{10} - \widehat{y}_{10}$.

frequency are identical for this scenario. Therefore, the estimation performances purely can be compared according to the respective observer tunings only. The fundamental signal $y = y_1$ undergoes step-like changes in amplitude, phase and amplitude and phase as described above.

The estimation performances of fundamental mSOGI (——), fundamental sSOGI (——), and fundamental ANF (——) are shown in Fig. 7. The first and second subplots show input signal $y = y_1$ (- - -) and its estimates $\widehat{y} = \widehat{y}_1$ and the estimation errors $e_y = y_1 - \widehat{y}_1$, respectively. All three observers are capable of estimating the input signal $y$. All estimation errors $e_y \to 0$ tend to

# Introduction: LMRES selected research results

## Smart grid/renewables/power systems (grid synchronisation) [18]

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### A Unified Method for Generic Signal Parameter Estimation of Arbitrarily Distorted Single-Phase Grids With DC-Offset

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**ABSTRACT** A unified method is presented which allows to estimate dc-offset, all harmonic components *and* fundamental frequency in arbitrarily distorted single-phase grids using a *Frequency Adaptive Observer (FAO)* consisting of *modified Second-Order Generalized Integrators (mSOGIs)*, an adaptive *DC-Integrator (DCI)* and a *modified Frequency Locked Loop (mFLL)*. DCI and mSOGIs are tuned by *pole placement* which allows for an arbitrarily fast detection of dc-offset and harmonic components if the fundamental frequency is known. If the fundamental frequency must be estimated as well, an mFLL with *Gain Normalization (GN)*, *Rate Limitation (RL)*, *Anti-Windup (AW)* strategy and *low-pass filters (LPF)* must be employed. The effectiveness of the proposed FAO is validated by experimental results and its enhanced performance is shown and compared to existing estimation methods.

**INDEX TERMS** Dc-offset estimation, frequency adaptive observer, frequency estimation, frequency locked loop, harmonics estimation, second-order generalized integrator.

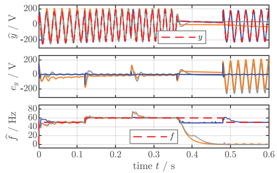



**FIGURE 10.** Measurement results for Scenario (S3) (fundamental signal with dc-offset and unknown frequency): The signals shown are input $y$ (- - -), estimate $\hat{y}$, estimation error $e_y = y - \hat{y}$, frequency $f$ and its estimate $\hat{f}$ of sFAO$_{0,1}$ (——), sFAO$_{\emptyset,n}$ (——) and mFAO$_{0,n}$ (——), respectively.

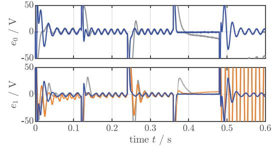
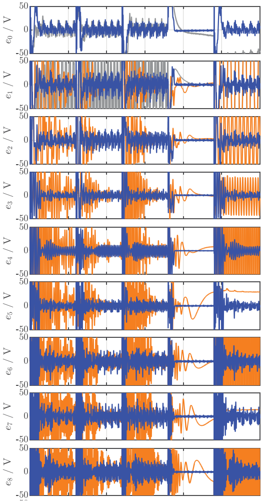



**FIGURE 11.** Zoomed-in estimation errors of dc-offset and harmonic signal for Scenario (S3) (fundamental signal with dc-offset and *unknown* frequency): The signals shown are estimation errors $e_0 = y_0 - \hat{y}_0$ and $e_1 = y_1 - \hat{y}_1$ of sFAO$_{0,1}$ (——), sFAO$_{\emptyset,n}$ (——) and mFAO$_{0,n}$ (——), respectively.



# Phase-locked loop (PLL): Motivation

Conventional power generation: **Nuclear power plant** Grundremmingen (Block C: $1\,344$ MW)

www.wikipedia.de

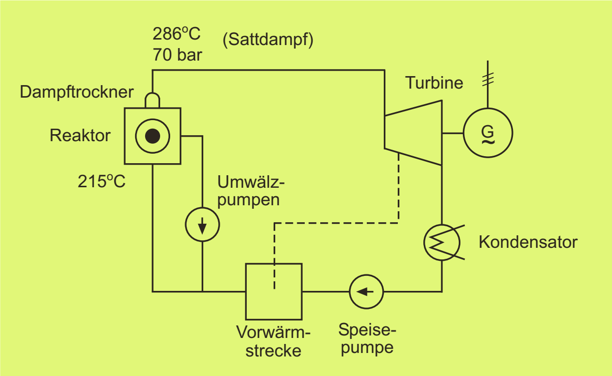



Bild 5.15 from [164]

# Phase-locked loop (PLL): Motivation

Conventional power generation: **Coal power plant** Neurath ($850\,\mathrm{MW}$)

www.deutschlandfunk.de (dpa/Oliver Berg)

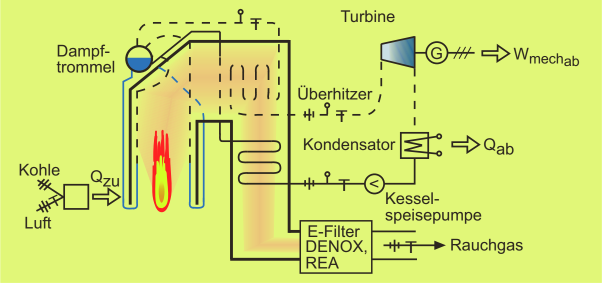



Bild 4.15 from [164]

# Phase-locked loop (PLL): Motivation

Conventional power generation: **Hydro power plant** Klingenberg ($400$ kW)

enso-blog.de

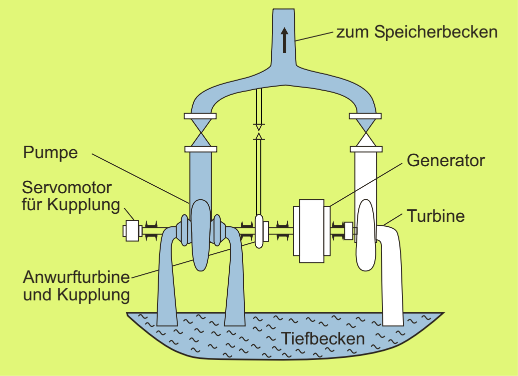



Bild 6.4 from [164]

# Phase-locked loop (PLL): Motivation

Conventional power generation: **Gas and steam power plant** Hamm-Uentrop ($850$ MW)

www.gsw-kamen.de

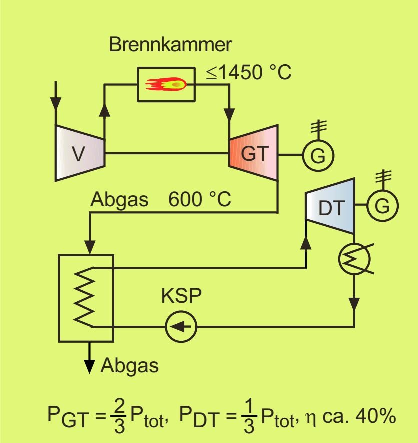
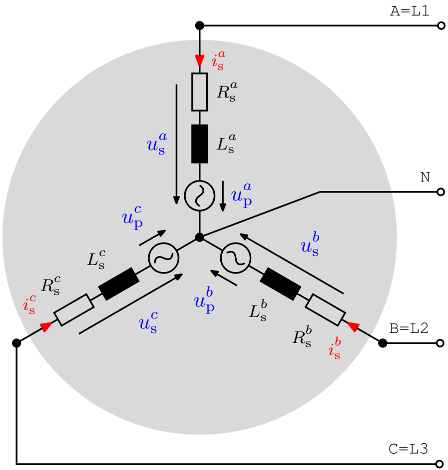


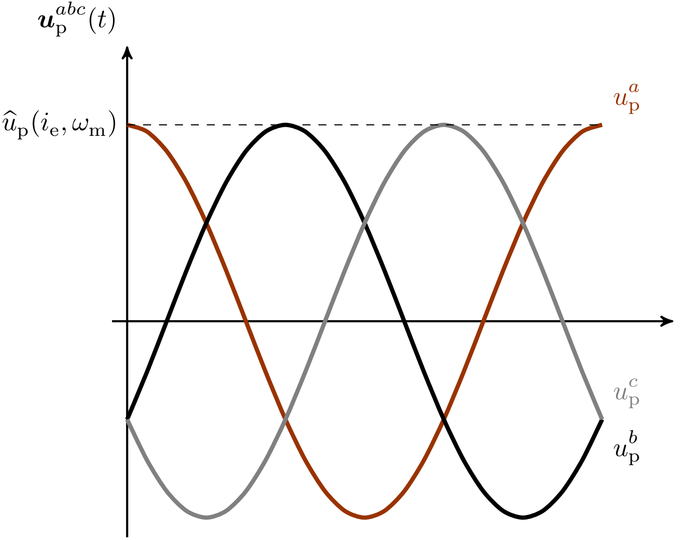

Bild 4.38 from [164]

# Phase-locked loop (PLL)

Motivation: Generators are **voltage sources**

## Erzeugung



# Phase-locked loop (PLL): Motivation

Renewable energy sources: **Wind turbine system with synchronous generator** (Siemens; $2 - 5$ MW)

www.siemens.de

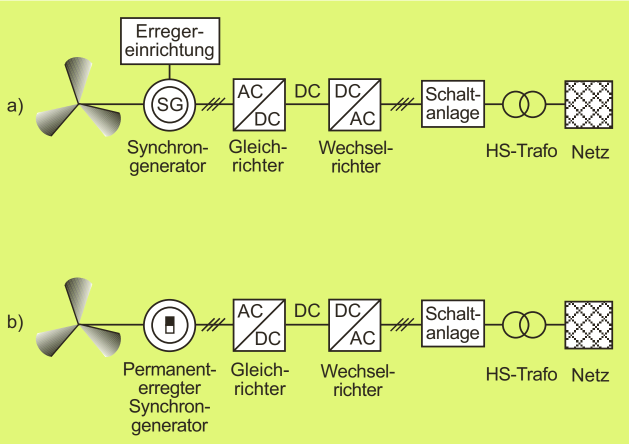



Bild 6.11 aus [164]

# Phase-locked loop (PLL): Motivation

Renewable energy sources: **Wind turbine system with doubly-fed induction generator** (Nordex; $2 - 5$ MW)

www.nordex.de

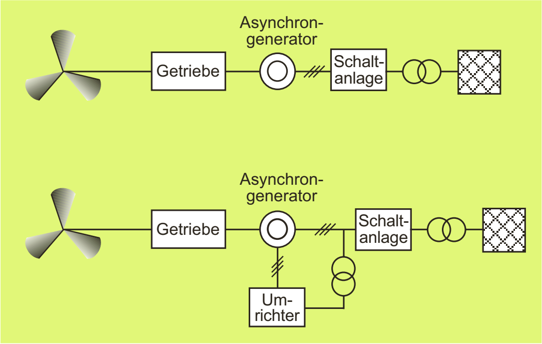
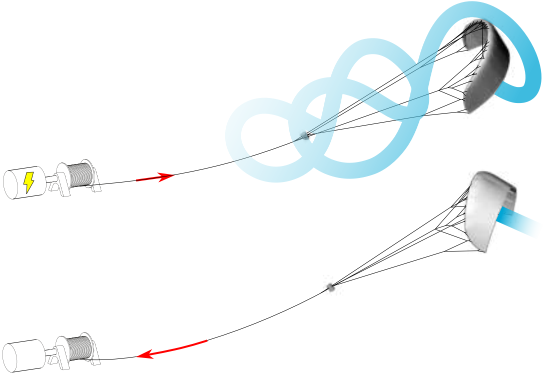



Bild 6.10 aus [164]

# Phase-locked loop (PLL): Motivation

Renewable energy sources: **Airborne wind energy systems** (Enerkite)

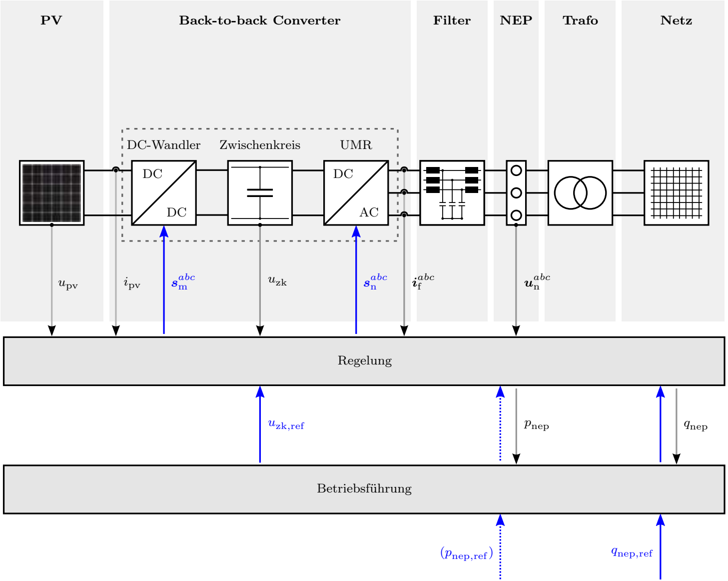
www.enerkite.de



www.awesco.eu

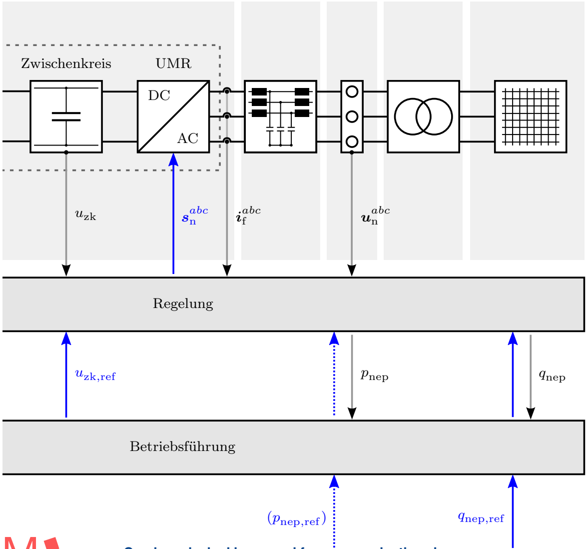
# Phase-locked loop (PLL): Motivation

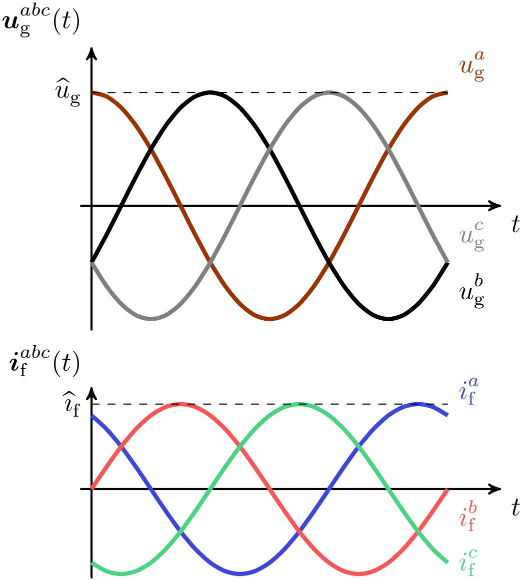
Renewable energy sources: **Photovoltaic (PV) systems**



# Phase-locked loop (PLL): Motivation

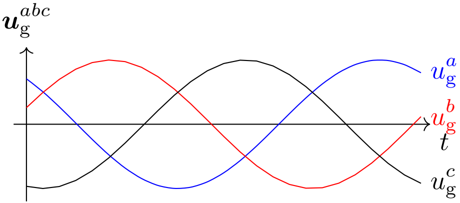
Renewable energy sources: Converters are (currently mostly) **current sources**

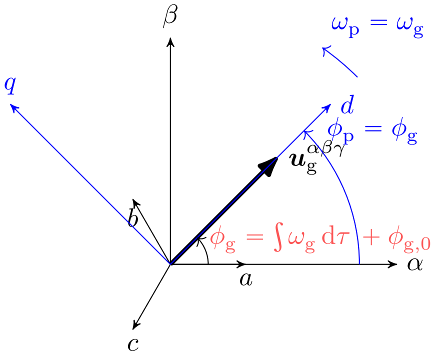


# Phase-locked loop (PLL): Problem statement

Modeling of the grid in voltage orientation

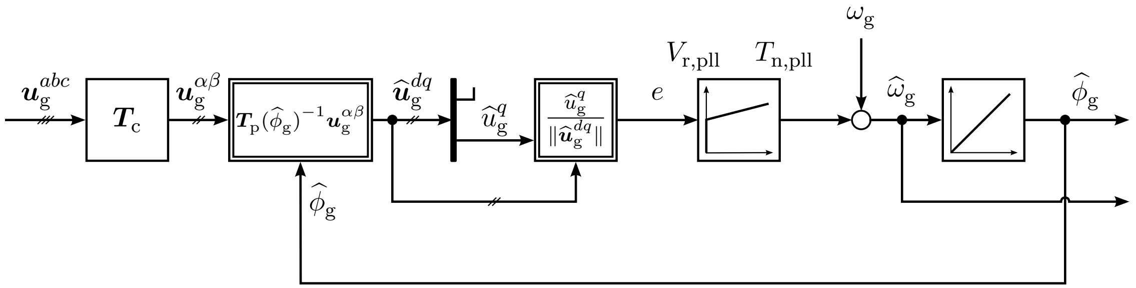



- $\boldsymbol{u}_{\mathrm{g}}^{dq\gamma} = \begin{pmatrix} \widehat{u}_{\mathrm{g}} \\ 0 \end{pmatrix} = \boldsymbol{T}_{\mathrm{p}}(\phi_{\mathrm{g}})^{-1}\boldsymbol{u}_{\mathrm{g}}^{\alpha\beta\gamma} = \boldsymbol{T}_{\mathrm{p}}(\phi_{\mathrm{g}})^{-1}\boldsymbol{T}_{\mathrm{c}}\boldsymbol{u}_{\mathrm{g}}^{abc}$
- Estimation of $\phi_{\mathrm{p}} = \phi_{\mathrm{g}}$ (and $\phi_{\mathrm{g},0}$) with Phase-locked Loop (PLL)

# Phase-locked loop (PLL): Solution

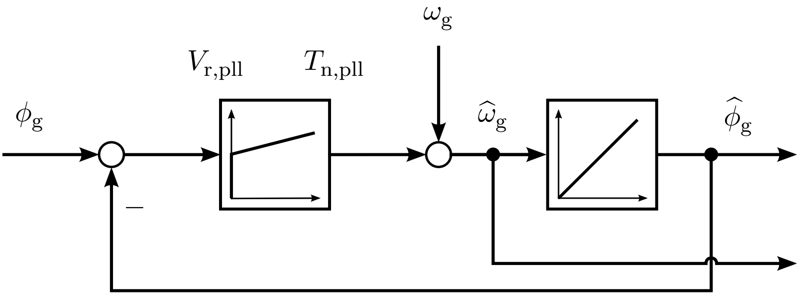
Implementation of a PLL (nonlinear system!)




- Why should we normalize by $\|\boldsymbol{u}_g^{dq}\|$?
- Why should we feedforward $\omega_g$?
- How should we tune PI controller parameters $V_{r,pll}$ and $T_{n,pll}$ of PLL?

# Phase-locked loop (PLL): Solution

## Tuning of the PLL by pole placement




- Why is simplified block diagram admissible for tuning?
- How to achieve tuning of PLL by pole placement?

# Frequency-adaptive observer (FAO): 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!

# Frequency-adaptive observer (FAO): Problem statement

What do we want?

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.

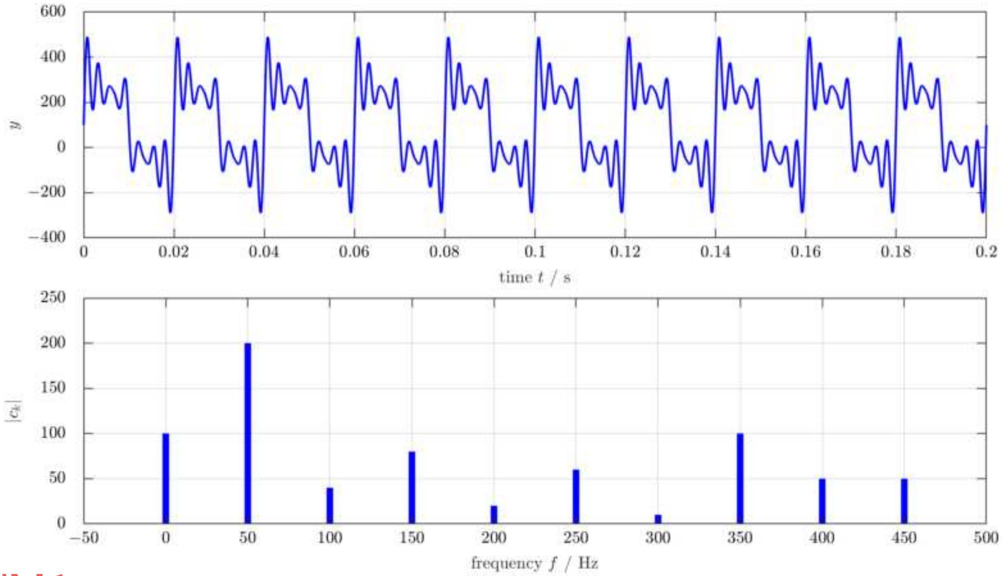
$$\forall t \geqslant t_{\mathrm{set}}: \; |y(t) - \hat{y}(t)| \leqslant \varepsilon_y \quad \text{with} \quad \hat{y}(t) := \hat{a}_0 + \sum_{\nu \in \mathbb{H}_n} \underbrace{\hat{a}_\nu(t)\cos\big(\hat{\phi}_\nu(t)\big)}_{=:\hat{y}_\nu(t)}; \tag{2}$$

(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 $\nu \in \mathbb{H}_n$ .

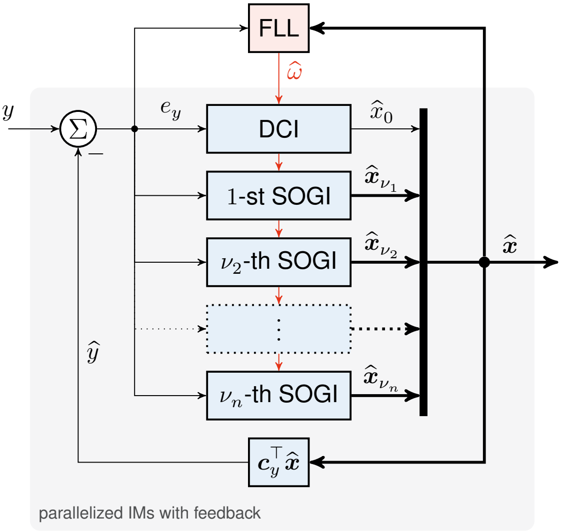
# Frequency-adaptive observer (FAO): Problem statement

Illustration (of problem statement)



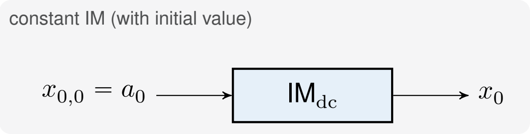
# Frequency-adaptive observer (FAO): Proposed solution

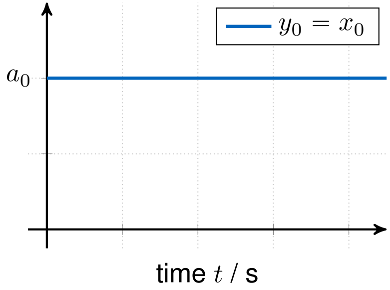
Time-varying observer consisting of parallelized IMs with feedback and FLL



# Frequency-adaptive observer (FAO): Internal model principle

## Constant signal reduplication



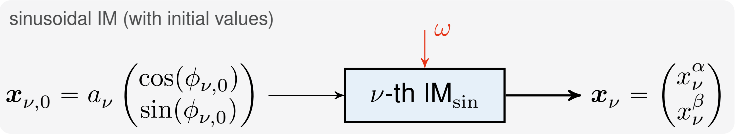



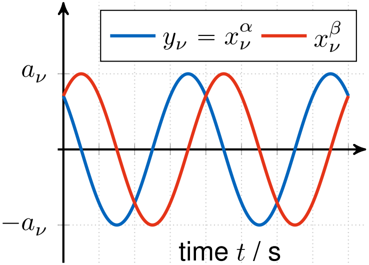

$$\frac{\mathrm{d}}{\mathrm{d}t} x_0 = 0, \quad x_0(0) = x_{0,0}$$

$$y_0 = x_0$$

# Frequency-adaptive observer (FAO): Internal model principle

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



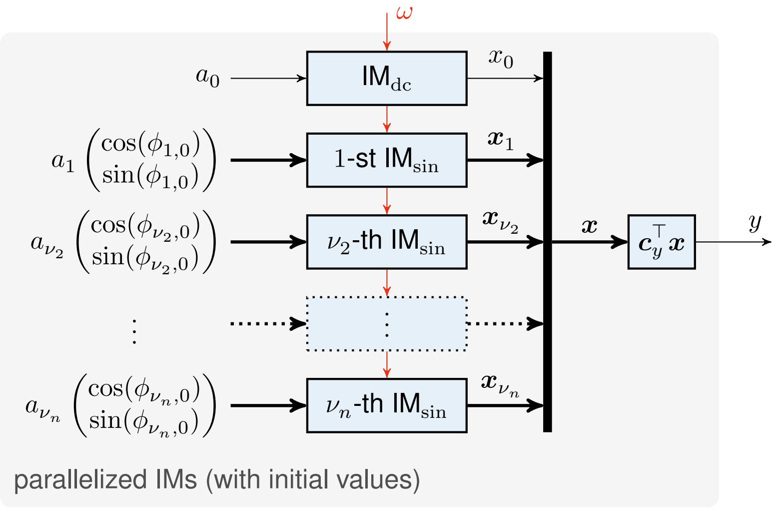




$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}_\nu = \omega(t)\begin{bmatrix} 0 & -\nu \\ \nu & 0 \end{bmatrix}\boldsymbol{x}_\nu, \quad \boldsymbol{x}_\nu(0) = \boldsymbol{x}_{\nu,0}$$

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

# Frequency-adaptive observer (FAO): Internal model principle

Overall signal reduplication by parallelization of IMs



# Frequency-adaptive observer (FAO): Internal model principle

Dynamics of parallelized IMs

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

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

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

# Frequency-adaptive observer (FAO): Internal model principle

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

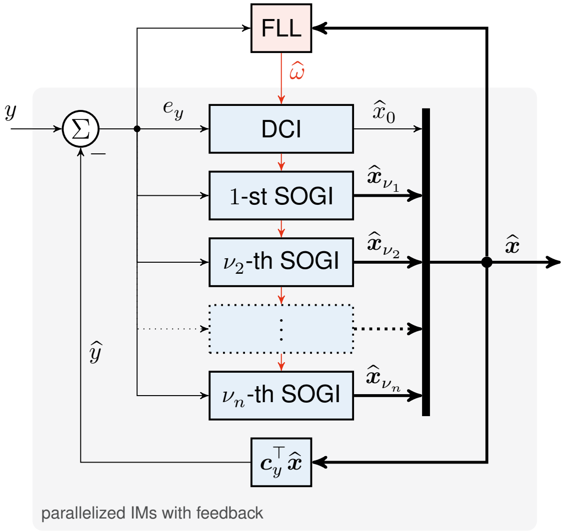
$$
\operatorname{rank}\begin{bmatrix} \boldsymbol{c}_y^\top \\ \boldsymbol{c}_y^\top \boldsymbol{A} \\ \boldsymbol{c}_y^\top \boldsymbol{A}^2 \\ \boldsymbol{c}_y^\top \boldsymbol{A}^3 \\ \boldsymbol{c}_y^\top \boldsymbol{A}^4 \\ \vdots \\ \boldsymbol{c}_y^\top \boldsymbol{A}^{2n-1} \\ \boldsymbol{c}_y^\top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

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

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

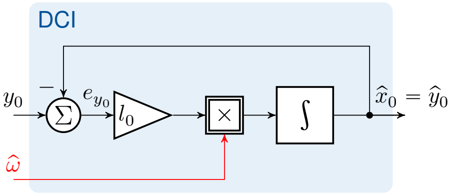
# Frequency-adaptive observer (FAO): Observer design

## Overall observer structure



# Frequency-adaptive observer (FAO): Observer design

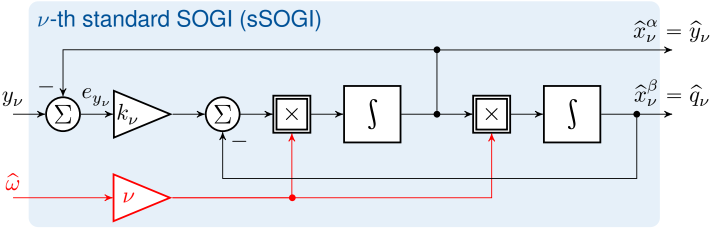
DC-Integrator (DCI) for constant signal estimation: IM$_{\mathrm{dc}}$ with **feedback**




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

# Frequency-adaptive observer (FAO): Observer design

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

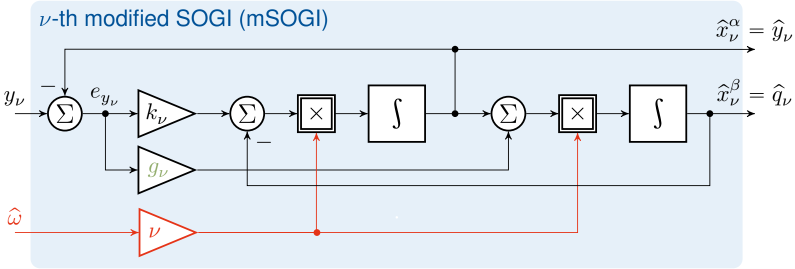



$$\frac{\mathrm{d}}{\mathrm{d}t}\overbrace{\begin{pmatrix}\widehat{x}_\nu^\alpha(t)\\ \widehat{x}_\nu^\beta(t)\end{pmatrix}}^{=:\widehat{\boldsymbol{x}}_\nu(t)\in\mathbb{R}^2} = \widehat{\omega}(t)\overbrace{\begin{bmatrix}0 & -\nu\\ \nu & 0\end{bmatrix}}^{=:\boldsymbol{A}_\nu - \boldsymbol{l}_\nu(k_\nu)\boldsymbol{c}_y^\top}\widehat{\boldsymbol{x}}_\nu(t)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

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

# Frequency-adaptive observer (FAO): Observer design

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

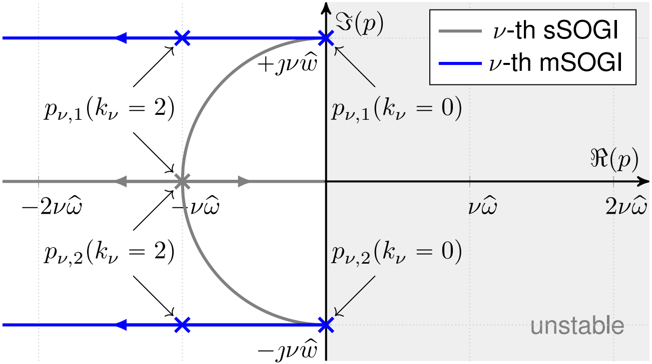



$$\frac{\mathrm{d}}{\mathrm{d}t}\widehat{\boldsymbol{x}}_\nu(t) = \widehat{\omega}(t)\overbrace{\begin{bmatrix} -\nu k_\nu & -\nu \\ \nu - \nu g_\nu & 0 \end{bmatrix}}^{=:\boldsymbol{A}_\nu - \boldsymbol{l}_\nu(k_\nu)\boldsymbol{c}_y^\top}\widehat{\boldsymbol{x}}_\nu(t) + \widehat{\omega}(t)\overbrace{\begin{pmatrix}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

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

# Frequency-adaptive observer (FAO): Observer design

Comparison of root loci of $\nu$-th sSOGI and mSOGI




**sSOGI**

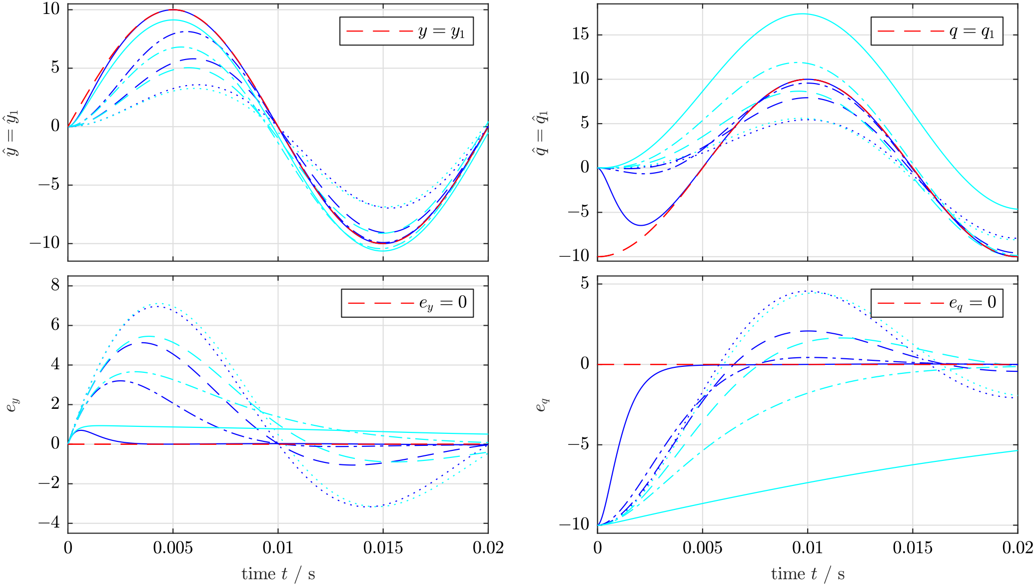
$$p_{\nu,1/2} = -\frac{\nu\widehat{\omega}k_\nu}{2}\left(1 \pm \sqrt{1 - \frac{4}{k_\nu^2}}\right)$$

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

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

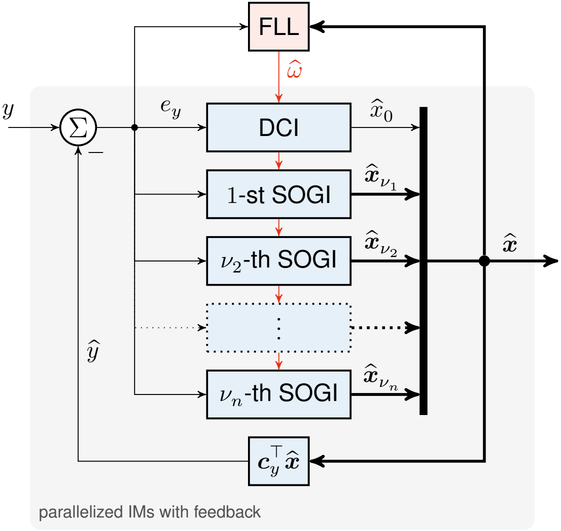
# Frequency-adaptive observer (FAO): Observer design

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



# Frequency-adaptive observer (FAO): Observer design

## Pole placement for overall observer



# Frequency-adaptive observer (FAO): Observer design

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

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

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

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

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

# Frequency-adaptive observer (FAO): Observer design

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

- **Error dynamics** $\boldsymbol{e}_x := \boldsymbol{x} - \widehat{\boldsymbol{x}}$ and $e_\omega := \omega - \widehat{\omega}$ $\implies$ $\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{e}_x = \boldsymbol{f}(\boldsymbol{e}_x, e_\omega, \dots)$
- **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 $\implies \forall \boldsymbol{Q} = \boldsymbol{Q}^\top > 0\ \exists \boldsymbol{P} = \boldsymbol{P}^\top > 0:\ \boldsymbol{H}^\top \boldsymbol{P} + \boldsymbol{P}\boldsymbol{H} = -\boldsymbol{Q} < 0$ [165, Cor. 3.3.47]
  - $\forall a, b, m \in \mathbb{R}:\ 2\,a\,b = \frac{a^2}{m} + mb^2 - \left(\frac{a}{\sqrt{m}} - \sqrt{m}\,b\right)^2 \leqslant \frac{a^2}{m} + m\,b^2$

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

  - Bellmann-Gronwall Lemma [46, Lemma 5.50]

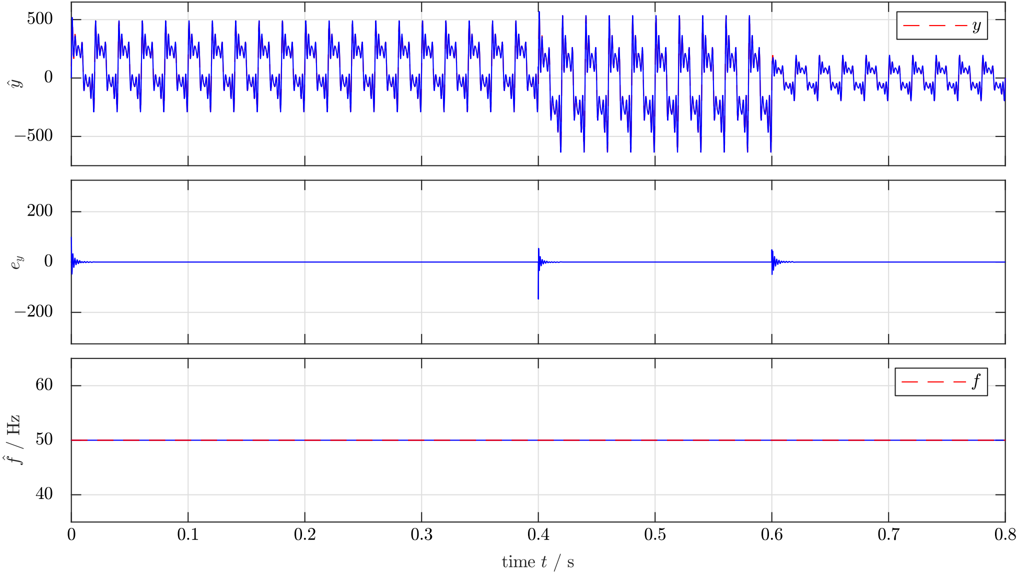
$$\implies \forall t \geqslant t_i:\ V(\boldsymbol{e}_x(t)) \leqslant V(\boldsymbol{e}_x(t_i))\mathrm{e}^{-\mu_V\,(t-t_i)} + c_\omega \int_{t_i}^{t} e_\omega(\tau)^2 \mathrm{e}^{-\mu_V\,(t-\tau)}\,\mathrm{d}\tau$$

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

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

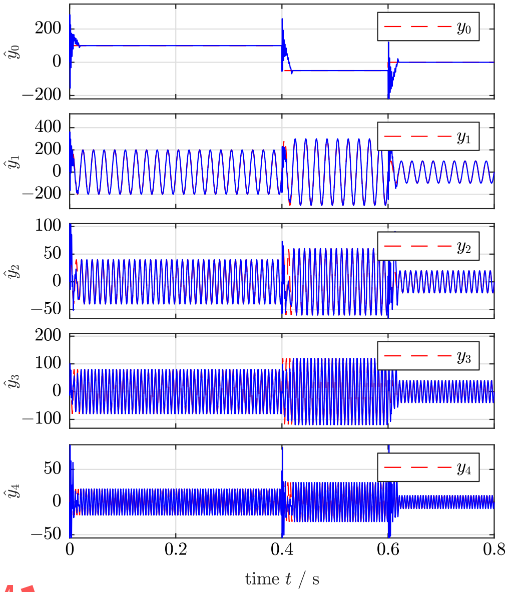
# Frequency-adaptive observer (FAO): Observer design

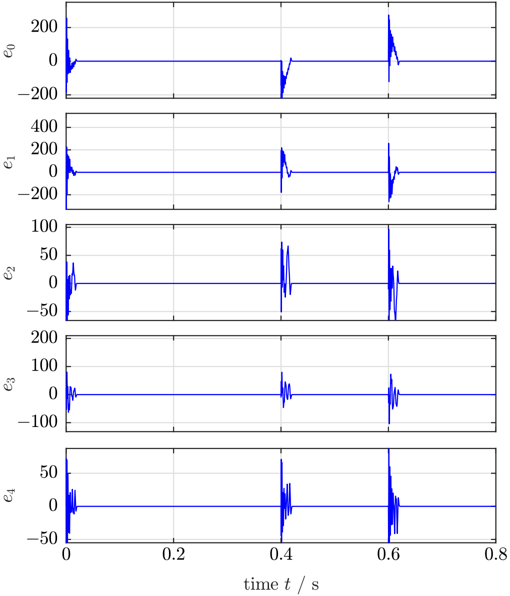
**Simulation results**: Estimate $\widehat{y}$, estimation error $e_y = y - \widehat{y}$ and estimated frequency $\widehat{f} = \frac{\widehat{\omega}}{2\pi}$



# Frequency-adaptive observer (FAO): Observer design

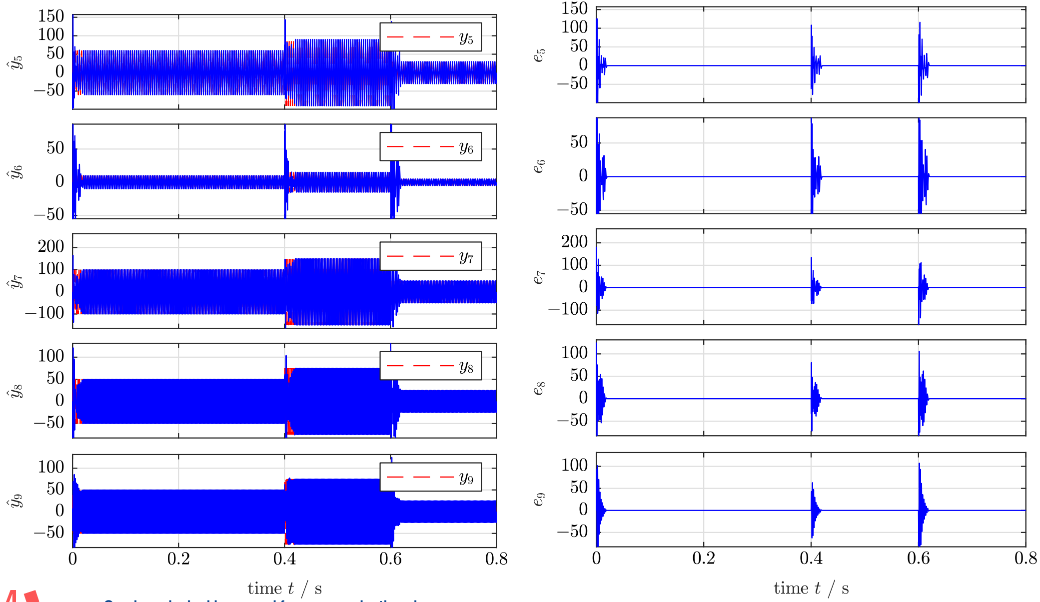
**Simulation results**: Estimate $\widehat{y}_\nu$ (left) and estimation error $e_\nu = y_\nu - \widehat{y}_\nu$ (right)



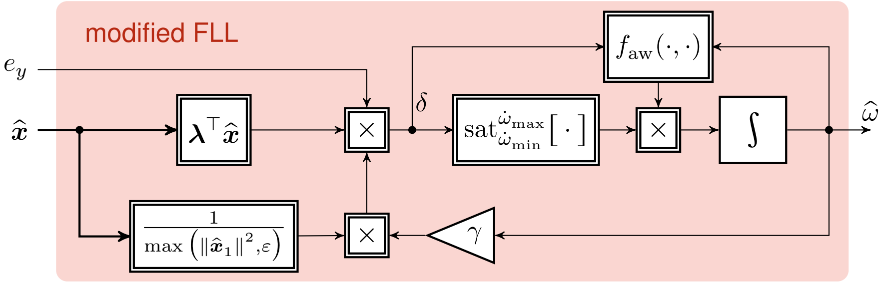
# Frequency-adaptive observer (FAO): Observer design

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



# Frequency-adaptive observer (FAO): Frequency estimation

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

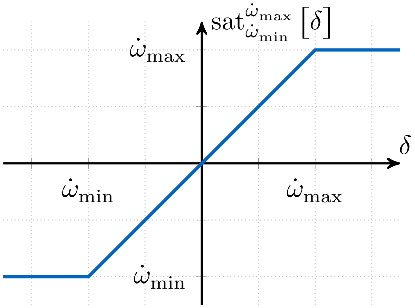



$$\frac{\mathrm{d}}{\mathrm{d}t}\widehat{\omega} = f_{\mathrm{aw}}(\widehat{\omega}, \delta) \cdot \underset{\dot{\omega}_{\min}}{\overset{\dot{\omega}_{\max}}{\mathrm{sat}}}\Bigg[ \underbrace{\frac{\gamma\, \widehat{\omega}\, e_y\, \boldsymbol{\lambda}^\top \widehat{\boldsymbol{x}}}{\max\left(\|\widehat{\boldsymbol{x}}_1\|^2,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

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

# Frequency-adaptive observer (FAO): Frequency estimation

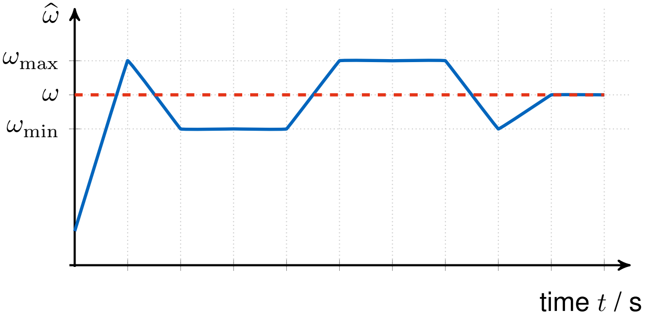
Modified FLL: Saturation of derivative of angular frequency estimate (rate limitation)




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

# Frequency-adaptive observer (FAO): Frequency estimation

## Modified FLL: Sign-correct anti-windup

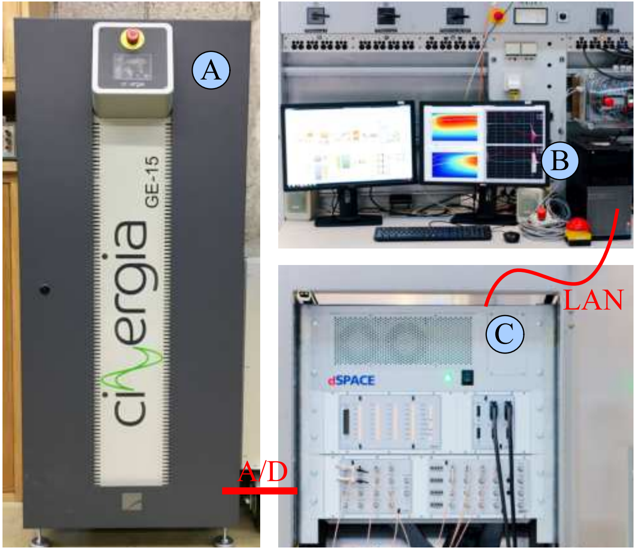



$$f_{\mathrm{aw}}\left(\widehat{\omega}, \tfrac{\mathrm{d}}{\mathrm{d}t}\widehat{\omega}\right) := \begin{cases} 0, & \text{for } \left(\widehat{\omega} \geqslant \omega_{\max} \wedge \tfrac{\mathrm{d}}{\mathrm{d}t}\widehat{\omega} > 0\right) \vee \left(\widehat{\omega} \leqslant \omega_{\min} \wedge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

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

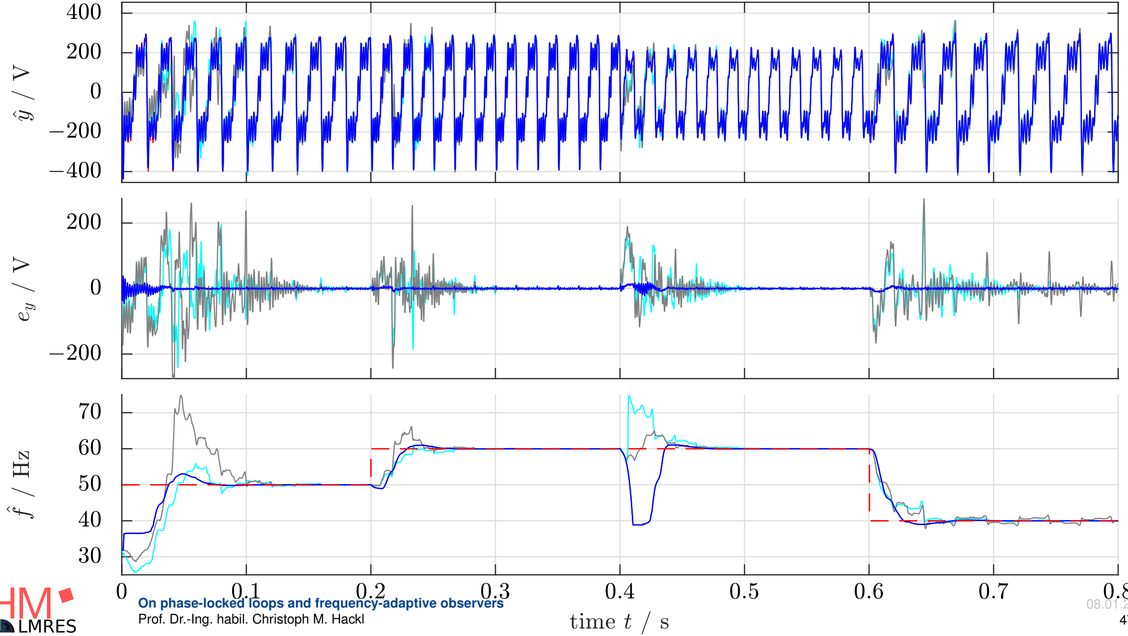
# Frequency-adaptive observer (FAO): Frequency estimation

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



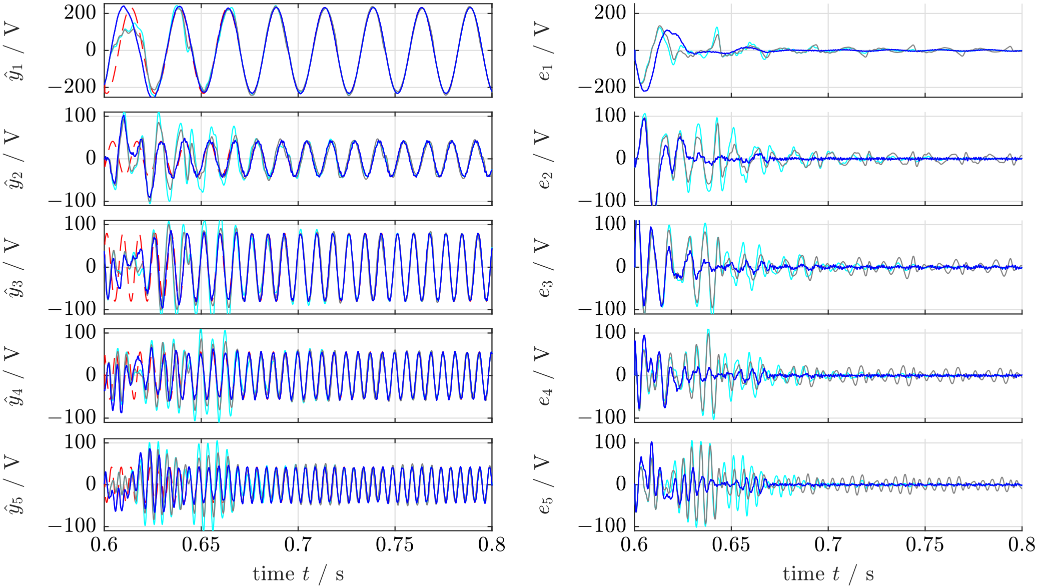
# Frequency-adaptive observer (FAO): Frequency estimation

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



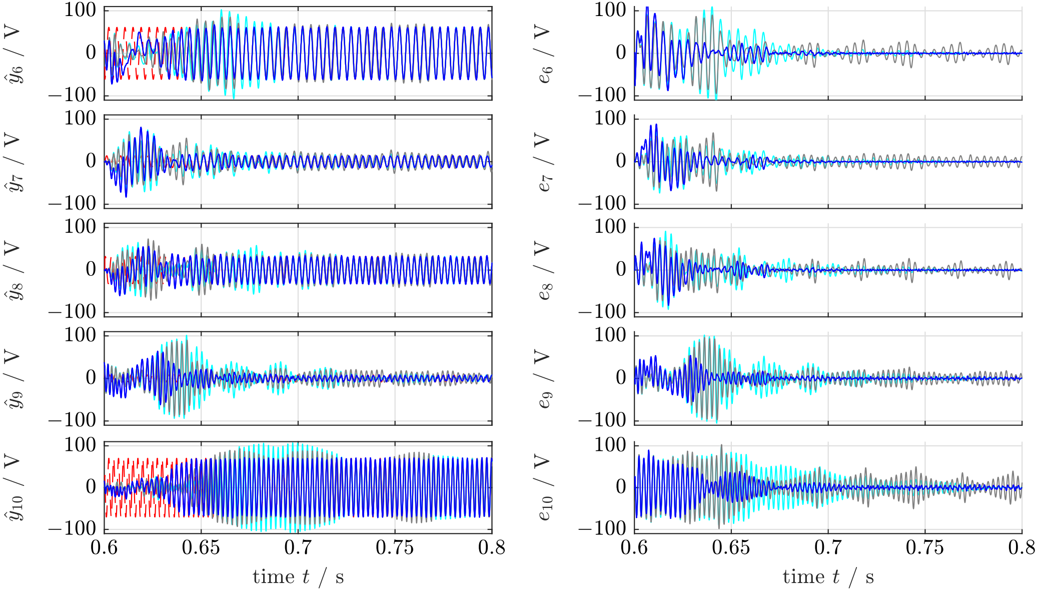
# Frequency-adaptive observer (FAO): Frequency estimation

**Measurement results with FLL [Zoom]**: mSOGI, sSOGI, ANF, $y_\nu$ (left)



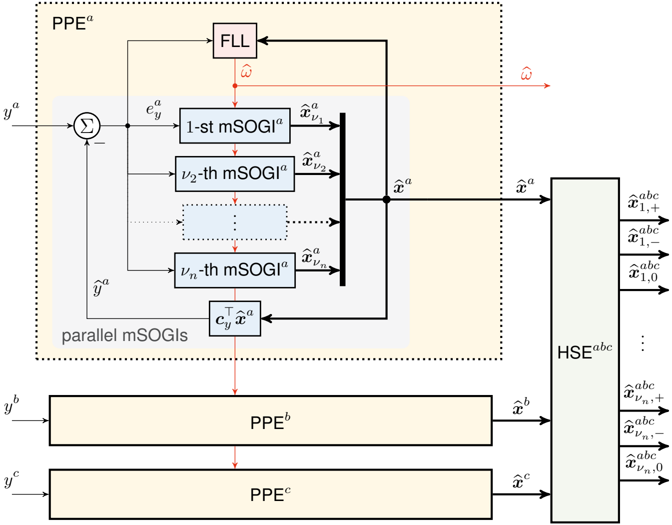
# Frequency-adaptive observer (FAO): Frequency estimation

**Measurement results with FLL [Zoom]**: mSOGI, sSOGI, ANF, $y_\nu$ (left)



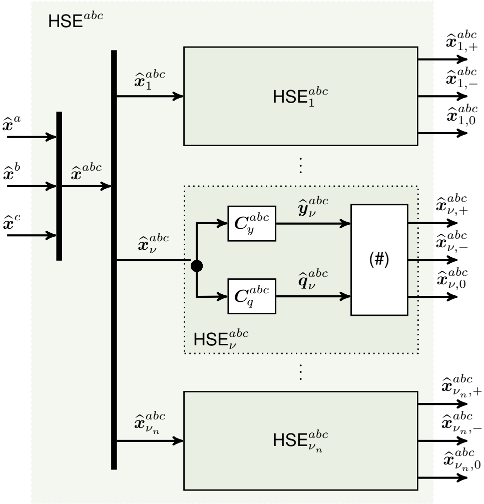
# Frequency-adaptive observer (FAO): Harmonic sequence extraction

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



# Frequency-adaptive observer (FAO): Harmonic sequence extraction

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



# Frequency-adaptive observer (FAO): Harmonic sequence extraction

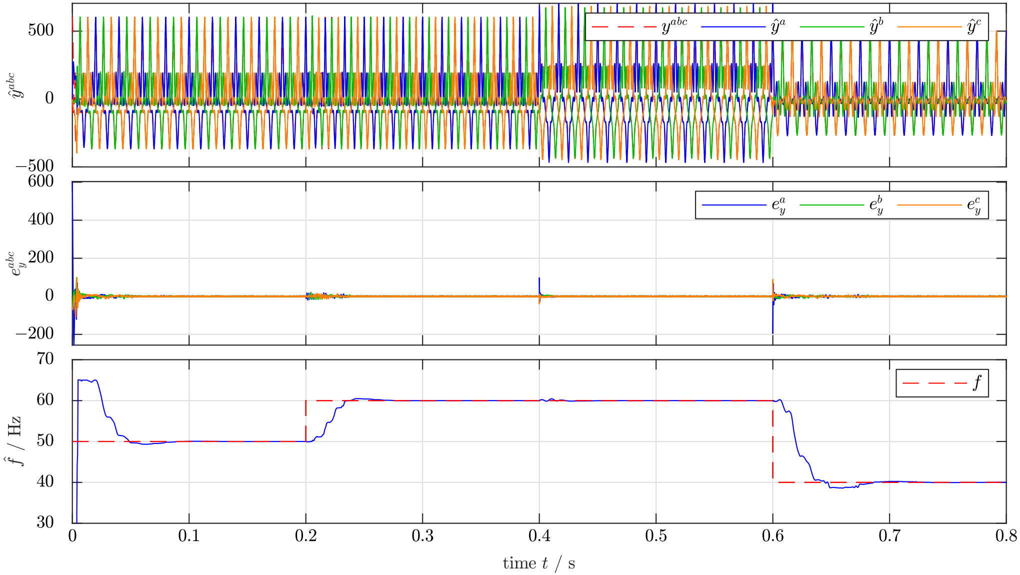
Positive, negative and zero sequence estimation of $\nu$-th harmonic

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

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

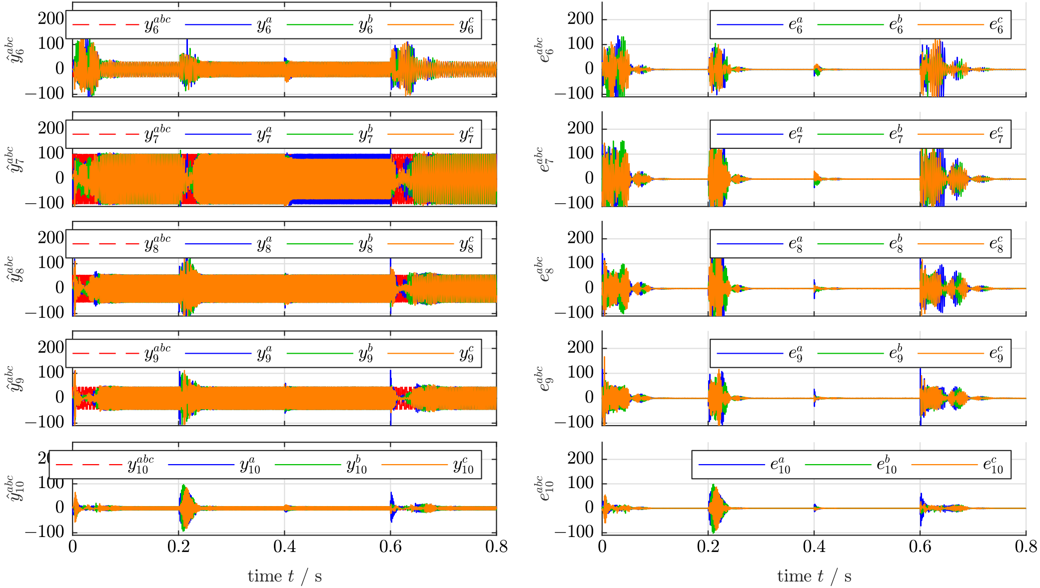
# Frequency-adaptive observer (FAO): Harmonic sequence extraction

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



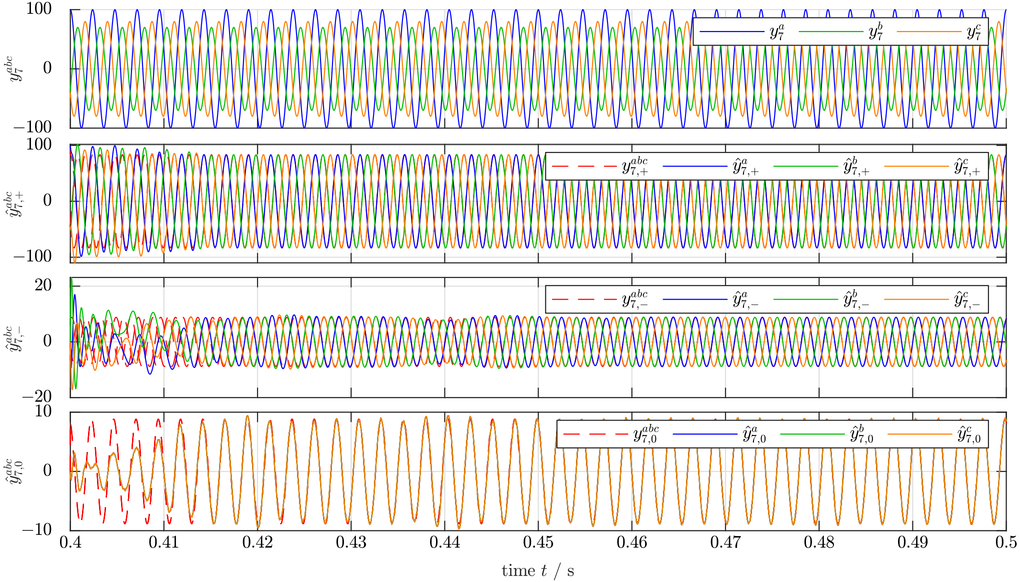
# Frequency-adaptive observer (FAO): Harmonic sequence extraction

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



# Frequency-adaptive observer (FAO): Harmonic sequence extraction

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



# Conclusion

Summary and outlook

## To take home

- **Phase-locked loop (PLL)** simple and effective for undistorted grids
- **Frequency-adaptive observer (FAO)**: **unified theory** for grid state estimation [16, 18, 22], 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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