Hochschule
München (HM)
University of
Applied Sciences

Laboratory for
Mechatronic
and Renewable
Energy Systems
(LMRES)

Frequency-adaptive pole placement for parallelized proportional, integral and resonant control systems

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2026.01.06, Pontifical Catholic University of Chile, Chile

HM

ISES

Outline

Introduction

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

HM ISES LMRES

HM – Munich University of Applied Sciences

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

ISES – Institute for Sustainable Energy Systems

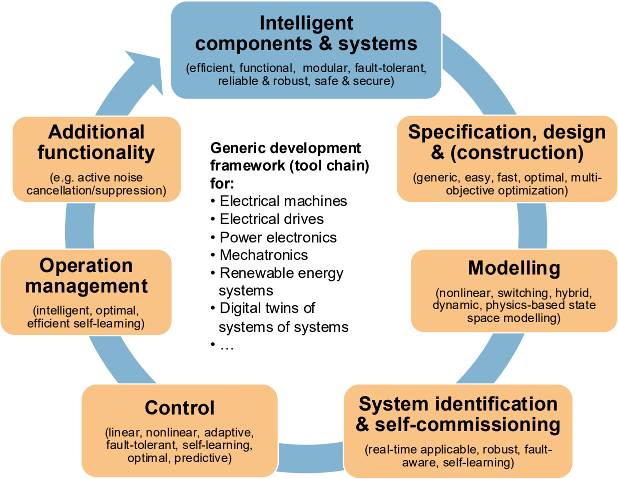
- 8 research labs (8 professors)
- 45 PhD candidates

LMRES – Laboratory for Mechatronic and Renewable Energy Systems

- International team
- 15 PhD candidates
- >150 publications / >10.7 Mio. € raised

Introduction

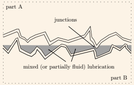
LMRES – Research projects and research goals (funding: > 9.2 million €; e.g. DAAD, Bavaria, BMBF, BMWi, DFG, EU)



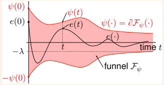
Introduction

LMRES – Interdisciplinary expertise & publications (>150 peer-reviewed contributions)

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) [159–165]

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, 141–158]

Electrical machines & drives [13, 15, 17, 23–27, 30, 32, 33, 45, 46, 51, 55, 57, 69, 77, 78, 80, 89–140]

Introduction

Frequency-adaptive pole placement [166]

Frequency-adaptive pole placement for parallelized proportional, integral and resonant control systems

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***Abstract*—A novel and generic frequency-adaptive pole placement (FAPP) algorithm for parallelized proportional, integral and resonant (PIR) control systems is proposed. It allows to place arbitrarily many closed-loop poles at desired locations in the complex plane (usually negative complex half-plane) with individual damping and settling time characteristics. The closed-loop system with parallelized PIR controllers is then capable of tracking any linear combination of *constant* and *sinusoidal* reference signals asymptotically. The proposed FAPP algorithm achieves a better damped closed-loop system behaviour than Matlab's `place` command. Moreover, even when `place` fails to place the poles at the desired locations in the complex plane, the proposed FAPP will do the job. Additionally, the PIR controller is equipped with a simple anti-windup strategy and an effective reference feedforward control. The proposed approach is illustrated and validated by several simulation examples including multi-harmonic current control of a nonlinear electrical drive.**

***Index Terms*—frequency-adaptive pole placement, proportional, integral and resonant control**

NOTATION

$\mathbb{N}, \mathbb{R}, \mathbb{C}, \mathbb{Q}$: natural, real, complex and rational numbers. $\mathbb{R}_{\geq 0} := [0, \infty)$: positive real numbers with zero. $\mathbb{C}_{<0}$: negative complex half-plane, i.e., all $z \in \mathbb{C}_{<0}$ have negative real parts $\Re\{z\} < 0$. For the following, let $n \in \mathbb{N}$. $\boldsymbol{x} := (x_1, \cdots, x_n)^\top \in \mathbb{R}^n$: column vector (where $:=$ means "is defined as" and $^\top$ means "transposed"). $\mathbf{0}_n := (0, 0, , \cdots, 0)^\top \in \mathbb{R}^n$: 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. $\boldsymbol{O}_{n \times m} \in \mathbb{R}^{n \times m}$: zero (non-square) matrix. $\boldsymbol{I}_n := \mathrm{diag}(\mathbf{1}_n) \in \mathbb{R}^{n \times n}$: identity matrix. $\boldsymbol{J} := \left[\begin{smallmatrix} 0 & -1 \\ 1 & 0 \end{smallmatrix}\right]$: rotation matrix rotating a vector by $\frac{\pi}{2}$ (counterclockwise).

I. INTRODUCTION

A. Motivation

Several applications require active control of constant and

reference signal containing not only constant terms but also multiple sinusoidal components. After Clarke transformation with Clarke transformation factor $\kappa \in \{\frac{2}{3}, \sqrt{\frac{2}{3}}\}$ (allowing for amplitude or power invariant transformation [12, Section 14.2.4]), such a time-varying reference signal $\boldsymbol{y}_{\mathrm{ref}}(t) := \boldsymbol{y}^{\alpha\beta}_{\mathrm{ref}}(t)$ in the (α, β)-reference frame[1] is given by

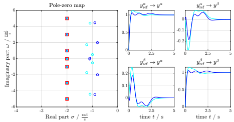
$$\boldsymbol{y}_{\mathrm{ref}}(t) = \underbrace{\begin{pmatrix} A^{\alpha}_{\mathrm{dc}}(t) \\ A^{\beta}_{\mathrm{dc}}(t) \end{pmatrix}}_{=:\boldsymbol{y}^{\alpha\beta}_{\mathrm{dc,ref}}(t)\ \text{[dc part]}} + \underbrace{\sum_{\nu \in \mathbb{H}} \overbrace{\tfrac{3}{2\kappa} A_\nu(t) \begin{pmatrix} \cos(\phi_\nu(t) + \varphi_\nu) \\ \sin(\phi_\nu(t) + \varphi_\nu) \end{pmatrix}}^{=:\boldsymbol{y}^{\alpha\beta}_{\nu,\mathrm{ref}}(t)}}_{=:\boldsymbol{y}^{\alpha\beta}_{\mathrm{ac,ref}}(t)\ \text{[ac part (harmonics)]}}. \tag{1}$$

It consists of desired dc reference $\boldsymbol{y}^{\alpha\beta}_{\mathrm{dc,ref}}(t)$ with possibly time-varying individual dc components $A^{\alpha}_{\mathrm{dc}}(t)$ and $A^{\beta}_{\mathrm{dc}}(t)$ and desired sinusoidal reference $\boldsymbol{y}^{\alpha\beta}_{\mathrm{ac,ref}}(t) = \sum_{\nu \in \mathbb{H}} \boldsymbol{y}^{\alpha\beta}_{\nu,\mathrm{ref}}(t)$ with a possibly time-varying amplitude $A_\nu(t)$, time-varying angle

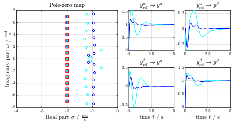
$$\phi_\nu(t) := \int_0^t \nu \omega_{\mathrm{f}}(\tau)\, \mathrm{d}\tau \quad \text{with harmonic order } \nu \in \mathbb{H} \subset \mathbb{Q},$$

which depends on the time-varying fundamental angular frequency $\omega_{\mathrm{f}}(t)$, and constant phase offset φ_ν, respectively for each harmonic order $\nu \in \mathbb{H}$. The set $\mathbb{H}$ of harmonic orders may contain any rational numbers $\nu \in \mathbb{Q}$ including e.g. positive $(\nu_+ > 0)$ and negative $(\nu_- < 0)$ sequence harmonic orders.

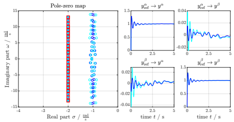
The internal model principle [13], well known in control theory, states that for such reference (or disturbance) signals, a parallelization of proportional, integral and (multiple) resonant controllers ($\mathrm{PIR}_{\mathbb{H}}$ controller) is necessary to achieve asymptotic tracking by reduplicating the constant and sinusoidal components of all harmonic orders $\nu \in \mathbb{H}$ of the reference signal in (1). However, the tuning of the parallel $\mathrm{PIR}_{\mathbb{H}}$ controller



(a) $\mathbb{H}_1 := \{3; 5\}$ with $h_1 = 2$ and $m_1 = 8$.



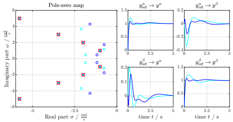
(b) $\mathbb{H} := \{2; 3; 4; 5; 6; 7\}$ with $h_2 = 6$ and $m_2 = 16$.



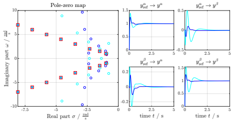
(c) $\mathbb{H}_3 := \{\pm 2; \pm 3; \pm 4; 5; -6; \pm 7; \pm 8; \pm 9; \pm 10; 11; -12; \pm 13\}$ with $h_3 = 20$ and $m_3 = 44$.

Figure 2: Illustrative simulation results for different harmonic set $\mathbb{H}$ (see subplots (a), (b) & (c)) and tuning according to **($\mathbf{ESG}_1$)** with `place` [—] and FAPP [—]: poles [×], zeros [○] & desired poles [□] (double pole on real axis in each subplot (a), (b) & (c)).

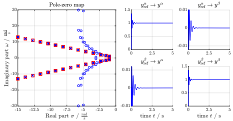
respectively. Pole placement with `place` (from Matlab) and FAPP are performed according to the Eigenvalue Selection Guidelines **($\mathbf{ESG}_1$)** and **($\mathbf{ESG}_2$)** (recall Section II-D3) and



(a) $\mathbb{H}_1 := \{3; 5\}$ with $h_1 = 2$ and $m_1 = 8$.



(b) $\mathbb{H}_2 := \{2; 3; 4; 5; 6; 7\}$ with $h_2 = 6$ and $m_2 = 16$.



(c) $\mathbb{H}_3 := \{\pm 2; \pm 3; \pm 4; 5; -6; \pm 7; \pm 8; \pm 9; \pm 10; 11; -12; \pm 13\}$ with $h_3 = 20$ and $m_3 = 44$ ("`place`" **fails**; not shown here).

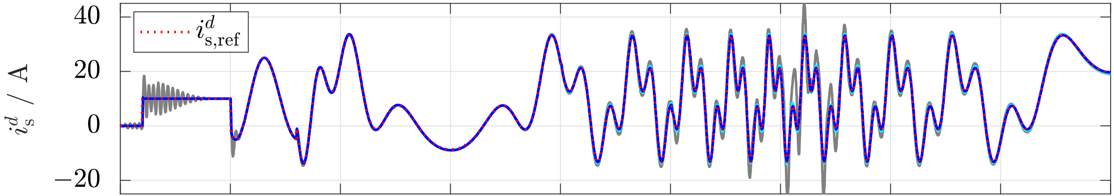
Figure 3: Illustrative simulation results for different harmonic set $\mathbb{H}$ (see subplots (a), (b) & (c)) and tuning according to **($\mathbf{ESG}_2$)** with `place` [—] and FAPP [—]: poles [×], zeros [○] & desired poles [□].

when compared with the desired Eigenvalues highlighted by red squares [□]. The respective step responses are also simular; however, the closed-loop systems tuned by `place` (see cyan lines [—]) exhibit more oscillations and are less well damped

Introduction

Motivation and problem statement

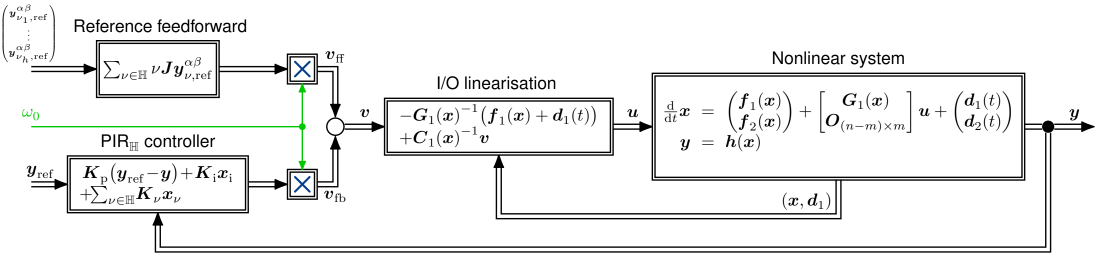
Reference signal with constant and (multiple) sinusoidal components



Can we achieve fast and accurate tracking ...

- with (almost) no overshoot ?
- with (asymptotically) vanishing tracking error ?
- while considering multiple harmonics and dc-offsets ?
- by which controller structure ?
- by which tuning even if the frequency is varying ?

Proposed controller structure



for **frequency-adaptive pole placement for parallelized proportional, integral and resonant control systems**, which is conducted in four steps:

- Step 1: Input/output (I/O) linearization;
- Step 2: Implementation of parallelized PIR$_{\mathbb{H}}$ controller;
- Step 3: Frequency-adaptive pole placement; and
- Step 4: Reference feedforward control.

Frequency-adaptive pole placement for parallelized systems

Step 1: I/O linearization

Considered system class with multi-input $\boldsymbol{u} \in \mathbb{R}^m$ multi-ouput $\boldsymbol{y} \in \mathbb{R}^m$ (MIMO) dynamics

$$\left.\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x} &= \begin{pmatrix} \boldsymbol{f}_1(\boldsymbol{x}) \\ \boldsymbol{f}_2(\boldsymbol{x}) \end{pmatrix} + \begin{bmatrix} \boldsymbol{G}_1(\boldsymbol{x}) \\ \boldsymbol{O}_{(n-m)\times m} \end{bmatrix} \boldsymbol{u} + \begin{pmatrix} \boldsymbol{d}_1(t) \\ \boldsymbol{d}_2(t) \end{pmatrix} \\ \boldsymbol{y} &= \boldsymbol{h}(\boldsymbol{x}) \end{aligned}\right\} \tag{1}$$

where $\boldsymbol{f}_1\colon \mathbb{R}^n \to \mathbb{R}^m$, $\boldsymbol{f}_2\colon \mathbb{R}^n \to \mathbb{R}^{n-m}$, $\boldsymbol{h}\colon \mathbb{R}^n \to \mathbb{R}^m$, $\boldsymbol{G}_1\colon \mathbb{R}^n \to \mathbb{R}^{m\times m}$ with $\det \boldsymbol{G}_1(\boldsymbol{x}) \neq 0$ and

$$\left[\tfrac{\mathrm{d}}{\mathrm{d}\boldsymbol{x}}\boldsymbol{h}(\boldsymbol{x})\right]^\top = \Big[\underbrace{\tfrac{\mathrm{d}}{\mathrm{d}(x_1,\ldots,x_m)}\boldsymbol{h}(\boldsymbol{x}),}_{=:\boldsymbol{C}_1(\boldsymbol{x})\in\mathbb{R}^{m\times m}} \quad \boldsymbol{O}_{m\times(n-m)}\Big]$$

with $\det \boldsymbol{C}_1(\boldsymbol{x}) \neq 0$ for all $\boldsymbol{x} \in \mathbb{R}^n$ (i.e., $\boldsymbol{G}_1(\boldsymbol{x})$ and $\boldsymbol{C}_1(\boldsymbol{x})$ are invertible).

Step 1: Input/output (I/O) linearization

$$\boxed{\boldsymbol{u} = -\boldsymbol{G}_1(\boldsymbol{x})^{-1}\big(\boldsymbol{f}_1(\boldsymbol{x}) + \boldsymbol{d}_1(t) + \boldsymbol{C}_1(\boldsymbol{x})^{-1}\boldsymbol{v}\big),} \tag{2}$$

gives $\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{y} \overset{(1),(2)}{=} \boldsymbol{C}_1(\boldsymbol{x})\Big[\boldsymbol{f}_1(\boldsymbol{x}) + \boldsymbol{G}_1(\boldsymbol{x}) \cdot \Big(-\boldsymbol{G}_1(\boldsymbol{x})^{-1}\big(\boldsymbol{f}_1(\boldsymbol{x})+\boldsymbol{d}_1(t)+\boldsymbol{C}_1(\boldsymbol{x})^{-1}\boldsymbol{v}\big)\Big)+\boldsymbol{d}_1(t)\Big]=\boldsymbol{v}$.

Frequency-adaptive pole placement for parallelized systems

Step 2: Implementation of parallelized $\mathrm{PIR}_{\mathbb{H}}$ controller

Properties of controller:

- Let $m=2 \to 2$-input, 2-output system of form (1)
- Choose set $\mathbb{H}$ of harmonic orders with cardinality $|\mathbb{H}| =: h \in \mathbb{N}$
- Choose the $\mathrm{PIR}_{\mathbb{H}}$ controller's feedback vector $\boldsymbol{v}_{\mathrm{fb}} \in \mathbb{R}^2$ with $2h+2$ states $\boldsymbol{x}_{\mathrm{pir}} := (\boldsymbol{x}_{\mathrm{i}}^\top, \boldsymbol{x}_{\nu_1}^\top, \cdots, \boldsymbol{x}_{\nu_h}^\top)^\top \in \mathbb{R}^{2h+2}$, including integral states $\boldsymbol{x}_{\mathrm{i}} \in \mathbb{R}^2$ and h resonant double states $\boldsymbol{x}_\nu \in \mathbb{R}^2$ for all $\nu \in \mathbb{H}$.

Hence, the **parallelized $\mathrm{PIR}_{\mathbb{H}}$ controller** is given by

$$\left.\begin{aligned}
\boldsymbol{v}_{\mathrm{fb}} &= \omega_0 \Big[\boldsymbol{K}_{\mathrm{p}}\big(\boldsymbol{y}_{\mathrm{ref}} - \boldsymbol{y}\big) + \boldsymbol{K}_{\mathrm{i}}\boldsymbol{x}_{\mathrm{i}} + \sum_{\nu\in\mathbb{H}} \boldsymbol{K}_\nu \boldsymbol{x}_\nu\Big] \\
\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}_{\mathrm{pir}} &= \underbrace{\omega_0 \overbrace{\begin{bmatrix} \boldsymbol{O} & \boldsymbol{O} & \cdots & \boldsymbol{O} \\ \boldsymbol{O} & \nu_1\boldsymbol{J} & \ddots & \vdots \\ \vdots & \ddots & \ddots & \boldsymbol{O} \\ \boldsymbol{O} & \cdots & \boldsymbol{O} & \nu_h\boldsymbol{J} \end{bmatrix}}^{=:\boldsymbol{A}_{\mathrm{pir}}} \boldsymbol{x}_{\mathrm{pir}} + \omega_0 \overbrace{\begin{bmatrix} \boldsymbol{I}_2 \\ \boldsymbol{I}_2 \\ \vdots \\ \boldsymbol{I}_2 \end{bmatrix}}^{=:\boldsymbol{B}_{\mathrm{pir}}} \big(\boldsymbol{y}_{\mathrm{ref}} - \boldsymbol{y}\big)}_{=:\boldsymbol{f}_{\mathrm{pir}}(\boldsymbol{x}_{\mathrm{pir}},\boldsymbol{y}_{\mathrm{ref}}-\boldsymbol{y},\omega_0,\omega_{\mathrm{i}},\omega_{\mathrm{f}},\ldots,\omega_{\nu_h})}
\end{aligned}\right\} \tag{3}$$

Remark: Note that all gain matrices $\boldsymbol{K}_{\mathrm{p}}$, $\boldsymbol{K}_{\mathrm{i}}$ and $\boldsymbol{K}_{\nu_1}, \ldots, \boldsymbol{K}_{\nu_h}$ are element of $\mathbb{R}^{2\times 2}$ and may be scaled by some angular frequency $\omega_0 \geq 1$. Anti-windup should also be implemented.

Frequency-adaptive pole placement for parallelized systems

Step 3: Frequency-adaptive pole placement

The **frequency-adaptive tuning rule for the controller gain matrices**

$$\boldsymbol{K} := \left[-\boldsymbol{K}_{\mathrm{p}}, \quad \boldsymbol{K}_{\mathrm{i}}, \quad \boldsymbol{K}_{\nu_1}, \quad \cdots, \quad \boldsymbol{K}_{\nu_h}\right] \in \mathbb{R}^{2\times m} \tag{4}$$

is obtained as

$$\boxed{\boldsymbol{K} = \left[\boldsymbol{\Lambda}^\star_{\mathbb{R},1} \quad \cdots \quad \boldsymbol{\Lambda}^\star_{\mathbb{R},l}\right] \begin{bmatrix} \boldsymbol{I}_2 & \cdots & \boldsymbol{I}_2 \\ \boldsymbol{T}_{2,1} & \cdots & \boldsymbol{T}_{2,l} \\ \vdots & \ddots & \vdots \\ \boldsymbol{T}_{l,1} & \cdots & \boldsymbol{T}_{l,l} \end{bmatrix}^{-1} \quad \text{with } \boldsymbol{\Lambda}^\star_{\mathbb{R},k} := \begin{bmatrix} -\sigma^\star_k & -\omega^\star_k \\ \omega^\star_k & -\sigma^\star_k \end{bmatrix} = -\sigma^\star_k \boldsymbol{I}_2 + \omega^\star_k \boldsymbol{J},} \tag{5}$$

where, for all $i \in \{2, \cdots, l\}$ and $j \in \{1, \cdots, l\}$,

$$\boxed{\boldsymbol{T}_{i,j} = \alpha_1 \left[\alpha_i \boldsymbol{J} - \boldsymbol{\Lambda}^\star_{\mathbb{R},j}\right]^{-1}.} \tag{6}$$

Remark: The simple definition above is based on the introduction of $\alpha_1 := 1$, $\alpha_2 := 0$, $\alpha_3 := \nu_1$, $\alpha_4 := \nu_2, \ldots, \alpha_l := \nu_h$. All $\boldsymbol{T}_{i,j}$ depend solely on known quanteties such as the harmonic orders $\nu_1 = \alpha_3, \nu_2 = \alpha_4, \ldots, \nu_h = \alpha_l$, and real $\sigma^\star_j$ and imaginary $\omega^\star_j$ parts of the j-th desired pole pair $\lambda^\star_j = -\sigma^\star_j + \jmath\omega^\star_j$ and $\overline{\lambda^\star_j} = -\sigma^\star_j - \jmath\omega^\star_j$, respectively.

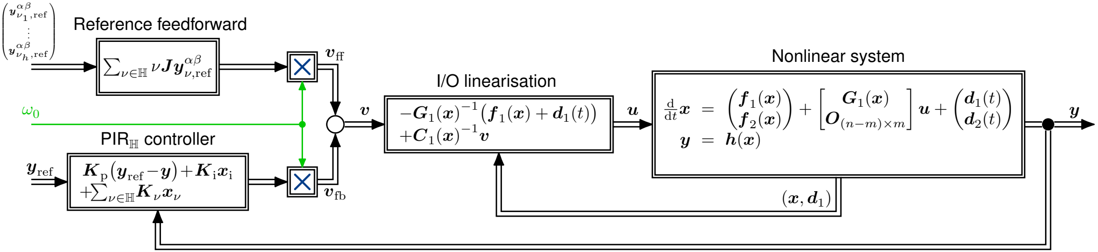
Frequency-adaptive pole placement for parallelized systems

Step 4: Reference feedforward control

Invoking the Internal Model Principle, the desired **reference feedforward control** has the following form

$$\boxed{\boldsymbol{v}_{\mathrm{ff}} = \sum\nolimits_{\nu\in\mathbb{H}} \omega_\nu \boldsymbol{J}\boldsymbol{y}^{\alpha\beta}_{\nu,\mathrm{ref}} = \omega_0 \sum\nolimits_{\nu\in\mathbb{H}} \nu\boldsymbol{J}\boldsymbol{y}^{\alpha\beta}_{\nu,\mathrm{ref}},} \tag{7}$$

which only depends on the actual reference components of the respective harmonic order $\nu \in \mathbb{H}$. Combining all four steps gives the **overall control system** (as introduced above):



Implementation and simulative validation

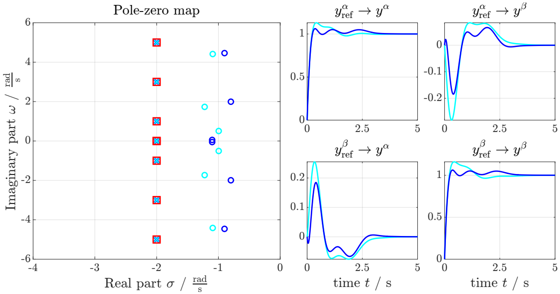
Illustrative examples – Example 1: $\mathbb{H}_1 := \{3; 5\}$ with $h_1 = 2$ and $m_1 = 8$.

Considered simple dynamical system (pure integrator; e.g., after I/O linearization):

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{y} = \frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} y^\alpha \\ y^\beta \end{pmatrix} = \boldsymbol{u} := \begin{pmatrix} u^\alpha \\ u^\beta \end{pmatrix}$$

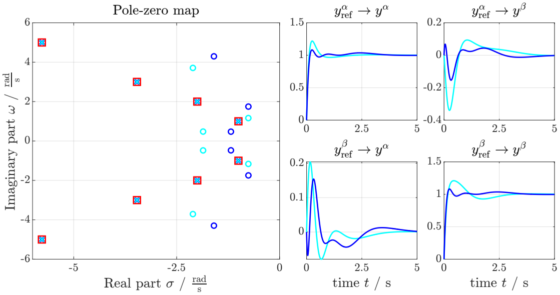
Eigenvalue Selection Guideline 1:

$$\sigma_j^\star = \alpha^\star \wedge \omega_j^\star = \nu_j^\star \Rightarrow \lambda_j^\star = -\alpha^\star \pm \jmath\nu_j^\star$$



Eigenvalue Selection Guideline 2:

$$\sigma_j^\star = \frac{\nu_j^\star}{\sqrt{1-(D^\star)^2}} \wedge \omega_j^\star = \nu_j \Rightarrow \lambda_j^\star = -\nu_j^\star\left(\frac{1}{\sqrt{1-(D^\star)^2}} \pm \jmath\right)$$



Legend: `place` [—] and FAPP [—]: poles [$\times$], zeros [$\circ$]

Implementation and simulative validation

Illustrative examples – Example 2: $\mathbb{H}_2 := \{2;3;4;5;6;7\}$ with $h_2 = 6$ and $m_2 = 16$.

Considered simple dynamical system (pure integrator; e.g., after I/O linearization):

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{y} = \frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} y^\alpha \\ y^\beta \end{pmatrix} = \boldsymbol{u} := \begin{pmatrix} u^\alpha \\ u^\beta \end{pmatrix}$$

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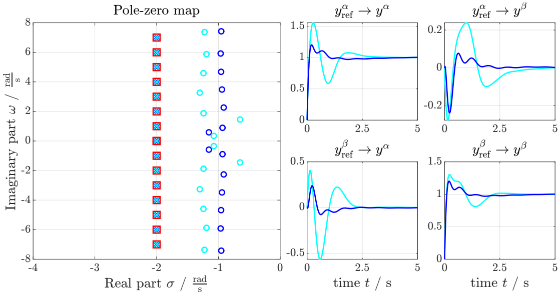

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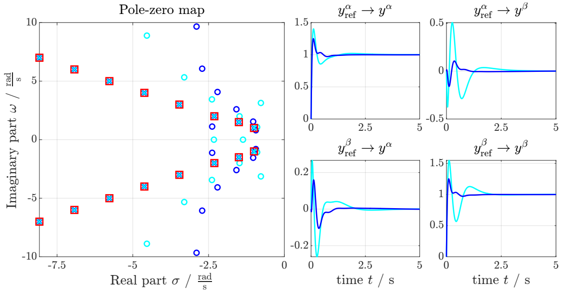

Legend: `place` [—] and FAPP [—]: poles [$\times$], zeros [$\circ$]

Implementation and simulative validation

Illustrative examples – Example 3: $\mathbb{H}_3 := \{\pm 2; \pm 3; \pm 4; 5; -6; \pm 7; \pm 8; \pm 9; \pm 10; 11; -12; \pm 13\}$ with $h_3 = 20$ and $m_3 = 44$

Considered simple dynamical system (pure integrator; e.g., after I/O linearization):

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{y} = \frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} y^\alpha \\ y^\beta \end{pmatrix} = \boldsymbol{u} := \begin{pmatrix} u^\alpha \\ u^\beta \end{pmatrix}$$

Eigenvalue Selection Guideline 1:

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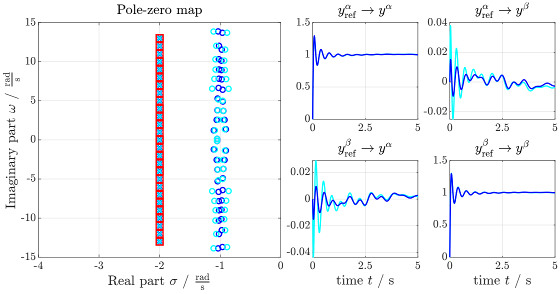
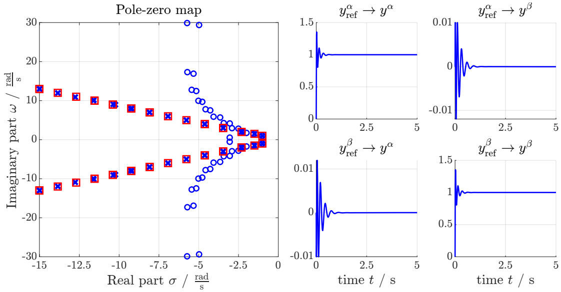


Eigenvalue Selection Guideline 2: ("`place`" fails!)

$$\sigma_j^\star = \frac{\nu_j^\star}{\sqrt{1-(D^\star)^2}} \wedge \omega_j^\star = \nu_j \Rightarrow \lambda_j^\star = -\nu_j^\star\left(\frac{1}{\sqrt{1-(D^\star)^2}} \pm \jmath\right)$$



—————- Legend: `place` [—] and FAPP [—]: poles [×], zeros [∘] —————

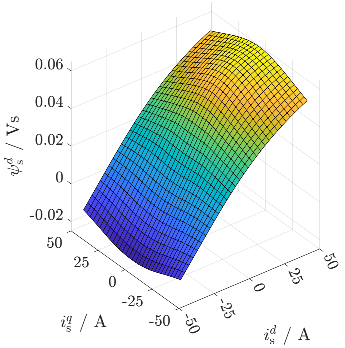
Implementation and simulative validation

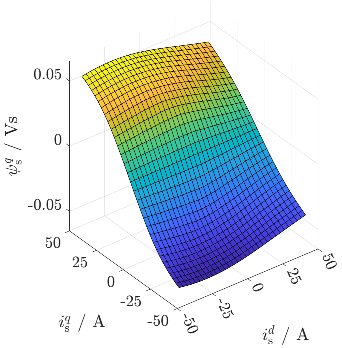
Multi-harmonic current control of nonlinear IPMSM – machine model

Nonlinear machine dynamics

$$\left.\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_\mathrm{s}^{dq} &= \left(\boldsymbol{L}_\mathrm{s}^{dq}\right)^{-1}\left(\boldsymbol{u}_\mathrm{s}^{dq} - \boldsymbol{R}_\mathrm{s}^{dq}\boldsymbol{i}_\mathrm{s}^{dq} - n_\mathrm{p}\omega_\mathrm{m}\boldsymbol{J}\boldsymbol{\psi}_\mathrm{s}^{dq}\right)\\ \frac{\mathrm{d}}{\mathrm{d}t}\omega_\mathrm{m} &= \frac{1}{\Theta_\mathrm{m}}\left(m_\mathrm{m} - m_\mathrm{l}\right),\\ \frac{\mathrm{d}}{\mathrm{d}t}\phi_\mathrm{m} &= \omega_\mathrm{m}.\end{aligned}\right\} \tag{8}$$

with nonlinear flux linkage maps



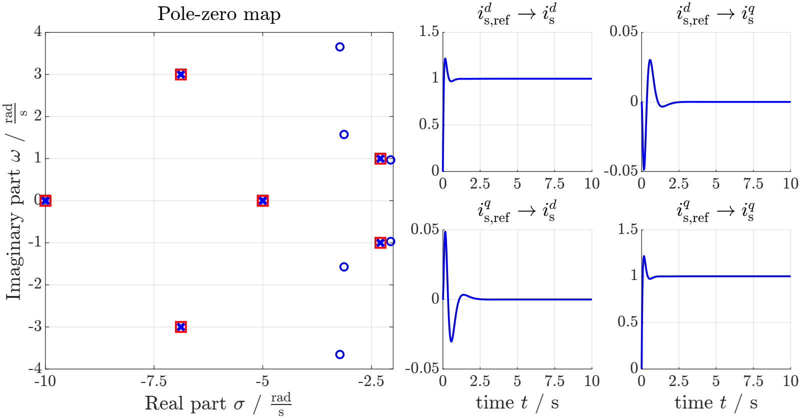


Implementation and simulative validation

Multi-harmonic current control of nonlinear IPMSM

Controller specifications / tuning:

- Desired harmonics $\mathbb{H}_{\mathrm{ipmsm}} := \{1; 3\} \Rightarrow$ number of harmonics $h_{\mathrm{ipmsm}} = 2$ and states $m_{\mathrm{ipmsm}} = 8$;
- Pole placement with (unscaled) desired poles $\sigma_j^\star$, $\omega_j^\star$ as in figure below (see [ ])
- Varying speeds $\Rightarrow$ frequency adaptation $\alpha_{\mathrm{m}} n_{\mathrm{p}} \omega_{\mathrm{m,R}} \left(\beta_{\mathrm{m}} + \frac{|\omega_{\mathrm{m}}(t)|}{\omega_{\mathrm{m,R}}}\right)$ with $\alpha_{\mathrm{m}} = 1$ and $\beta_{\mathrm{m}} = 0.05$



Implementation and simulative

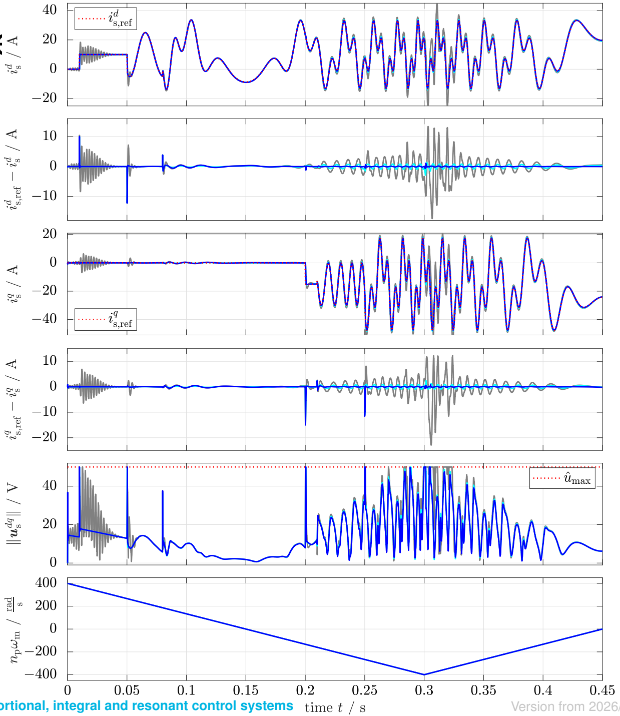
Multi-harmonic current control of nonlinear IPMSM

High-fidelity simulation results:
Three different controller implementations to compare multi-harmonic current control performace for nonlinear IPMSM:

(C1) $\mathrm{PIR}_{\mathbb{H}}$ controller *without* reference feedforward control and *without* frequency adaption (w/o RFF & w/o FA) [—];

(C2) $\mathrm{PIR}_{\mathbb{H}}$ controller *without* reference feedforward control but *with* frequency adaption (w/o RFF & w/ FA) [—] and

(C3) $\mathrm{PIR}_{\mathbb{H}}$ controller *with* reference feedforward control and *with* frequency adaption (w/ RFF & w/ FA) [—]



Conclusion

To take home

- Novel and generic frequency-adaptive pole placement (FAPP) algorithm (beats `place`!)
- Applicable for for parallelized proportional, integral and resonant (PIR) control systems has been presented. Additionally, a simple conditional-integration based anti-windup strategy
- Effective reference feedforward control

Future work

- descrete-time and real-time implementation;
- experimental validation in the laboratory;
- sensitivity and robustness analysis / consideration of parameter/model uncertainties; and
- avoidance of the need of matrix inversion (to avoid risk of numerical instability).

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