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University of
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Laboratory for
Mechatronic
and Renewable
Energy Systems
(LMRES)

Transient response shaping and its application to nonlinear PI-based current control systems

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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

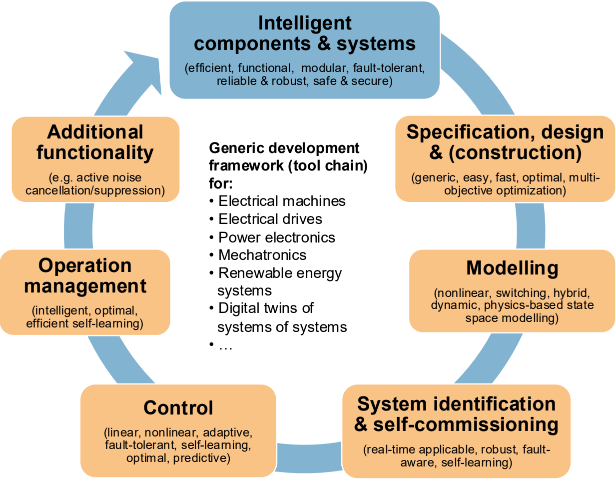
- 8 research labs (8 professors)
- 45 PhD candidates

LMRES – Laboratory for Mechatronic and Renewable Energy Systems

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

Introduction

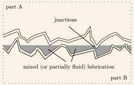
LMRES – Research projects and research goals (funding: > 9.2 million €; e.g. DAAD, Bavaria, BMBF, BMWi, DFG, EU)



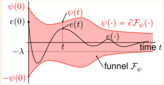
Introduction

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

System identification [9–26]



Friction [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

Transient response shaping [166]

Transient response shaping and its application to nonlinear PI-based current control systems

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***Abstract*—A novel and modular approach for transient response shaping (TRS) of a broad class of nonlinear input/output linearizable systems controlled by nonlinear PI controllers with anti-windup is introduced. It allows to shape the transient response of the closed-loop system to match a prescribed linear reference system (e.g., first-, second-, or nth-order lag system). The derived transient response shaping networks (TRSNs) are simple to tune and guarantee prescribed overshoot, rise time, and settling time. Besides, the TRSNs can be easily and seamlessly integrated into existing PI-based control structures without the need of retuning of the PI controllers, emphasizing the modularity of the proposed approach. Several high-fidelity simulation results, including, e.g., high-performance current control of a nonlinear interior permanent-magnet synchronous machine drive, demonstrate effectiveness, functionality and benefits of the proposed TRS approach compared to classical approaches.**

***Index Terms*—Transient response shaping, input/output linearization control, nonlinear PI-based current control**

NOTATION

$\mathbb{N},\mathbb{R}$: natural and real numbers. 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). $a\overset{!}{=}b$: a should equal b.

I. INTRODUCTION

Almost all industrial applications require active control of certain quantities [1]. For electrical drives [2, 3], typical control problems are *current control*, *speed control* or, for certain applications, encoderless control with *phase-locked loop (PLL)*. Mostly, PI controllers are adopted and must be tuned properly. Tuning is achieved by a variety of methods

A. Problem statement (motivating example)

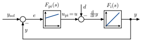


Figure 1: Block diagram of a simple, linear closed-loop system.

In Fig. 1, the block diagram of a linear closed-loop system is illustrated. A proportional-integral (PI) controller

$$F_{\mathrm{pi}}(s)=\frac{u_{\mathrm{pi}}(s)}{y_{\mathrm{ref}}(s)-y(s)}=k_{\mathrm{p}}+\frac{k_{\mathrm{i}}}{s}=\frac{k_{\mathrm{p}}s+k_{\mathrm{i}}}{s} \tag{1}$$

drives a simple integrator-like system

$$F_{\mathrm{i}}(s)=\frac{y(s)}{u(s)}=\frac{1}{s}. \tag{2}$$

A disturbance d may also be present, i.e. $u(s)=u_{\mathrm{pi}}(s)-d(s)$. One obtains the second-order closed-loop transfer function

$$F_{\mathrm{cl}}(s)=\frac{y(s)}{y_{\mathrm{ref}}(s)}=\frac{\frac{k_{\mathrm{p}}s+k_{\mathrm{i}}}{s}\frac{1}{s}}{1+\frac{k_{\mathrm{p}}s+k_{\mathrm{i}}}{s}\frac{1}{s}}=\frac{1+\frac{k_{\mathrm{p}}}{k_{\mathrm{i}}}s}{1+\frac{k_{\mathrm{p}}}{k_{\mathrm{i}}}s+\frac{1}{k_{\mathrm{i}}}s^2}. \tag{3}$$

With a proper tuning of the controller's parameters $k_{\mathrm{p}}>0$ and $k_{\mathrm{i}}>0$ (e.g. by pole placement [1, Section 10-2]), the transient response of (3) will be as fast as desired (neglecting input saturation). However, due to the proportional-derivative (PD) term $1+\frac{k_{\mathrm{p}}}{k_{\mathrm{i}}}s$ in the numerator, it will exhibit significant overshoot (see [—] in Fig. 5). The undesirable overshoot can be compensated for by a prefilter of the form [2, Section 6.6]

$$F_{\mathrm{pre}}(s)=\frac{y'_{\mathrm{ref}}(s)}{y_{\mathrm{ref}}(s)}=\frac{1}{1+\frac{k_{\mathrm{p}}}{k_{\mathrm{i}}}s}. \tag{4}$$

Nevertheless, this would heavily decelerate (see [—] in Fig. 5) the resulting (filtered) transient response given by

(C$_2$) PI controller (1) with prefilter (4) (see [—] in Fig. 5)
(C$_3$) PI controller (1) with TRSN$_1$ (8) (see [—] in Fig. 5)
(C$_4$) PI controller (1) with TRSN$_2$ (12) (see [—] in Fig. 5)
(C$_5$) PI controller (1) with TRSN$_n$ (16) (see [—] in Fig. 5)

All PI controllers have identical tuning with $k_{\mathrm{p}}=200$ and $k_{\mathrm{i}}=10000$ (obtained by pole placement). The prefilter is designed accordingly. All transient response shaping networks TRSN$_1$, TRSN$_2$ and TRSN$_n$ are tuned by $T_1=\frac{k_{\mathrm{p}}}{k_{\mathrm{i}}}=0.02\,\mathrm{s}$; whereas, for TRSN$_1$, $T_1^\star=0.005\,\mathrm{s}$ and $k_1=0.02$ were chosen. For TRSN$_2$, $D^\star=0.9$, $\omega_0^\star=500\,\frac{\mathrm{rad}}{\mathrm{s}}$, $k_2=0.02778$ and $T_2=0.001\,11\,\mathrm{s}$ were selected. Finally, TRSN$_n$ was designed for $n=4$ with $k_n=0.042226$, $\boldsymbol{A}_{\mathrm{nols}}=\left[\begin{smallmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ -30257000000 & -24740000 & -8050\end{smallmatrix}\right]$, $\boldsymbol{b}_{\mathrm{nols}}=\left(\begin{smallmatrix}0\\ 0\\ 1452000000000\end{smallmatrix}\right)$ and $\boldsymbol{c}_{\mathrm{nols}}^\top=\left(\begin{smallmatrix}1 & 0 & 0\end{smallmatrix}\right)$. Intentionally, TRSN$_n$ has a very aggressive (rather unrealistic) tuning to show what control performance is achievable with transient response shaping. All three controllers (C$_3$) [—], (C$_4$) [—] and (C$_5$) [—] with TRS exactly follow without overshoot their desired reference dynamics $F^\star_{\mathrm{fols}}(s)$, $F^\star_{\mathrm{sols}}(s)$ and $F^\star_{\mathrm{nols}}$(s), respectively (see [···] in Fig. 5 after the reference step at $t=0.05\,\mathrm{s}$). (C$_5$) [—] has the best tracking performance and the best disturbance rejection capability but requires the most aggressive control action. Controllers (C$_1$) [—] and (C$_2$) [—] without TRS have the worst control performance and the worst (actually identical) disturbance rejection capability. While (C$_1$) [—] overshoots significantly, (C$_2$) [—] has the slowest transient response due to the prefilter. (C$_4$) [—] with TRSN$_2$ provides the best compromise between required control action, transient response and disturbance rejection capability.

E. Controller design with transient response shaping

For $n>m\in\mathbb{N}$, a nonlinear system class described by the multi-input $\boldsymbol{u}\in\mathbb{R}^m$ multi-ouput $\boldsymbol{y}\in\mathbb{R}^m$ (MIMO) dynamics

$$\left.\begin{aligned}\tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}&=\begin{pmatrix}\boldsymbol{f}_1(\boldsymbol{x})\\ \boldsymbol{f}_2(\boldsymbol{x})\end{pmatrix}+\begin{bmatrix}\boldsymbol{G}_1(\boldsymbol{x})\\ \boldsymbol{O}_{(n-m)\times m}\end{bmatrix}\boldsymbol{u}+\begin{pmatrix}\boldsymbol{d}_1(t)\\ \boldsymbol{d}_2(t)\end{pmatrix}\\ \boldsymbol{y}&=\boldsymbol{h}(\boldsymbol{x})\end{aligned}\right\} \tag{18}$$

is considered, 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 $\boldsymbol{C}_1(\boldsymbol{x})$

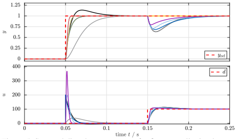


Figure 5: Step and disturbance response for five controller implementations: (C$_1$) [—], (C$_2$) [—], (C$_3$) [—], (C$_4$) [—] and (C$_5$) [—].

Step 3: Implementation of the desired transient response shaping network (see Section II-E3).

1) Input/Ouput (I/O) linearization [12, Section 5.2]: If disturbances $\boldsymbol{d}_1$ and states $\boldsymbol{x}$ are available for feedback, system (18) can be (partially) linearized by feedback of the form

$$\boxed{\boldsymbol{u}=-\boldsymbol{G}_1(\boldsymbol{x})^{-1}\big(\boldsymbol{f}_1(\boldsymbol{x})+\boldsymbol{d}_1(t)+\boldsymbol{C}_1(\boldsymbol{x})^{-1}\boldsymbol{v}\big),} \tag{19}$$

which leads to the integrator-like output system dynamics

$$\tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{y}=\left[\tfrac{\mathrm{d}}{\mathrm{d}\boldsymbol{x}}\boldsymbol{h}_1(\boldsymbol{x})\right]^\top\tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}\overset{(18),(19)}{=}\boldsymbol{C}_1(\boldsymbol{x})\Big[\boldsymbol{f}_1(\boldsymbol{x})+\boldsymbol{G}_1(\boldsymbol{x})\cdot$$
$$\cdot\big(-\boldsymbol{G}_1(\boldsymbol{x})^{-1}\big)\big(\boldsymbol{f}_1(\boldsymbol{x})+\boldsymbol{d}_1(t)+\boldsymbol{C}_1(\boldsymbol{x})^{-1}\boldsymbol{v}\big)+\boldsymbol{d}_1(t)\Big]=\boldsymbol{v}, \tag{20}$$

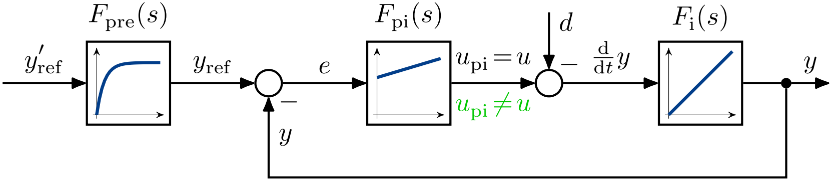
with auxiliary input vector $\boldsymbol{v}\in\mathbb{R}^m$. This represents a MIMO extension of the scalar integrator as introduced in Fig. 1.

2) Implementation of PI controller with anti-windup: The MIMO PI controller has m additional integral states $\boldsymbol{x}_{\mathrm{i}}\in\mathbb{R}^m$ resulting in the dynamics and feedback vector

$$\left.\begin{aligned}\boldsymbol{v}_{\mathrm{pi}}&=-\boldsymbol{K}_{\mathrm{p}}\big(\boldsymbol{y}-\boldsymbol{y}_{\mathrm{ref}}\big)-\boldsymbol{K}_{\mathrm{i}}\boldsymbol{x}_{\mathrm{i}}\\ \tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}_{\mathrm{i}}&=f_{\mathrm{aw}}(\boldsymbol{u},u_{\max})\big(\boldsymbol{y}-\boldsymbol{y}_{\mathrm{ref}}\big)\ \text{where}\\ f_{\mathrm{aw}}(\boldsymbol{u},u_{\max})&:=\begin{cases}1, & \|\boldsymbol{u}\|\le u_{\max}\\ 0, & \|\boldsymbol{u}\|>u_{\max}\end{cases}\end{aligned}\right\} \tag{21}$$

is an anti-windup decision function, which enables integration of the integral states $\boldsymbol{x}_{\mathrm{i}}$ if the requested control action $\boldsymbol{u}$ is feasible and disables integration if the maximum amplitude $u_{\max}$ of the control action is exceeded [5, Section 10.4.1]. Hence, (21) mitigates windup problems by conditional integration if the control action is constrained by $\|\boldsymbol{u}\|\le u_{\max}$. The gain matrices $\boldsymbol{K}_{\mathrm{p}}\in\mathbb{R}^{m\times m}$ and $\boldsymbol{K}_{\mathrm{i}}\in\mathbb{R}^{m\times m}$ may be

Block diagram of simple closed-loop system (e.g., current/speed control or phase-locked loop)



Transfer function

$$F_{\mathrm{cl}}(s) := \frac{y(s)}{y_{\mathrm{ref}}(s)} = \frac{\frac{k_{\mathrm{p}}s+k_{\mathrm{i}}}{s}\frac{1}{s}}{1+\frac{k_{\mathrm{p}}s+k_{\mathrm{i}}}{s}\frac{1}{s}} = \frac{1+\frac{k_{\mathrm{p}}}{k_{\mathrm{i}}}s}{1+\frac{k_{\mathrm{p}}}{k_{\mathrm{i}}}s+\frac{1}{k_{\mathrm{i}}}s^2} \tag{1}$$

with prefilter $\Rightarrow$ slow transient response / no transient response shaping possible $\Rightarrow$ alternative?

$$F'_{\mathrm{cl}}(s) := \frac{y(s)}{y'_{\mathrm{ref}}(s)} := \underbrace{\frac{1}{1+\frac{k_{\mathrm{p}}}{k_{\mathrm{i}}}s}}_{=:F_{\mathrm{pre}}(s)} \cdot F_{\mathrm{cl}}(s) = \frac{1}{1+\frac{k_{\mathrm{p}}}{k_{\mathrm{i}}}s+\frac{1}{k_{\mathrm{i}}}s^2} \tag{2}$$

Transient response shaping (TRS)

TRS with desired first-order lag system (fols) behavior

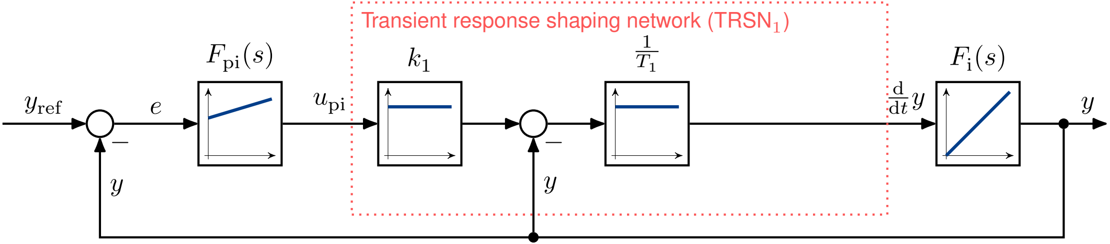
Transient response shaping network (TRSN$_1$)

$\boxed{F_{\text{fols}}(s) = \frac{u(s)}{u_{\text{pi}}(s)} = \frac{k_1}{1+sT_1}}$ with $T_1 \overset{!}{=} \frac{k_{\text{p}}}{k_{\text{i}}}$, $k_1 \overset{!}{=} \frac{1}{k_{\text{i}}T_1^\star}$ and $T_1^\star > 0$ (arbitrary)

achieves desired closed-loop behavior $\boxed{F_{\text{fols}}^\star(s) := \frac{y(s)}{y_{\text{ref}}(s)} := \frac{1}{1+sT_1^\star}} \overset{!}{=} F_{\text{cl-fols}}(s)$, since

$$F_{\text{cl-fols}}(s) = \frac{y(s)}{y_{\text{ref}}(s)} = \frac{F_{\text{pi}}(s)F_{\text{fols}}(s)}{1+F_{\text{pi}}(s)F_{\text{fols}}(s)} = \frac{k_{\text{i}}\frac{\cancel{1+k_{\text{p}}/k_{\text{i}}s}}{s}\frac{k_1}{\cancel{1+sT_1}}}{1+k_{\text{i}}\frac{\cancel{1+k_{\text{p}}/k_{\text{i}}s}}{s}\frac{k_1}{\cancel{1+sT_1}}} = \frac{1}{1+s\frac{1}{k_{\text{i}}k_1}}. \tag{3}$$

Implementation



Transient response shaping (TRS)

TRS with desired second-order lag system (sols) behavior

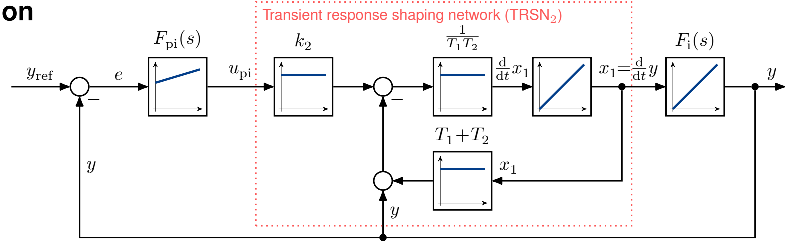
Transient response shaping network (TRSN_2)

$$\boxed{F_{\text{sols}}(s) = \frac{u(s)}{u_{\text{pi}}(s)} = \frac{k_2}{(1+sT_1)(1+sT_2)}} \text{ with } T_1 \overset{!}{=} \frac{k_{\text{p}}}{k_{\text{i}}},\; k_2 \overset{!}{=} \frac{\omega_0^\star}{2D^\star k_{\text{i}}} \text{ and } T_2 = \frac{k_{\text{i}} k_2}{(\omega_0^\star)^2} \overset{!}{=} \frac{1}{2D^\star \omega_0^\star}$$

achieves desired closed-loop behavior $\boxed{F^\star_{\text{sols}}(s) := \frac{y(s)}{y_{\text{ref}}(s)} := \frac{1}{1+s\frac{2D^\star}{\omega_0^\star}+s^2\frac{1}{(\omega_0^\star)^2}}} \overset{!}{=} F_{\text{cl-sols}}(s)$, since

$$F_{\text{cl-sols}}(s) = \frac{y(s)}{y_{\text{ref}}(s)} = \frac{F_{\text{pi}}(s)F_{\text{sols}}(s)}{1+F_{\text{pi}}(s)F_{\text{sols}}(s)} = \frac{k_{\text{i}}\frac{\cancel{1+k_{\text{p}}/k_{\text{i}}s}}{s}\frac{k_2}{\cancel{(1+sT_1)}(1+sT_2)}}{1+k_{\text{i}}\frac{\cancel{1+k_{\text{p}}/k_{\text{i}}s}}{s}\frac{k_2}{\cancel{(1+sT_1)}(1+sT_2)}} = \frac{1}{1+s\frac{1}{k_{\text{i}}k_2}+s^2\frac{T_2}{k_{\text{i}}k_2}}. \tag{4}$$

Implementation



Transient response shaping (TRS)

TRS with desired nth-order lag system (nols) behavior

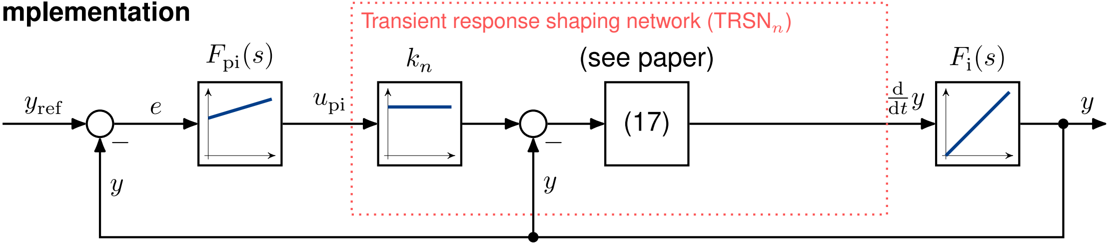
Transient response shaping network (TRSN$_n$)

$$\boxed{F_{\mathrm{nols}}(s) = \frac{u(s)}{u_{\mathrm{pi}}(s)} = \frac{k_n}{(1+sT_1)(1+s\,a_1+\cdots+s^{n-1}\,a_{n-1})}}$$ with $T_1 \overset{!}{=} \frac{k_{\mathrm{p}}}{k_{\mathrm{i}}}$, $k_n \overset{!}{=} \frac{1}{k_{\mathrm{i}} a_1^\star}$ and $\forall l \in \{1,\ldots,n{-}1\}: a_l = \frac{a_{l+1}^\star}{a_1^\star}$

achieves desired closed-loop behavior $\boxed{F^\star_{\mathrm{nols}}(s) := \frac{y(s)}{y_{\mathrm{ref}}(s)} := \frac{1}{1+s\,a_1^\star+\cdots+s^n\,a_n^\star}} \overset{!}{=} F_{\mathrm{cl\text{-}nols}}(s)$, since

$$F_{\mathrm{cl\text{-}nols}}(s) = \frac{y(s)}{y_{\mathrm{ref}}(s)} = \frac{F_{\mathrm{pi}}(s)F_{\mathrm{nols}}(s)}{1+F_{\mathrm{pi}}(s)F_{\mathrm{nols}}(s)} = \frac{k_{\mathrm{i}}\frac{\cancel{1+k_{\mathrm{p}}/k_{\mathrm{i}}\,s}}{s}\frac{k_n}{\cancel{(1+sT_1)}(1+s\,a_1+\cdots+s^{n-1}\,a_{n-1})}}{1+k_{\mathrm{i}}\frac{\cancel{1+k_{\mathrm{p}}/k_{\mathrm{i}}\,s}}{s}\frac{k_n}{\cancel{(1+sT_1)}(1+sa_1+\cdots+s^{n-1}a_{n-1})}} = \frac{1}{1+s\,\frac{1}{k_{\mathrm{i}}k_n}+\cdots+s^n\,\frac{a_{n-1}}{k_{\mathrm{i}}k_n}}.$$

Implementation



Transient response shaping (TRS)

Illustration of achievable closed-loop control performance (comparative simulation results)

Five different controller implementations:

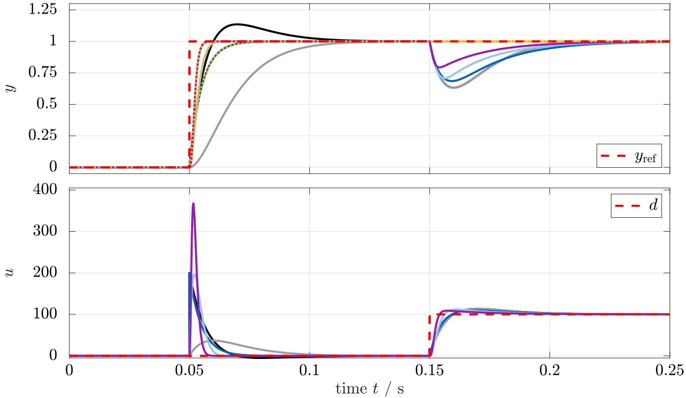
(C$_1$) PI controller (see [—])

(C$_2$) PI controller with prefilter (see [—])

(C$_3$) PI controller with TRSN$_1$ (see [—])

(C$_4$) PI controller with TRSN$_2$ (see [—])

(C$_5$) PI controller with TRSN$_n$ (see [—])



Application

Controller design with TRS for nonlinear system (in three steps)

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

$$\left.\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x} &= \begin{pmatrix} \boldsymbol{f}_1(\boldsymbol{x}) \\ \boldsymbol{f}_2(\boldsymbol{x}) \end{pmatrix} + \begin{bmatrix} \boldsymbol{G}_1(\boldsymbol{x}) \\ \boldsymbol{O}_{(n-m)\times m} \end{bmatrix} \boldsymbol{u} + \begin{pmatrix} \boldsymbol{d}_1(t) \\ \boldsymbol{d}_2(t) \end{pmatrix} \\ \boldsymbol{y} &= \boldsymbol{h}(\boldsymbol{x}) \end{aligned}\right\} \tag{5}$$

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

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

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).

Controller design with transient response shaping is conducted in three steps:

- Step 1: Input/output (I/O) linearization;
- Step 2: Implementation of PI controller;
- Step 3: Implementation of the desired transient response shaping network.

Application

Controller design steps

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

$$\boxed{\boldsymbol{u} = -\boldsymbol{G}_1(\boldsymbol{x})^{-1}\big(\boldsymbol{f}_1(\boldsymbol{x}) + \boldsymbol{d}_1(t)\big) + \boldsymbol{C}_1(\boldsymbol{x})^{-1}\boldsymbol{v},} \tag{6}$$

gives $\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{y} \overset{(5),(6)}{=} \boldsymbol{C}_1(\boldsymbol{x})\Big[\boldsymbol{f}_1(\boldsymbol{x}) + \boldsymbol{G}_1(\boldsymbol{x}) \cdot \Big(-\boldsymbol{G}_1(\boldsymbol{x})^{-1}\big(\boldsymbol{f}_1(\boldsymbol{x}) + \boldsymbol{d}_1(t)\big) + \boldsymbol{C}_1(\boldsymbol{x})^{-1}\boldsymbol{v}\Big) + \boldsymbol{d}_1(t)\Big] = \boldsymbol{v}$.

Step 2: Implementation of (MIMO) PI controller with anti-windup (conditional integration)

$$\left.\begin{aligned} \boldsymbol{v}_{\mathrm{pi}} &= -\boldsymbol{K}_{\mathrm{p}}\big(\boldsymbol{y} - \boldsymbol{y}_{\mathrm{ref}}\big) - \boldsymbol{K}_{\mathrm{i}}\boldsymbol{x}_{\mathrm{i}} \\ \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}_{\mathrm{i}} &= f_{\mathrm{aw}}(\boldsymbol{u}, u_{\max})\big(\boldsymbol{y} - \boldsymbol{y}_{\mathrm{ref}}\big) \text{ where} \\ f_{\mathrm{aw}}(\boldsymbol{u}, u_{\max}) &:= \begin{cases} 1, & \|\boldsymbol{u}\| \leq u_{\max} \\ 0, & \|\boldsymbol{u}\| > u_{\max} \end{cases} \end{aligned}\right\} \tag{7}$$

Step 3: Implementation of the desired transient response shaping network

Since I/O linearization (6) achieves decoupling of each output y_k of $\boldsymbol{y} \in \mathbb{R}^m$ and each input u_k of $\boldsymbol{u} \in \mathbb{R}^m$, the introduced transient response shaping networks TRSN_1, TRSN_2 or TRSN_n can be implemented for each individual subsystem $\frac{\mathrm{d}}{\mathrm{d}t}y_k = v_k$ where $k \in \{1, \ldots, m\}$. The input to each chosen transient response shaping network is the k-th controller output $v_{\mathrm{pi},k}$ of the MIMO PI controller (7) with output vector $\boldsymbol{v}_{\mathrm{pi}} \in \mathbb{R}^m$.

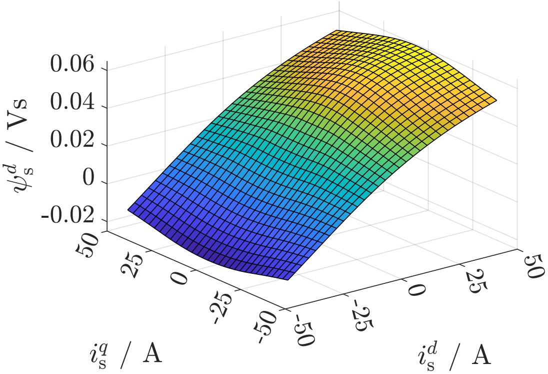
Application

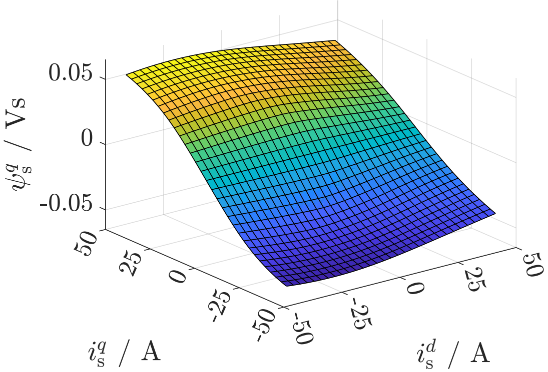
Nonlinear interior permanent-magnet synchronous machine (IPMSM) model

Nonlinear machine dynamics

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

Nonlinear flux linkage maps



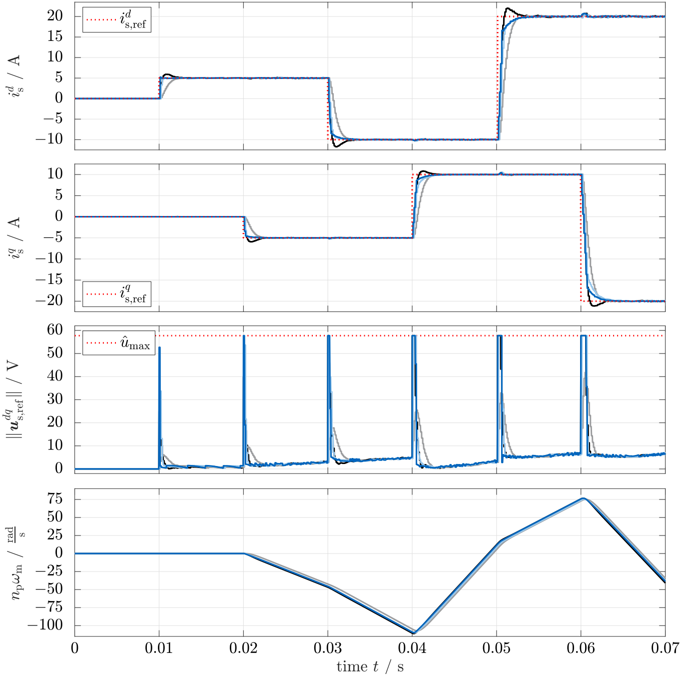


Application

Simulative validation (including VSI with SVM)

In right figure, the IPMSM time series plots are shown for four different controller implementations with tuning as in Tab. I (see paper):

- (C_1) PI controller (see [—])
- (C_2) PI controller with prefilter (see [—])
- (C_3) PI controller with TRSN$_1$ (see [—])
- (C_4) PI controller with TRSN$_2$ (see [—])



Conclusion

To take home

- Basic idea of transient response shaping (TRS) was introduced
- Arbitrary transient response shaping possible by implementation of appropriate transient response shaping networks (TRSN)
- Approach is modular and applicable to a wide range of nonlinear systems

Future work

- real-time implementation,
- validation in the laboratory,
- sensitivity and robustness analysis against parameter/model uncertainties,
- impact of not exact state estimation on the required I/O linearization state feedback (if not all states are measured); and
- consideration and compensation of input delays (e.g., due to the voltage source inverter) in the transient response shaping networks.

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