# Current PI-funnel control with anti-windup for reluctance synchronous machines (RSMs)

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12.02.2016

Colloquium on the occasion of the 60th birthday of Achim Ilchmann

# Outline

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1. Funnel control
   - Principle idea
   - The beginning
   - Successful implementations in mechatronics

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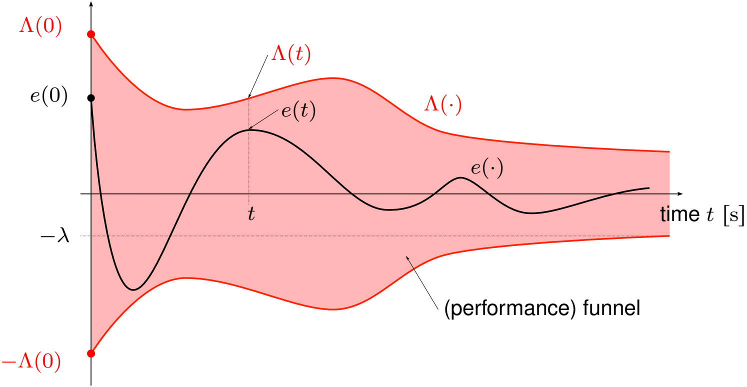
# Funnel control

## Tracking with prescribed transient behaviour




$$u(t) = k(t)e(t) \quad \text{with} \quad k(t) = \frac{1}{\Lambda(t) - |e(t)|}$$

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# Funnel control

## The beginning ... (at least for me in 2004)

**ESAIM: Control, Optimisation and Calculus of Variations** July 2002, Vol. 7, 471–493
URL: http://www.emath.fr/cocv/ DOI: 10.1051/cocv:2002064

**TRACKING WITH PRESCRIBED TRANSIENT BEHAVIOUR***

Achim Ilchmann[1], E.P. Ryan[2] and C.J. Sangwin[3]

**Abstract**. Universal tracking control is investigated in the context of a class $\mathcal{S}$ of $M$-input, $M$-output dynamical systems modelled by functional differential equations. The class encompasses a wide variety of nonlinear and infinite-dimensional systems and contains – as a prototype subclass – all finite-dimensional linear single-input single-output minimum-phase systems with positive high-frequency gain. The control objective is to ensure that, for an arbitrary $\mathbb{R}^M$-valued reference signal $r$ of class $W^{1,\infty}$ (absolutely continuous and bounded with essentially bounded derivative) and every system of class $\mathcal{S}$, the tracking error $e$ between plant output and reference signal evolves within a prespecified performance envelope or funnel in the sense that $\varphi(t)\|e(t)\| < 1$ for all $t \geq 0$, where $\varphi$ a prescribed real-valued function of class $W^{1,\infty}$ with the property that $\varphi(s) > 0$ for all $s > 0$ and $\liminf_{s\to\infty} \varphi(s) > 0$. A simple (neither adaptive nor dynamic) error feedback control of the form $u(t) = -\alpha(\varphi(t)\|e(t)\|)e(t)$ is introduced which achieves the objective whilst maintaining boundedness of the control and of the scalar gain $\alpha(\varphi(\cdot)\|e(\cdot)\|)$.

**Mathematics Subject Classification.** 93D15, 93C30, 34K20.

Received February 7, 2002. Revised April 17, 2002.

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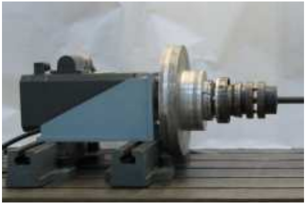
# Funnel control

## Successful implementations in mechatronics (since 2004, [1–33])

### Industrial drives



speed & position control

### Industrial robots


position control

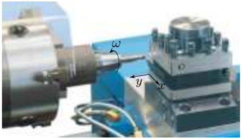
### Wind turbine systems

speed control

### Elastic drive trains


speed & position control + damping

### Machine tools




speed & position control

### Electrical machines

current control

# Outline

2 Current PI-funnel control with anti-windup for RSMs [1]

- Motivation and problem formulation
- Structural system properties of the RSM
- PI-funnel control with anti-windup
- Implementation and results

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# Motivation and problem formulation

## Reluctance synchronous machine (RSM): A viable alternative?


http://www.abb.com

**advantages [34–36]**:

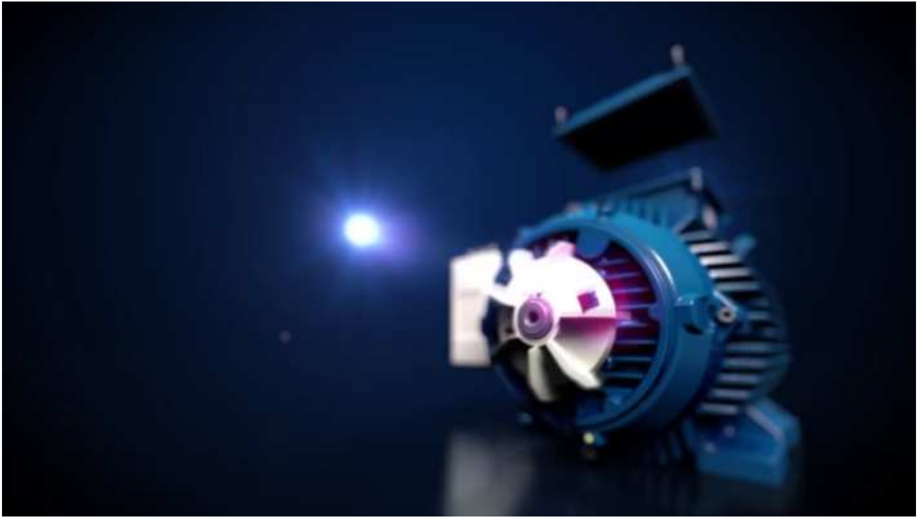
- (very) cheap
- high efficiency feasible (IE4)
- high power density and torque-per-volume ratio
- sensorless control feasible

**disadvantages:**

- power factor
- highly nonlinear
- inverter necessary
- (nonlinear control and good system knowledge necessary)

# Motivation and problem formulation

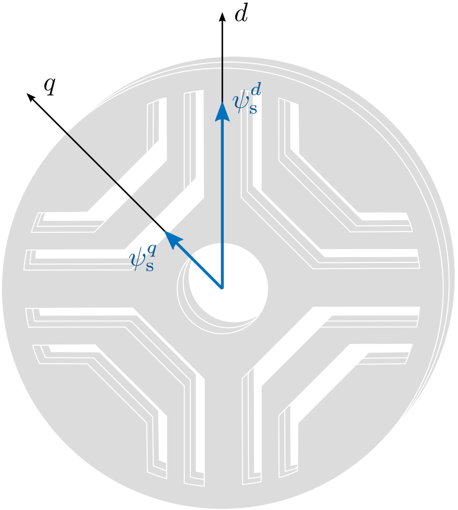
## Reluctance synchronous machine: A look inside

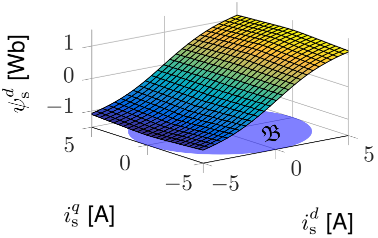


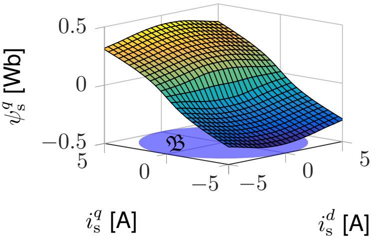
http://www.youtube.com/watch?v=69mtuom774E&index=4&list=PLg4s1do3XuVlwc1LnpyZgvfjd_o4wtA_D (cut version/duration: 0:26 min)

# Motivation and problem formulation

## Flux linkage in the RSM



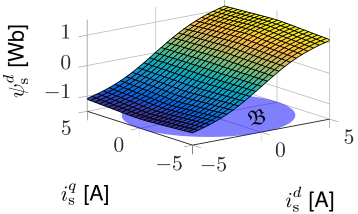



# Motivation and problem formulation

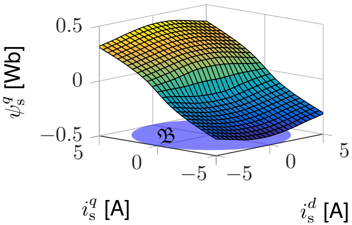
## Control objective: Current reference tracking with prescribed transient accuracy

$$\boldsymbol{u}_s^k(t) = R_s \boldsymbol{i}_s^k(t) + \frac{d}{dt}\boldsymbol{\psi}_s^k\big(\boldsymbol{i}_s^k(t)\big) + \omega_k(t) \underbrace{\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}}_{=:\boldsymbol{J}} \boldsymbol{\psi}_s^k\big(\boldsymbol{i}_s^k(t)\big), \tag{1}$$

$$\frac{d}{dt}\omega_k(t) = \frac{p}{\Theta}\Big[ \underbrace{\frac{3}{2} p\, \boldsymbol{i}_s^k(t)^\top \boldsymbol{J} \boldsymbol{\psi}_s^k\big(\boldsymbol{i}_s^k(t)\big)}_{\text{machine torque}} - \underbrace{m_l(t)}_{\text{loads}} - \underbrace{\big(\nu\omega_k(t) + (\mathfrak{F}\omega_k)(t)\big)}_{\text{friction}} \Big], \tag{2}$$




$d$-flux linkage




$q$-flux linkage

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2 Current PI-funnel control with anti-windup for RSMs [1]

- Motivation and problem formulation
- Structural system properties of the RSM
- PI-funnel control with anti-windup
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# Structural system properties of the RSM

## Derivation of the nonlinear current dynamics

- To be derived: Nonlinear current dynamics

$$\tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{k}(t) = \ldots \tag{3}$$

- Given: Stator voltage equation

$$\boldsymbol{u}_{\mathrm{s}}^{k}(t) = R_{\mathrm{s}}\boldsymbol{i}_{\mathrm{s}}^{k}(t) + \tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{k}\big(\boldsymbol{i}_{\mathrm{s}}^{k}(t)\big) + \omega_{k}(t)\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{k}\big(\boldsymbol{i}_{\mathrm{s}}^{k}(t)\big), \qquad \boldsymbol{\psi}_{\mathrm{s}}^{k}\big(\boldsymbol{i}_{\mathrm{s}}^{k}(0)\big) = \boldsymbol{\psi}_{s,0}^{k}$$

### Assumption 1

Flux linkage $\boldsymbol{\psi}_{\mathrm{s}}^{k}$ $[\mathrm{Wb}]^2$ is a continuously differentiable function of the stator currents $\boldsymbol{i}_{\mathrm{s}}^{k}$ $[\mathrm{A}]^2$, i.e.

$$\boldsymbol{\psi}_{\mathrm{s}}^{k}: \quad \mathbb{R}^2 \to \mathbb{R}^2, \quad \boldsymbol{i}_{\mathrm{s}}^{k} \mapsto \boldsymbol{\psi}_{\mathrm{s}}^{k}(\boldsymbol{i}_{\mathrm{s}}^{k}) \quad \wedge \quad \boldsymbol{\psi}_{\mathrm{s}}^{k}(\cdot) \in \mathcal{C}^1(\mathbb{R}^2;\mathbb{R}^2) \tag{4}$$

# Structural system properties of the RSM

## Inductance matrix

### Definition 1

Inductance matrix $\boldsymbol{L}_{\mathrm{s}}^k\,[\mathrm{H}]^{2\times 2}$ is defined by

$$\boldsymbol{L}_{\mathrm{s}}^k(\boldsymbol{i}_{\mathrm{s}}^k) := \begin{bmatrix} L_{\mathrm{s}}^{dd}(\boldsymbol{i}_{\mathrm{s}}^k) & L_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^k) \\ L_{\mathrm{s}}^{qd}(\boldsymbol{i}_{\mathrm{s}}^k) & L_{\mathrm{s}}^{qq}(\boldsymbol{i}_{\mathrm{s}}^k) \end{bmatrix} := \left.\begin{bmatrix} \frac{\partial \psi_{\mathrm{s}}^d(\boldsymbol{i}_{\mathrm{s}}^k)}{\partial i_{\mathrm{s}}^d} & \frac{\partial \psi_{\mathrm{s}}^d(\boldsymbol{i}_{\mathrm{s}}^k)}{\partial i_{\mathrm{s}}^q} \\ \frac{\partial \psi_{\mathrm{s}}^q(\boldsymbol{i}_{\mathrm{s}}^k)}{\partial i_{\mathrm{s}}^d} & \frac{\partial \psi_{\mathrm{s}}^q(\boldsymbol{i}_{\mathrm{s}}^k)}{\partial i_{\mathrm{s}}^q} \end{bmatrix}\right|_{\boldsymbol{i}_{\mathrm{s}}^k} = \left.\frac{\partial \boldsymbol{\psi}_{\mathrm{s}}^k(\boldsymbol{i}_{\mathrm{s}}^k)}{\partial \boldsymbol{i}_{\mathrm{s}}^k}\right|_{\boldsymbol{i}_{\mathrm{s}}^k} \tag{5}$$

- symmetric [37]:

$$\forall \boldsymbol{i}_{\mathrm{s}}^k \in \mathbb{R}^2:\ \boldsymbol{L}_{\mathrm{s}}^k(\boldsymbol{i}_{\mathrm{s}}^k) = \boldsymbol{L}_{\mathrm{s}}^k(\boldsymbol{i}_{\mathrm{s}}^k)^\top \Leftrightarrow L_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^k) = L_{\mathrm{s}}^{qd}(\boldsymbol{i}_{\mathrm{s}}^k) \tag{6}$$

- positive definite [37]:

$$\forall \boldsymbol{i}_{\mathrm{s}}^k \in \mathbb{R}^2:\ \boldsymbol{L}_{\mathrm{s}}^k(\boldsymbol{i}_{\mathrm{s}}^k) > 0 \Leftrightarrow L_{\mathrm{s}}^{dd}(\boldsymbol{i}_{\mathrm{s}}^k) > 0,\ L_{\mathrm{s}}^{qq}(\boldsymbol{i}_{\mathrm{s}}^k) > 0,\ \det(\boldsymbol{L}_{\mathrm{s}}^k(\boldsymbol{i}_{\mathrm{s}}^k)) > 0 \tag{7}$$

# Structural system properties of the RSM

## Generic model with nonlinear current dynamics

Time derivatives of the flux linkage are given by:

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_\mathrm{s}^k(\boldsymbol{i}_\mathrm{s}^k(t)) = \frac{\partial \boldsymbol{\psi}_\mathrm{s}^k(\boldsymbol{i}_\mathrm{s}^k(t))}{\partial \boldsymbol{i}_\mathrm{s}^k(t)} \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_\mathrm{s}^k(t) \overset{(5)}{=} \boldsymbol{L}_\mathrm{s}^k(\boldsymbol{i}_\mathrm{s}^k(t)) \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_\mathrm{s}^k(t) \tag{8}$$

Inserting (8) into (1) yields **nonlinear current dynamics**:

$$\boxed{\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_\mathrm{s}^k(t) &= \boldsymbol{L}_\mathrm{s}^k\left(\boldsymbol{i}_\mathrm{s}^k(t)\right)^{-1}\left[\mathbf{sat}_{\hat{u}}\left(\boldsymbol{u}_\mathrm{s}^k(t)\right) - R_\mathrm{s}\boldsymbol{i}_\mathrm{s}^k(t) - \omega_k(t)\boldsymbol{J}\boldsymbol{\psi}_\mathrm{s}^k\left(\boldsymbol{i}_\mathrm{s}^k(t)\right)\right] \\ \frac{\mathrm{d}}{\mathrm{d}t}\omega_k(t) &= \frac{p}{\Theta}\left[\underbrace{\tfrac{3}{2}p\,\boldsymbol{i}_\mathrm{s}^k(t)^\top \boldsymbol{J}\boldsymbol{\psi}_\mathrm{s}^k\left(\boldsymbol{i}_\mathrm{s}^k(t)\right)}_{\text{machine torque}} - \underbrace{m_l(t)}_{\text{loads}} - \underbrace{\left(\nu\omega_k(t) + (\mathfrak{F}\omega_k)(t)\right)}_{\text{friction}}\right] \end{aligned}} \tag{9}$$

with system properties (see Remark IV.1):

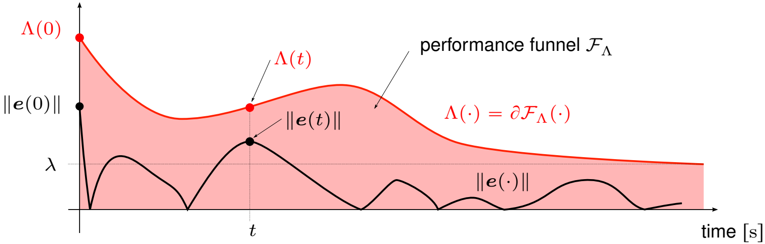
- 2-input 2-output system with vector relative degree **one**!
- BIBO stable internal dynamics, i.e. $\boldsymbol{i}_\mathrm{s}^k(\cdot) \in \mathcal{L}^\infty \wedge m_l(\cdot) \in \mathcal{L}^\infty \Rightarrow \omega_k(\cdot) \in \mathcal{L}^\infty$
- Euclidean input saturation [38], i.e. $\|\boldsymbol{u}_\mathrm{s}^k(t)\| \leqslant \hat{u} := \frac{u_\mathrm{dc}}{2}$ for all $t \geqslant 0$

# Outline

2 Current PI-funnel control with anti-windup for RSMs [1]

# Current PI-funnel control with anti-windup for RSMs

## Funnel control: Tracking with prescribed transient accuracy




Controller (applicable if feasibility condition $\widehat{u} \geqslant \widehat{u}_{\mathrm{feas}}$ holds, see Theorem IV.2):

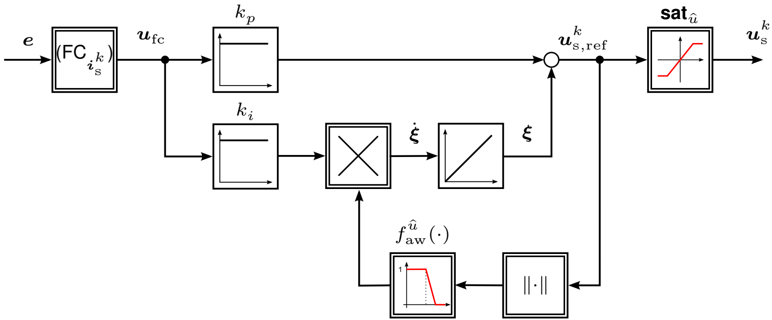
$$\boxed{\boldsymbol{u}_{\mathrm{fc}}(t) = k(t)\boldsymbol{e}(t)} \quad \Longrightarrow \quad \boxed{\|\boldsymbol{e}(t)\| < \Lambda(t)} \qquad (\mathrm{FC}_{\boldsymbol{i}_\mathrm{s}^k})$$

where

- $\boldsymbol{e}(t) = (e_s^d(t),\, e_s^q(t))^\top = \boldsymbol{i}_{\mathrm{s,ref}}^k(t) - \boldsymbol{i}_\mathrm{s}^k(t)$
- $k(t) = \dfrac{1}{\Lambda(t) - \|\boldsymbol{e}(t)\|} \geqslant \dfrac{1}{\Lambda(t)}$ and $\|\boldsymbol{e}(t)\| = \sqrt{e_s^d(t)^2 + e_s^q(t)^2}$

# Current PI-funnel control with anti-windup for RSMs

## PI-funnel control with anti-windup




$$\left.\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\xi}(t) &= k_i\, f_{\mathrm{aw}}^{\hat{u}}\Big(\boldsymbol{\xi}(t) + k_p\, \boldsymbol{u}_{\mathrm{fc}}(t)\Big)\, \boldsymbol{u}_{\mathrm{fc}}(t), & \boldsymbol{\xi}(0) &= \boldsymbol{\xi}^0 \in \mathbb{R}^n \\ \boldsymbol{u}_{\mathrm{s,ref}}^k(t) &= \boldsymbol{\xi}(t) + k_p\, \boldsymbol{u}_{\mathrm{fc}}(t), & \text{where } & k_p > 0, k_i \geqslant 0. \end{aligned}\right\} \quad (\mathrm{PI}^{\mathrm{aw}})$$

$\Longrightarrow$ $\boldsymbol{\xi}(\cdot)$ acts as bounded input disturbance (see Lemma III.1)

$\Longrightarrow$ PI-like extension for steady state accuracy

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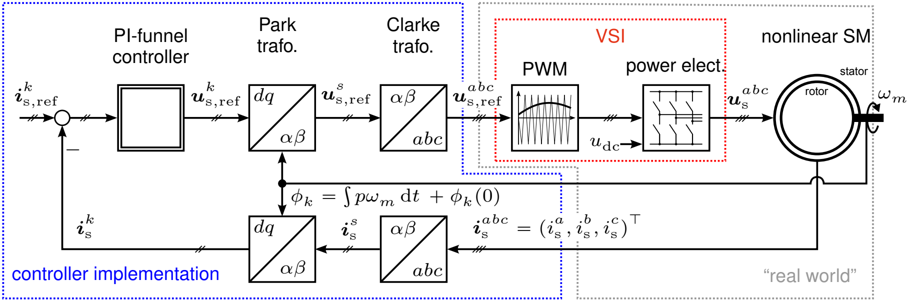
# Current PI-funnel control with anti-windup for RSMs

## Control-loop and implementation

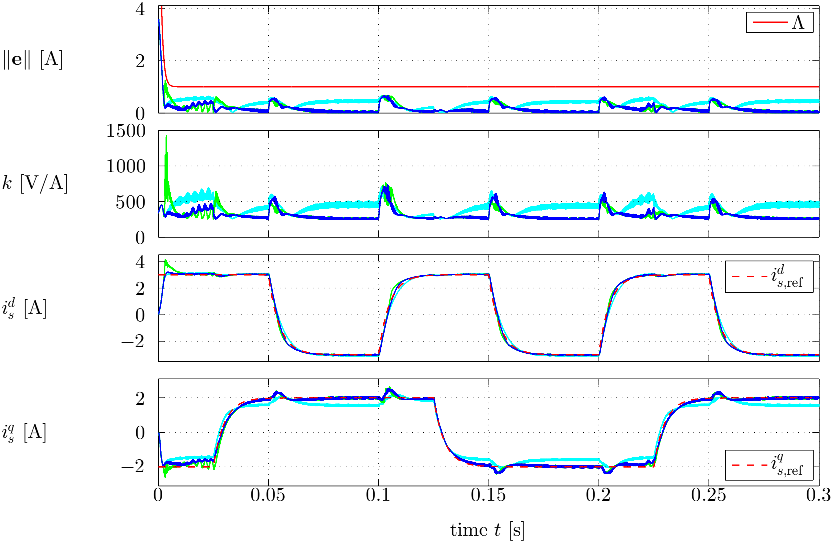



**Realistic modeling:**

- three-phase signals (machine, inverter, modulation, ...)
- pulse width modulation (PWM) and switching behavior of voltage source inverter (VSI)
- Park-/Clarke transformation

# Current PI-funnel control with anti-windup for RSMs

Simulation results (1.1 kW RSM): FC, FC+PI and FC+PI$^{\mathrm{aw}}$



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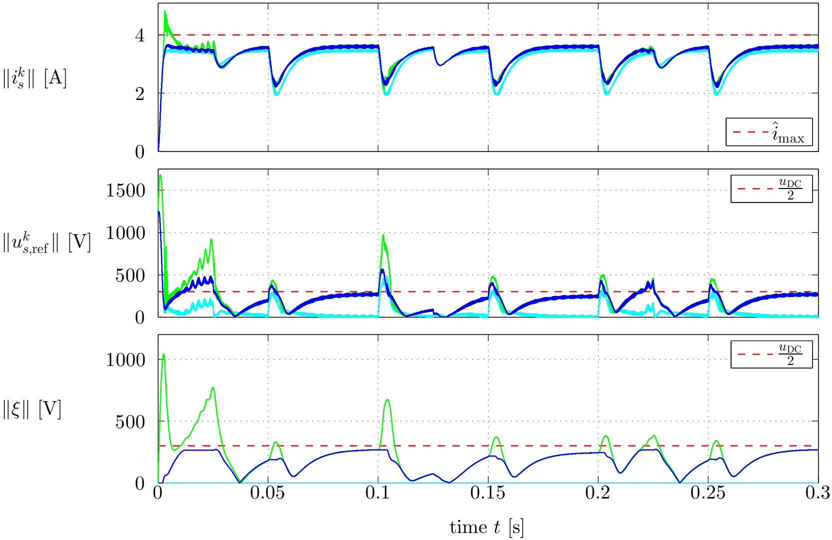
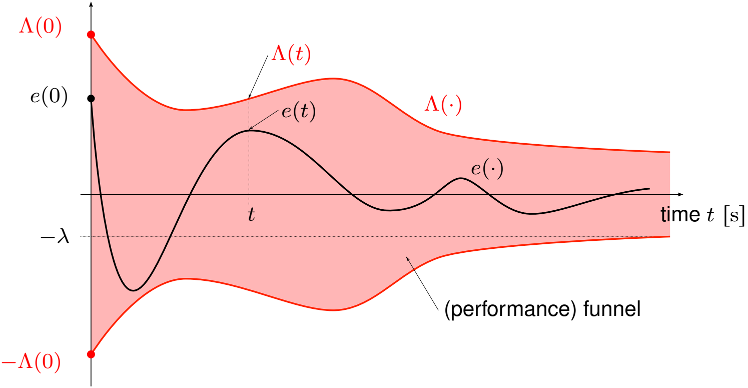


# Outline

# Conclusion

## Funnel control: Facts

- **simple** and **robust** controller
- Tracking with prescribed **transient behavior** (→ funnel design)




- **asymptotic accuracy** possible (→ internal model design, e.g. PI)

**— Happy Birthday, Achim and thank you for all your time and support! —**

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# Outline

# Structural system properties of the RSM

Nonlinear inductances $L_s^d := \frac{\partial \psi_s^d}{\partial i_s^d}$, $L_s^q := \frac{\partial \psi_s^q}{\partial i_s^q}$, $L_s^{dq} := \frac{\partial \psi_s^d}{\partial i_s^q} = \frac{\partial \psi_s^q}{\partial i_s^d} =: L_s^{qd}$