Speed funnel control with disturbance observer for wind turbine systems with elastic shaft

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Outline

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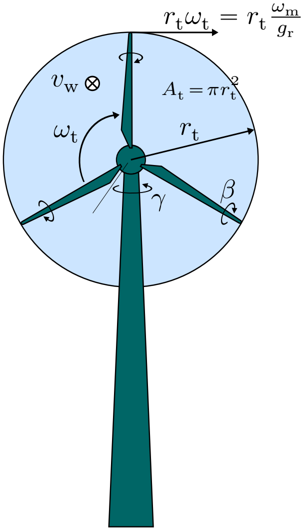
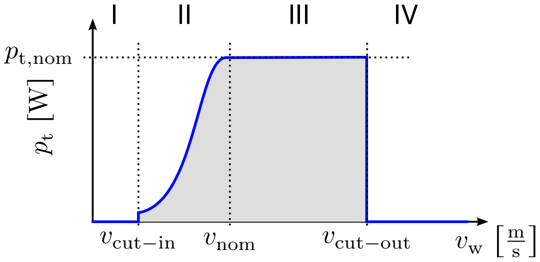
Motivation and problem statement

Regimes of operation of wind turbine systems



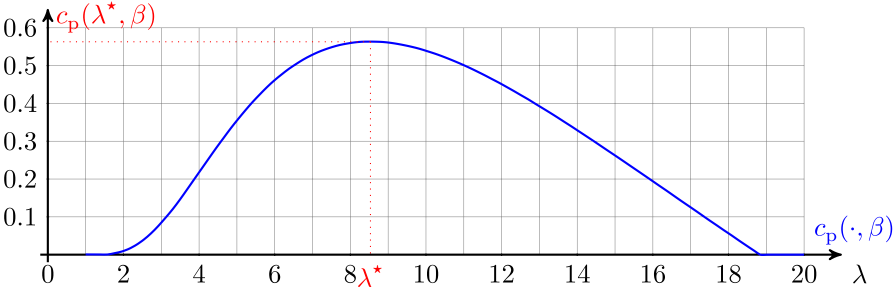


- Regime I: Standstill $p_t = 0$
- Regime II: Variable oper. $0 \leqslant p_t < p_{t,nom}$ (Goal: Maximum power point tracking)
- Regime III: Nominal oper. $p_t = p_{t,nom}$
- Regime IV: Standstill $p_t = 0$.

Motivation and problem statement

Turbine power & torque, power coefficient and control objective (in regime II)

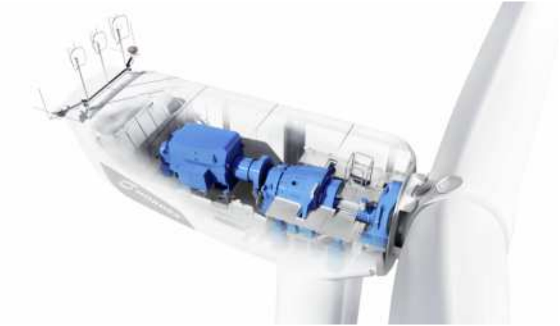
$$p_t = c_p(v_w, \beta, \omega_m)\underbrace{\frac{1}{2}\varrho r_t^2 \pi v_w^3}_{:=p_w} \implies m_t(v_w, \beta, \omega_m) = \frac{g_r c_p(v_w, \beta, \omega_m) p_w}{\omega_m} \tag{1}$$



$\implies$ **Control objective**: MPPT, i.e. $\lambda = \frac{r_t \omega_t}{v_w} = \frac{r_t \omega_m}{v_w g_r} \to \lambda^\star$ for $\beta = \beta_0 \geqslant 0$

Motivation and problem statement

Wind turbine system with elastic shaft



(www.nordex-online.com)

- reference tracking $\omega_{\mathrm{t}}(\cdot) \to \omega_{\mathrm{t,ref}}(\cdot) = \frac{v_{\mathrm{w}}(\cdot)}{r_{\mathrm{t}}}\lambda^{\star}$
- active damping of natural frequency $\omega_0 = \sqrt{\frac{c_{\mathrm{s}}\left(\Theta_{\mathrm{m}} + \frac{\Theta_{\mathrm{t}}}{g_{\mathrm{r}}^2}\right)}{\Theta_{\mathrm{m}}\Theta_{\mathrm{t}}}}$
- only ω_{m} available for feedback

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2 Funnel control
- Control objective and controller
- Admissible system class
- Properties of the closed-loop system

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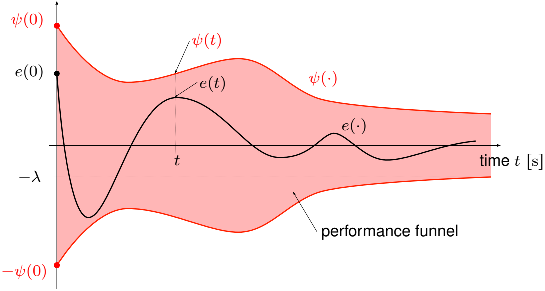
Funnel control

Control objective and controller

- control objective: tracking with prescribed transient accuracy



- funnel controller:

$$\boxed{u(t) = k(t)\big(\underbrace{y_{\mathrm{ref}}(t) - y(t)}_{=:e(t)}\big) \quad \text{where} \quad k(t) = \frac{\varsigma(t)}{\psi(t) - |e(t)|}} \qquad \text{(FC)}$$

- gain scaling $\varsigma(\cdot) \in \mathcal{C}(\mathbb{R}_{\geqslant 0}; \mathbb{R}_{>0})$ (e.g. such that $k(t) \geqslant \frac{\varsigma(t)}{\psi(t)}$ for all $t \geqslant 0$)

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Funnel control

Admissible system class $\mathcal{S}_1$: System description and structural properties

$$\left.\begin{aligned} \dot{\boldsymbol{x}}(t) &= \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{b}\big(u(t) + u_d(t)\big) + \boldsymbol{B}_{\mathfrak{T}}\Big(\boldsymbol{d}(t, \boldsymbol{x}(t)) + (\mathfrak{T}\boldsymbol{x})(t)\Big) \\ y(t) &= \boldsymbol{c}^\top \boldsymbol{x}(t), \end{aligned}\right\} \tag{2}$$

(sp$_1$) $\gamma_0 := \boldsymbol{c}^\top \boldsymbol{b} \neq 0$ and $\mathrm{sign}(\gamma_0)$ known;

(sp$_2$) $\forall\, s \in \mathbb{C}$ with $\Re(s) \geqslant 0$: $\quad \det \begin{bmatrix} s\boldsymbol{I}_n - \boldsymbol{A} & \boldsymbol{b} \\ \boldsymbol{c}^\top & 0 \end{bmatrix} \neq 0$;

(sp$_3$) $\mathfrak{T} \in \mathcal{T}$ (see Def. 1 in [1]) and
$M_{\mathfrak{T}} := \sup\left\{ \|(\mathfrak{T}\boldsymbol{\xi})(t)\| \,\middle|\, t \geqslant 0,\ \boldsymbol{\xi}(\cdot) \in \mathcal{C}([-h, \infty), \mathbb{R}^n) \right\} < \infty$;

(sp$_4$) $\boldsymbol{d}(t, \cdot) \in \mathcal{C}(\mathbb{R}^n; \mathbb{R}^m)$;

(sp$_5$) $u_d(\cdot) \in \mathcal{L}^\infty([-h, \infty); \mathbb{R})$ and $\boldsymbol{d}(\cdot, \cdot) \in \mathcal{L}^\infty([-h, \infty) \times \mathbb{R}^n; \mathbb{R}^m)$.

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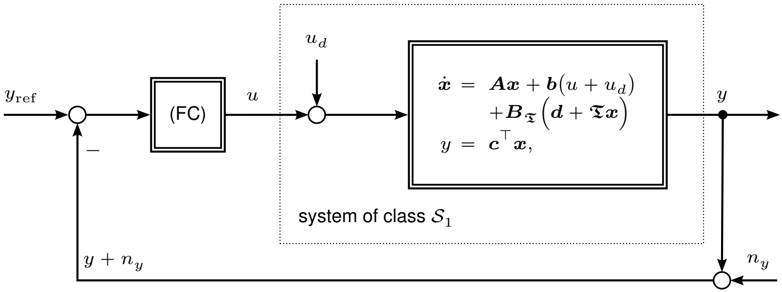
Funnel control

Properties of the closed-loop system



(i) there exists a solution $\boldsymbol{x}\colon [-h, T) \to \mathbb{R}^n$ which can be maximally extended and $T \in (0, \infty]$;

(ii) the solution does not have finite escape time, i.e. $T = \infty$;

(iii) the tracking error is uniformly bounded away from the funnel boundary, i.e. $\exists \varepsilon > 0\colon \quad |e(t)| < \psi(t)$ for all $t \geqslant 0$;

(iv) gain & input are bounded, i.e. $k(\cdot), u(\cdot) \in \mathcal{L}^\infty(\mathbb{R}_{>0}; \mathbb{R})$.

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- Model of WTS with elastic shaft
- Closed-loop system with disturbance observer (DO, based on [2])
- Simulation results

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Speed funnel control with DO of WTS with elastic shaft

Model of WTS with elastic shaft $\in \mathcal{S}_1$ (see Prop. IV.1)

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}_{\mathrm{S}}(t) = \boldsymbol{A}_{\mathrm{S}}\boldsymbol{x}_{\mathrm{S}}(t) + \boldsymbol{b}_{\mathrm{S}}\big(u(t)+u_{\mathrm{a}}(t)\big) + \boldsymbol{B}_{\mathrm{S}}\begin{pmatrix} -(\mathfrak{F}_{\mathrm{g}}\omega_{\mathrm{m}})(t) \\ m_{\mathrm{t}}\big(v_{\mathrm{w}}(t),\beta(t),\omega_{\mathrm{t}}(t)\big) - (\mathfrak{F}_{\mathrm{t}}\omega_{\mathrm{t}})(t)\end{pmatrix}$$

$$y(t) = \boldsymbol{c}_{\mathrm{S}}^{\top}\boldsymbol{x}_{\mathrm{S}}(t), \qquad \boldsymbol{x}_{\mathrm{S}}(0) = \boldsymbol{x}_{\mathrm{S}}^{0} \in \mathbb{R}^3$$

where $m_{\mathrm{t}}(\cdot,\cdot,\cdot)$ is as in (1) and *bounded* (see Lem. III.1), and

$$\boldsymbol{A}_{\mathrm{S}} = \begin{bmatrix} -\frac{d_{\mathrm{s}}+g_{\mathrm{r}}^2\nu_{\mathrm{m}}}{g_{\mathrm{r}}^2\Theta_{\mathrm{m}}} & -\frac{c_{\mathrm{s}}}{g_{\mathrm{r}}\Theta_{\mathrm{m}}} & \frac{d_{\mathrm{s}}}{g_{\mathrm{r}}\Theta_{\mathrm{m}}} \\ \frac{1}{g_{\mathrm{r}}} & 0 & -1 \\ \frac{d_{\mathrm{s}}}{g_{\mathrm{r}}\Theta_{\mathrm{t}}} & \frac{c_{\mathrm{s}}}{\Theta_{\mathrm{t}}} & -\frac{d_{\mathrm{s}}+\nu_{\mathrm{t}}}{\Theta_{\mathrm{t}}} \end{bmatrix}, \ \boldsymbol{b}_{\mathrm{S}} = \begin{pmatrix} \frac{k_a}{\Theta_{\mathrm{m}}} \\ 0 \\ 0 \end{pmatrix}, \boldsymbol{B}_{\mathrm{S}} = \begin{bmatrix} \frac{1}{\Theta_{\mathrm{m}}} & 0 \\ 0 & 0 \\ 0 & \frac{1}{\Theta_{\mathrm{t}}} \end{bmatrix}, \boldsymbol{c}_{\mathrm{S}} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix},$$

$$\begin{aligned} &\Theta_{\mathrm{m}},\ \Theta_{\mathrm{t}} > 0,\ c_{\mathrm{s}} > 0, && u_{\mathrm{a}}(\cdot), v_{\mathrm{w}}(\cdot),\ \beta(\cdot) \in \mathcal{L}^{\infty}(\mathbb{R}_{>0};\mathbb{R}), \\ &d_{\mathrm{s}} > 0,\ g_{\mathrm{r}} \geqslant 1, && \forall\, i \in \{\mathrm{g},\mathrm{t}\}:\ \mathfrak{F}_i \in \mathcal{T} \ \wedge \ M_{\mathfrak{F}_i} := \\ &\nu_{\mathrm{m}},\nu_{\mathrm{t}} > 0,\ k_{\mathrm{a}} > 0, && \sup\left\{ |(\mathfrak{F}_i\xi)(t)| \;\middle|\; t \geqslant 0,\ \xi(\cdot) \in \mathcal{C}(\mathbb{R}_{>0},\mathbb{R}) \right\} < \infty. \end{aligned}$$

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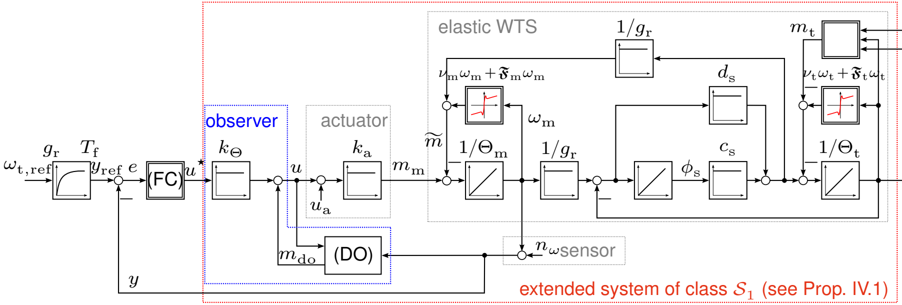
Closed-loop system with disturbance observer (DO)



$$\left.\begin{aligned}\dot{x}_{\mathrm{do}}(t) &= \frac{1}{T_{\mathrm{do}}}\left(-x_{\mathrm{do}}(t) + u(t) + \frac{\hat{\Theta}_{\mathrm{m}}\omega_{\mathrm{m}}(t)}{\hat{k}_{\mathrm{a}}T_{\mathrm{do}}}\right) \\ m_{\mathrm{do}}(t) &= (1-k_{\mathrm{do}})\left(x_{\mathrm{do}}(t) - \frac{\hat{\Theta}_{\mathrm{m}}\omega_{\mathrm{m}}(t)}{\hat{k}_{\mathrm{a}}T_{\mathrm{do}}}\right), \qquad x_{\mathrm{do}}(0) = 0.\end{aligned}\right\} \quad \text{(DO)}$$

Active damping for $k_{\mathrm{do}} > 1$: $\omega_0'(k_{\mathrm{do}}) = \sqrt{\dfrac{c_{\mathrm{s}}\left(\Theta_{\mathrm{m}} + \frac{\Theta_{\mathrm{t}}}{g_{\mathrm{r}}^2}k_{\mathrm{do}}\right)}{\Theta_{\mathrm{m}}\Theta_{\mathrm{t}}}} \wedge \zeta'(k_{\mathrm{do}}) = \dfrac{\omega_0(k_{\mathrm{do}})}{2}\dfrac{d_{\mathrm{s}}}{c_{\mathrm{s}}}.$

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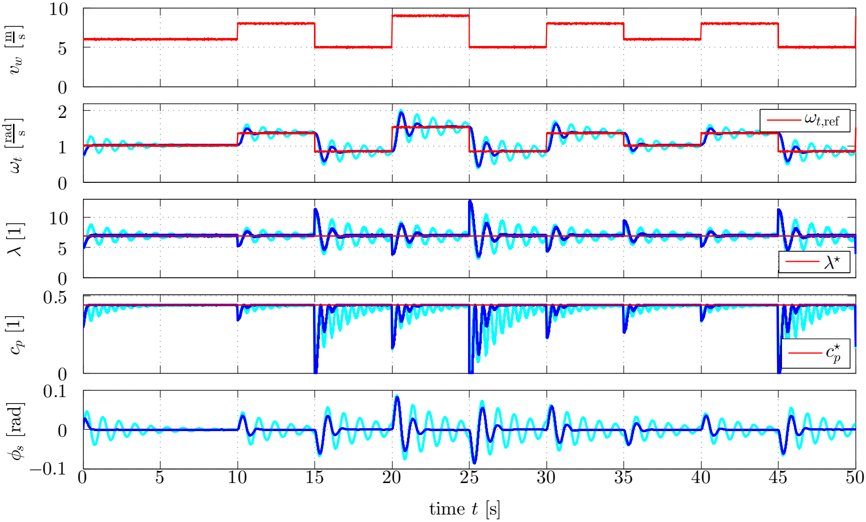
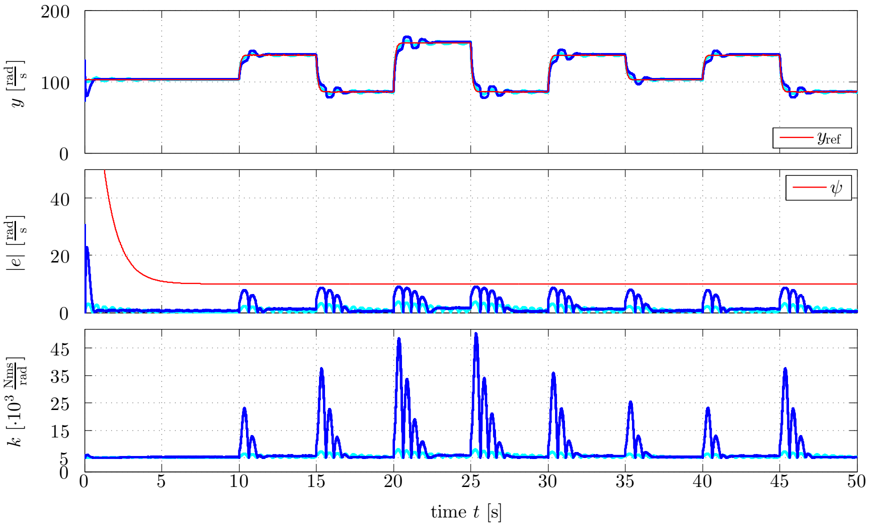
Speed funnel control with DO of WTS with elastic shaft

Simulation results: —(FC), — (FC)+(DO)



Speed funnel control with DO of WTS with elastic shaft

Simulation results: (FC), (FC)+(DO)



Outline

Conclusion

To take home:

Speed funnel control of wind turbine systems with disturbance observer ...

- is simple
- is robust ($\lambda^\star$ and g_r must be known; $\widehat{\Theta}_\mathrm{m}$ and $\widehat{k}_\mathrm{a}$ rough estimates)
- achieves active damping (for all $k_\mathrm{do} > 1$)
- only ω_m required for feedback (not ω_t)
- no problems due to non-ideal torque control [3]
- faster dynamics and more efficient than nonlinear controller $-k_\mathrm{p}^\star \omega_\mathrm{m}^2$ [4]

Current drawbacks:

- $|\omega_{\mathrm{t,ref}} - \omega_\mathrm{t}| < \frac{\psi}{g_\mathrm{r}}$ (and $|\lambda| < \lambda^\star - \varepsilon$) only in steady state
- wind speed measurement required (for $\omega_{\mathrm{t,ref}}(\cdot) = \frac{v_\mathrm{w}(\cdot)}{r_\mathrm{t}} \lambda^\star$)

References I

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[2] Y. Hori, H. Sawada, and Y. Chun, "Slow resonance ratio control for vibration suppression and disturbance rejection in torsional system," *IEEE Transactions on Industrial Electronics*, vol. 46, no. 1, pp. 162–168, 1999.

[3] C. M. Hackl and K. Schechner, "Non-ideal torque control of wind turbine systems: Impacts on annual energy production," in *Proceedings of the IEEE International Energy Conference (submitted)*, 2016.

[4] C. M. Hackl, "Funnel control for wind turbine systems," in *Proceedings of the 2014 IEEE International Conference on Control Applications*, pp. 1377–1382, 2014.