# DC-link control for airborne wind energy systems during pumping mode

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# Outline

1. Problem formulation
2. DC-link control
3. Conclusion and future work

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   - Airborne wind energy systems during pumping mode
   - Overview and control system

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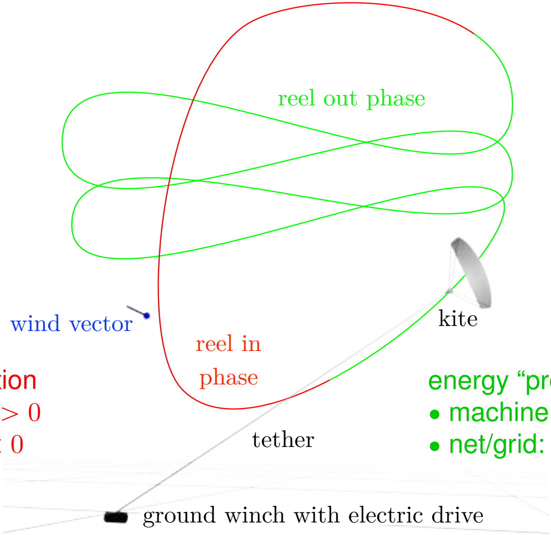
# Problem formulation

## Airborne wind energy systems during pumping mode $\Longrightarrow$ **Bidirectional** power flow




energy dissipation
- machine: $p_m > 0$
- net/grid: $p_n < 0$

energy “production”
- machine: $p_m < 0$
- net/grid: $p_n > 0$

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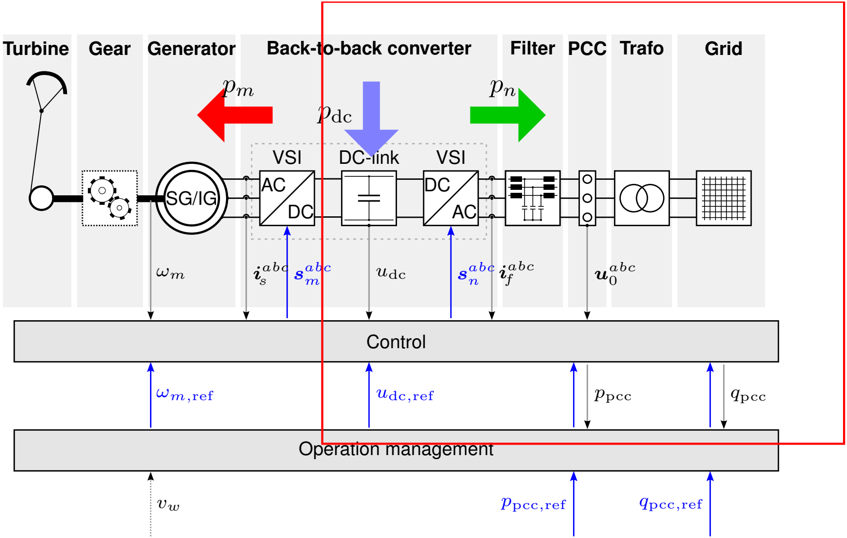
# Grid-side control

## Overview



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## 2 DC-link control

- Nonlinear dynamics of DC-link
- Classical DC-link PI controller
- Grid-side control structure in voltage orientation
  - Linearization and “structurally varying” system
  - “Structurally varying” system
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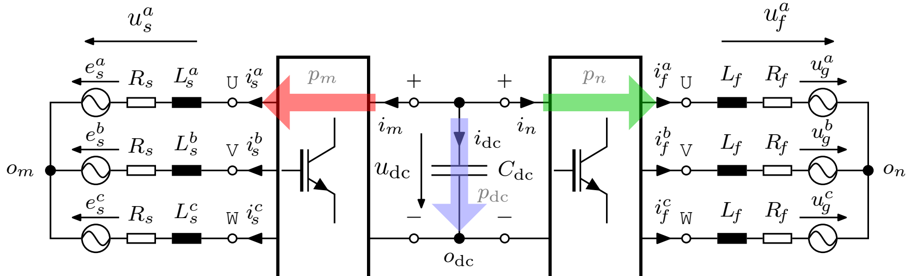
# Nonlinear dynamics of DC-link




- $p_{dc} = u_{dc} C_{dc} \frac{d}{dt} u_{dc} = -p_m - p_n \quad \Longrightarrow \quad \boxed{\frac{d}{dt} u_{dc} = \frac{1}{u_{dc} C_{dc}} \big( -p_m - p_n \big)}$
- $p_m = \underbrace{\frac{3}{2} R_s \left\| \boldsymbol{i}_s^k \right\|^2}_{p_{m,\text{loss}}} + \underbrace{\frac{3}{2} p \big( \psi_{pm} i_s^q + (L_s^d - L_s^q) i_s^d i_s^q \big) \omega_m}_{p_{\text{mech}} = m_m \omega_m} + \underbrace{\frac{3}{2} \frac{d}{dt} (\boldsymbol{i}_s^k)^\top \boldsymbol{L}_s^k \boldsymbol{i}_s^k}_{p_{\boldsymbol{L}_s^k}} =: p_m(t)$
- $p_n = \underbrace{\frac{3}{2} R_f \left\| \boldsymbol{i}_f^k \right\|^2}_{p_{\text{pcc,loss}}} + \underbrace{\frac{3}{2} \frac{d}{dt} L_f (\boldsymbol{i}_f^k)^\top \boldsymbol{i}_f^k}_{p_{L_f}} + \underbrace{\frac{3}{2} \hat{u}_g i_f^d}_{p_{\text{pcc}}}$

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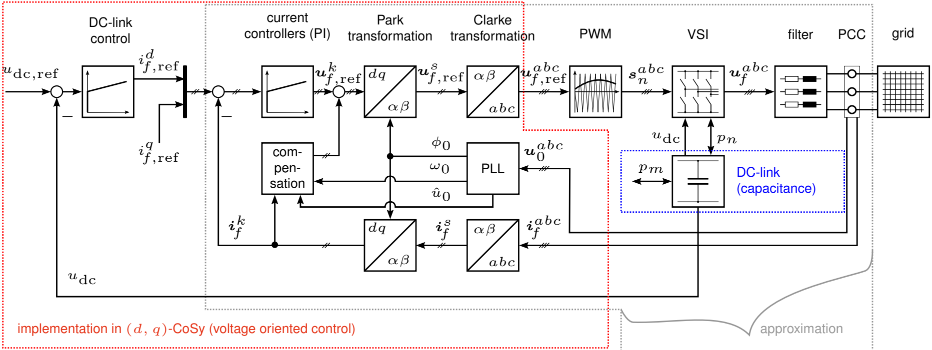
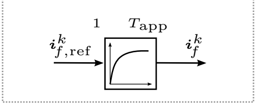
# Classical DC-link PI controller

## Grid-side control structure in voltage orientation with **constant** PI controller




PI controller with constant gains:

$$e(t) := u_{\rm dc,ref}(t) - u_{\rm dc}(t)$$

$$i^d_{f,\rm ref}(t) = V_R\, e(t) + \frac{V_R}{T_n}\int_0^t e(\tau)\,\mathrm{d}\tau\,, \quad V_R,\, T_n > 0$$

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# Linearized system [1]

For small signals $\widetilde{\boldsymbol{x}} := \boldsymbol{x} - \boldsymbol{x}^\star$, $\widetilde{\boldsymbol{u}} := \boldsymbol{u} - \boldsymbol{u}^\star$, $\widetilde{d} := d - d^\star$, where

$$\boldsymbol{x} := \begin{pmatrix} u_{\mathrm{dc}} \\ \boldsymbol{i}_f^k \end{pmatrix}, \quad \boldsymbol{u} := \boldsymbol{i}_{f,\mathrm{ref}}^k = \begin{pmatrix} i_f^d \\ i_f^q \end{pmatrix}, \quad d := p_m \quad \text{and} \quad \begin{pmatrix} \boldsymbol{x}^\star \\ \boldsymbol{u}^\star \\ d^\star \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} u_{\mathrm{dc}}^\star \\ \boldsymbol{i}_f^{k,\star} \end{pmatrix} \\ \boldsymbol{i}_{f,\mathrm{ref}}^{k,\star} \\ p_m^\star \end{pmatrix}, \tag{1}$$

it holds that

$$\frac{\mathrm{d}}{\mathrm{d}t}\widetilde{\boldsymbol{x}}(t) = \boldsymbol{A}\widetilde{\boldsymbol{x}}(t) + \boldsymbol{B}\widetilde{\boldsymbol{u}}(t) + \boldsymbol{b}_{\mathrm{d}}\widetilde{d}(t)$$

with

$$\boldsymbol{A} := \left.\frac{\partial \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u},d)}{\partial \boldsymbol{x}}\right|_{(1)}, \; \boldsymbol{B} := \left.\frac{\partial \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u},d)}{\partial \boldsymbol{u}}\right|_{(1)} = [\boldsymbol{b}_1, \boldsymbol{b}_2] \; \text{and} \; \boldsymbol{b}_{\mathrm{d}} := \left.\frac{\partial \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u},d)}{\partial d}\right|_{(1)}.$$

$$\boxed{\Longrightarrow \frac{\widetilde{u}_{\mathrm{dc}}(s)}{\widetilde{i}_{f,\mathrm{ref}}^d(s)} = (1,0,0)\big(s\boldsymbol{I}_3 - \boldsymbol{A}\big)^{-1}\boldsymbol{b}_1 = -\underbrace{\frac{3(\hat{u}_g + 2R_f i_f^{d,\star})}{2C_{\mathrm{dc}}u_{\mathrm{dc}}^\star}}_{=:V_S^\star = V_S^\star(\boldsymbol{x}^\star)} \frac{1 + s\overbrace{\left(\frac{L_f i_f^{d,\star}}{\hat{u}_g + 2R_f i_f^{d,\star}}\right)}^{=:T_V^\star = T_V^\star(\boldsymbol{x}^\star)}}{s(1 + sT_{\mathrm{app}})}}$$

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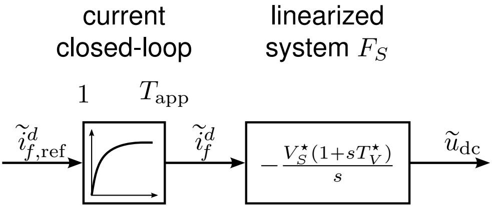
# “Structurally varying” system [2]




(Case 1) $p_n = 0 \implies i_f^{d,\star} = 0 \implies T_V^\star = 0 \implies \dfrac{\tilde{u}_{\mathrm{dc}}(s)}{\tilde{i}^d_{f,\mathrm{ref}}(s)} = \dfrac{V_S^\star}{s(1+sT_{\mathrm{app}})}$

(Case 2) $p_n > 0 \implies i_f^{d,\star} > 0 \implies T_V^\star > 0 \implies \dfrac{\tilde{u}_{\mathrm{dc}}(s)}{\tilde{i}^d_{f,\mathrm{ref}}(s)} = \dfrac{V_S^\star(1+sT_V^\star)}{s(1+sT_{\mathrm{app}})}$

(minimum-phase)

(Case 3) $p_n < 0 \implies i_f^{d,\star} < 0 \implies T_V^\star < 0 \implies \dfrac{\tilde{u}_{\mathrm{dc}}(s)}{\tilde{i}^d_{f,\mathrm{ref}}(s)} = \dfrac{V_S^\star(1-s|T_V^\star|)}{s(1+sT_{\mathrm{app}})}$

(**non**minimum-phase)

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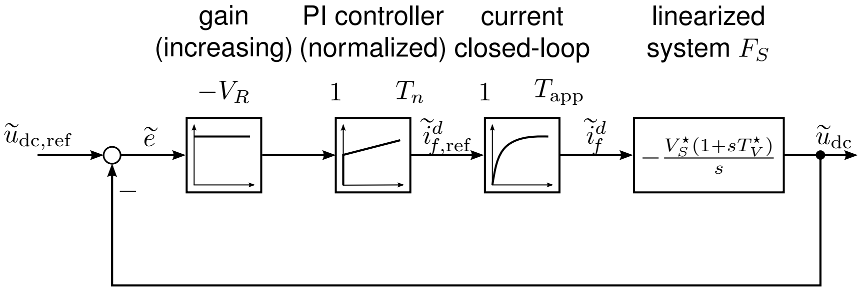
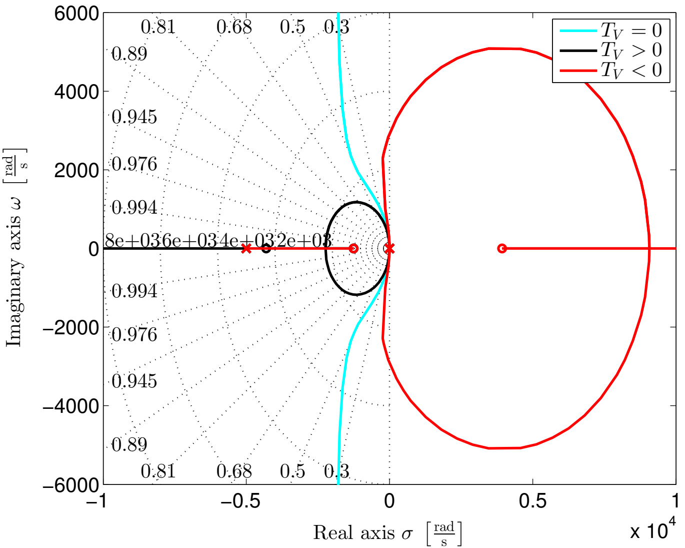
# Root locus of linearized system




open loop of linearized system

$$\frac{\widetilde{u}_{\text{dc}}(s)}{\widetilde{e}(s)} = \frac{V_R V_S^\star (1+sT_n)(1+sT_V^\star)}{s^2 T_n (1+sT_{\text{app}})}, \quad \begin{cases} T_{\text{app}}, T_n > 0, \ V_S^\star > 0 \\ T_V^\star \in \mathbb{R} \ \text{(depends on equilibrium!)} \\ V_R \to \infty \end{cases}$$

# Root locus ($T_V = T_V^\star$ depends on equilibrium!)



# Local stability analysis

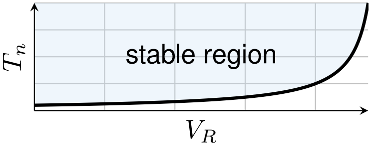
## Hurwitz criterion

Transfer function of (linearized) closed-loop system

$$F_{CL}(s) = \frac{u_{\mathrm{dc}}(s)}{u_{\mathrm{dc,ref}}(s)} = \frac{V_R V_S^\star (1 + sT_{\mathrm{app}})(1 + sT_V^\star)}{s^3 \underbrace{T_n T_{\mathrm{app}}}_{=:a_3} + s^2 \underbrace{T_n(1 + T_V^\star V_S^\star V_R)}_{=:a_2} + s \underbrace{(T_V^\star + T_n) V_S^\star V_R}_{=:a_1} + \underbrace{V_R V_S^\star}_{=:a_0}}$$

Sufficient condition for *local* stability

- $0 < V_R < \frac{1}{|T_V^\star| V_S^\star}$
- $T_n > \frac{T_{\mathrm{app}}}{1 - V_R V_S^\star |T_V^\star|} + |T_V^\star| > 0$




$\Longrightarrow a_0, a_1, a_2, a_3 > 0$ and $D_2 := a_2 a_1 - a_3 a_0 > 0$.

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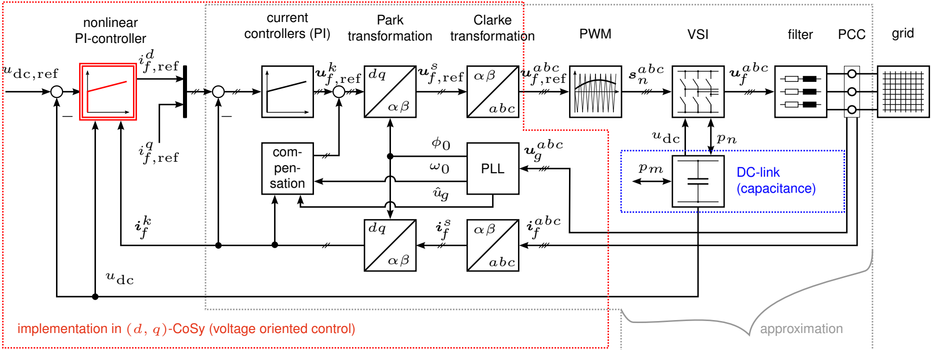
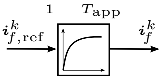
# Nonlinear DC-link PI controller

## Control system in voltage orientation with **nonlinear** PI controller




### **Nonlinear** PI controller

$$e(t) := u_{\mathrm{dc,ref}}(t) - u_{\mathrm{dc}}(t)$$

$$i_{f,\mathrm{ref}}^{d}(t) = V_R(\boldsymbol{i}_f^k, u_{\mathrm{dc}})\, e(t) + \frac{V_R(\boldsymbol{i}_f^k, u_{\mathrm{dc}})}{T_n(\boldsymbol{i}_f^k, u_{\mathrm{dc}})} \int_0^t e(\tau)\, \mathrm{d}\tau$$

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# Nonlinear DC-link PI controller

## Controller design and local stability analysis

Pole placement: Two tuning parameters $V_R$ & $T_n$; three poles $\lambda_1$ & $\lambda_2 \pm \imath\lambda_i$

$$\underbrace{s^3 T_n T_{\mathrm{app}}}_{=:a_3} + \underbrace{T_n(1 + T_V^\star V_S^\star V_R)}_{=:a_2} + s\,\underbrace{(T_V^\star + T_n)V_S^\star V_R}_{=:a_1} + \underbrace{V_R V_S^\star}_{=:a_0}$$

$$\stackrel{!}{=} (s - \lambda_1)(s - \lambda_2 + \jmath\lambda_i)(s - \lambda_2 - \jmath\lambda_i)$$

For given $\lambda_2 < 0$ and $\lambda_i \neq 0 \implies$ Computation of $V_R(T_V^\star, V_S^\star, \lambda_2, \lambda_i) > 0$, $T_n(T_V^\star, V_S^\star, \lambda_2, \lambda_i) > 0$ (analytic expression derived for online parameter adjustment) and $\lambda_1(T_V^\star, V_S^\star, \lambda_2, \lambda_i) < 0$.

Sufficient condition for *local* stability

- $0 < \lambda_i^2 < \frac{1}{|T_V^\star| T_{\mathrm{app}}}$
- $0 > \lambda_2 \geqslant \max\left\{-\frac{1}{2T_{\mathrm{app}}},\ \frac{1}{|T_V^\star|} - \sqrt{\frac{1}{(T_V^\star)^2} + \frac{1}{|T_V^\star| T_{\mathrm{app}}} - \lambda_i^2}\right\}$

$\implies a_0, a_1, a_2, a_3 > 0$, $D_2 := a_2 a_1 - a_3 a_0 > 0$ and $\lambda_1 < 0$.

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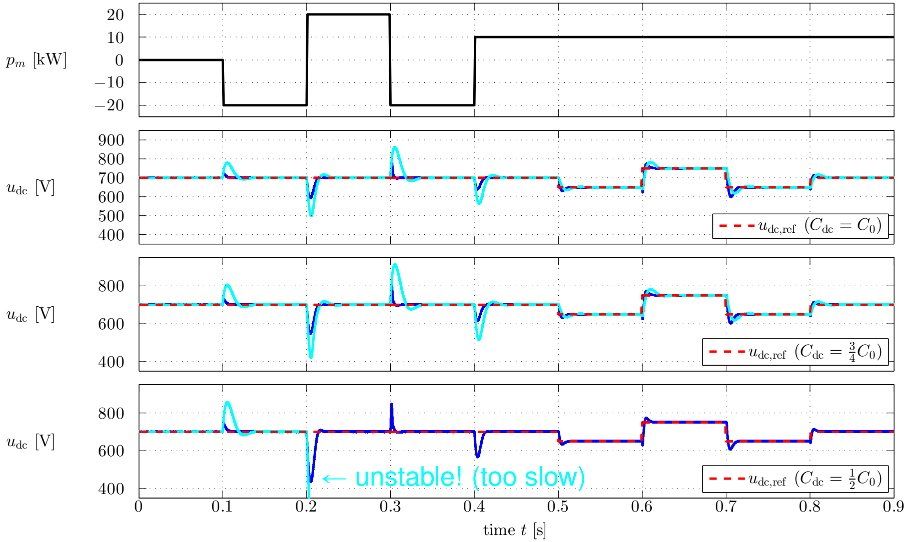
# Nonlinear PI-control for DC-link voltage

Simulation results for 20 kW AWE system: constant PI, nonlinear PI



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# Conclusion and future work

To take home:

- DC-link voltage control
  - nonlinear system dynamics with structurally varying nature
  - **non**minimum-phase behavior during reel-in phase
  - very conservative classical PI controller design necessary
- nonlinear PI controller
  - design based on pole placement and online parameter adjustment
  - faster tracking and disturbance rejection
  - smaller DC-link capacitance feasible ($\rightarrow$ cheaper)

Future work:

- Lyapunov-based stability analysis
- Measurement results (construction of test bench in progress)

# References

[1] C. Dirscherl, C. Hackl, and K. Schechner, “Explicit model predictive control with disturbance observer for grid-connected voltage source power converters,” in *Proceedings of the 2015 IEEE International Conference on Industrial Technology*, pp. 999–1006, 2015.

[2] C. Dirscherl, C. Hackl, and K. Schechner, “Modellierung und Regelung von modernen Windkraftanlagen: Eine Einführung *(available at the authors upon request)*,” in *Elektrische Antriebe – Regelung von Antriebssystemen* (D. Schröder, ed.), ch. 24, Springer-Verlag, 2015.