1^{st} MSE Winter School

Ohlstadt, 2^{nd} – 6^{th} February 2015

Part I – Renewable Energy Systems

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03.02.2015

MSE Research group
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Contact and further reading

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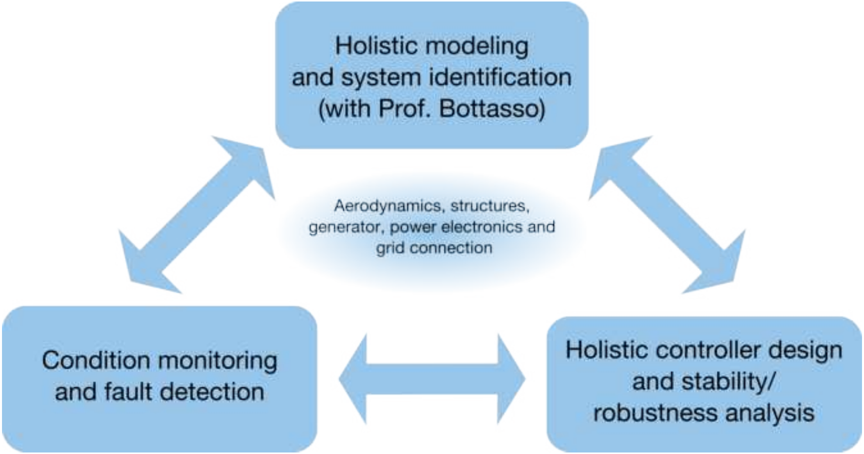
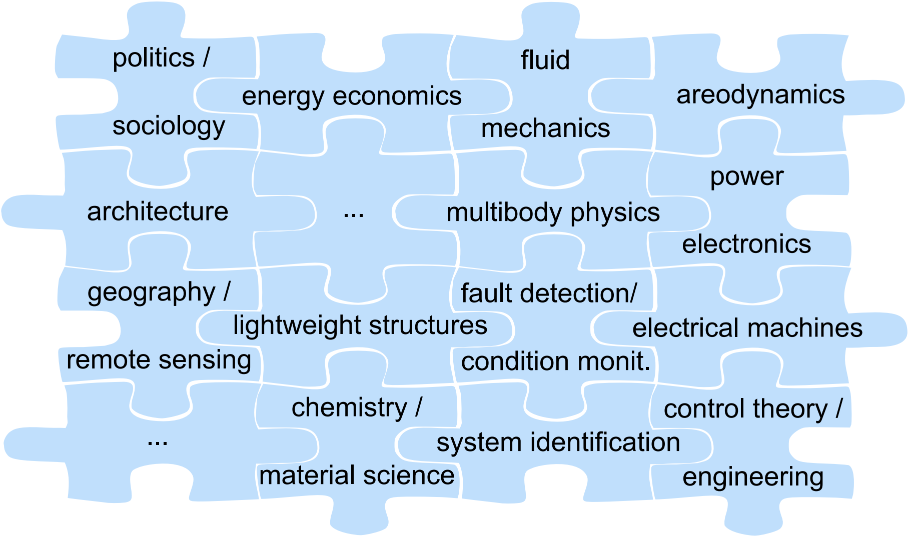
- www: `http://www.cres.mse.tum.de`
- teaching materials (dropbox): `https://www.dropbox.com/sh/1s9jvpt0zq7ll11/AABRSUwkqcwEw2_PnUmN9Tdia?dl=0`
- most content from: *C. Dirscherl, C. Hackl, K. Schechner, “Modellierung und Regelung von modernen Windkraftanlagen: Eine Einführung”, Chapter 24 in D. Schröder, “Elektrische Antriebe – Regelung von Antriebssystemen”, Springer-Verlag, Berlin, 2014* (see [1])

CRES Research foci



Energy research = interdisciplinary



Outcome of Part I – Renewable Energy Systems

After this day you should be able to:

- to understand, analyze and implement basic models of (electrical) components and actuators of renewable energy systems
- to understand, design and implement standard control methods for generator- and grid-side
- to understand the basic operation management of renewable energy systems

Required prior knowledge:

- *Linear algebra (norms, vectors, matrices, Eigenvalues, . . .)*
- *Linear control theory (ODEs, transfer functions, poles/zeros, Hurwitz analysis, . . .)*
- *Basic circuit theory (Kirchhof"s laws, Ohm's law, voltage & current dynamics for capacitance or inductance, . . .)*

Schedule: Part I – Renewable Energy Systems

Date	Time	Content
03.02.2015	08:30–10:00	*1st Lecture*: Introduction and modeling (part 1)
	10:00–10:30	*Coffee break*
	10:30–12:00	*2nd Lecture*: Modeling (part 2) and controller design (part 1)
	12:00–13:30	*Lunch*
	13:30–15:00	*Session I (presentations)*: Renewable Energy Systems
	15:00–15:30	*Coffee break*
	15:30–17:00	*3rd Lecture*: Controller design (part 2) and operation management
	17:00–17:30	*Coffee break*
	17:30–19:00	*Tutorial (exercise sheet)*: Renewable energy systems
	19:00–20:30	*Dinner*

Outline

Outline

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1. Introduction
   - Background information
     - Facts and figures
     - Evolution of wind power systems
     - Wind power in Germany
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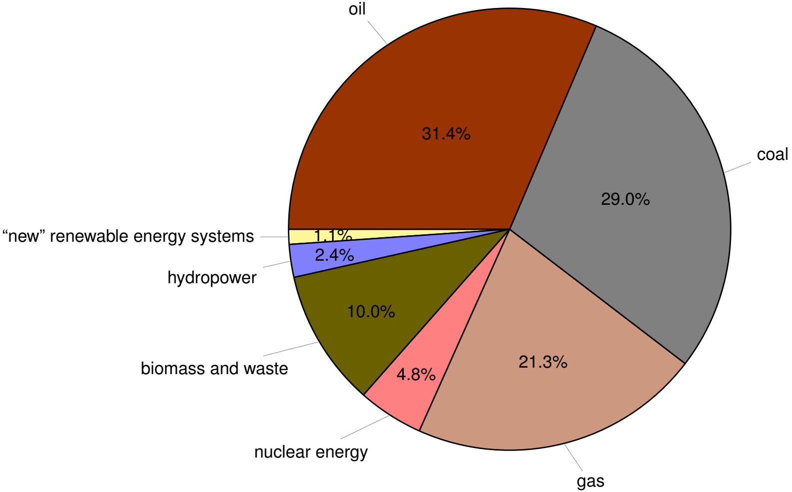
     - Core components
     - Configurations of wind turbine systems (WTS)
     - Component topologies
     - Operating regimes
     - Availability and failures

Outline

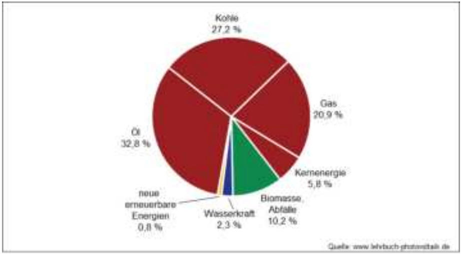
Use of primary energy worldwide 2012 (overall 13 371 Mtoe* $= 1{,}555 \cdot 10^{11}$ kW h, from [2])



* Mtoe = Million *tonne of oil equivalent (TOE)*.

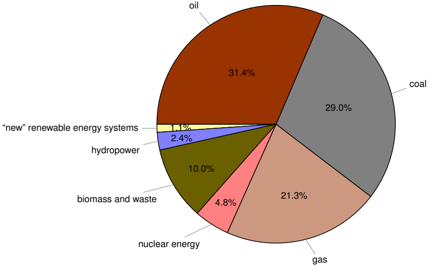
Use of primary energy worldwide
$\Longrightarrow$ Use of fossil energy is increasing!

2009



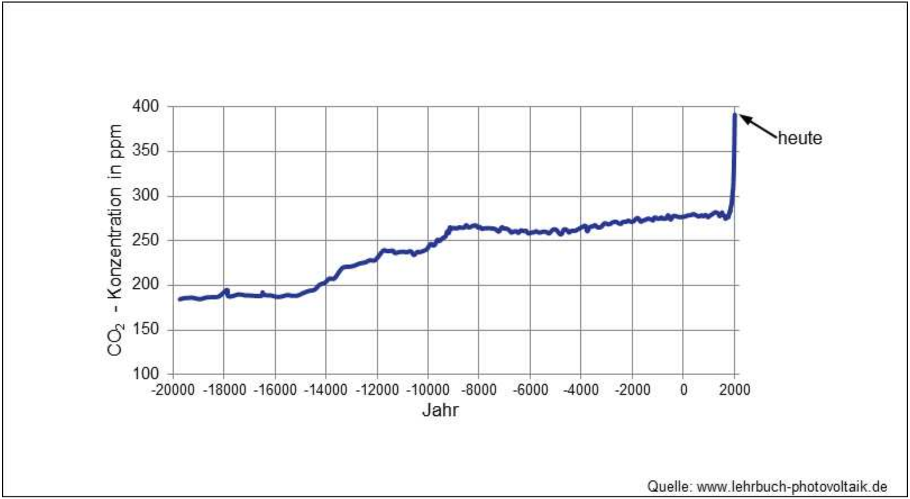
80,9 % fossil

2012

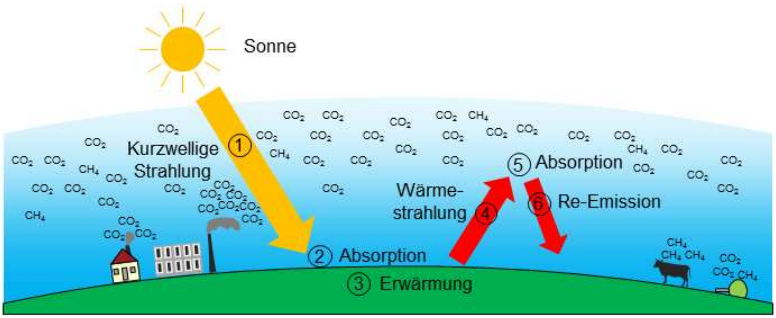


81,7 % fossil

Trend of CO_2 concentration in the atmosphere

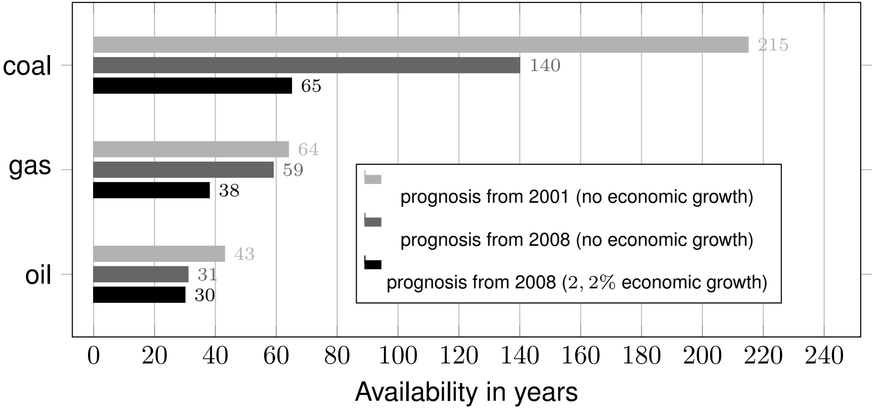


Greenhouse effect ⇒ Global warming



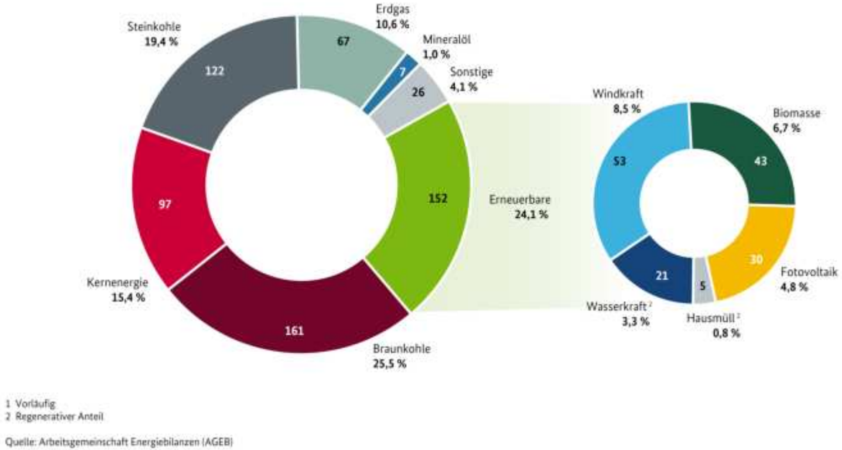
Quelle: www.lehrbuch-photovoltaik.de

Scarcity of resources



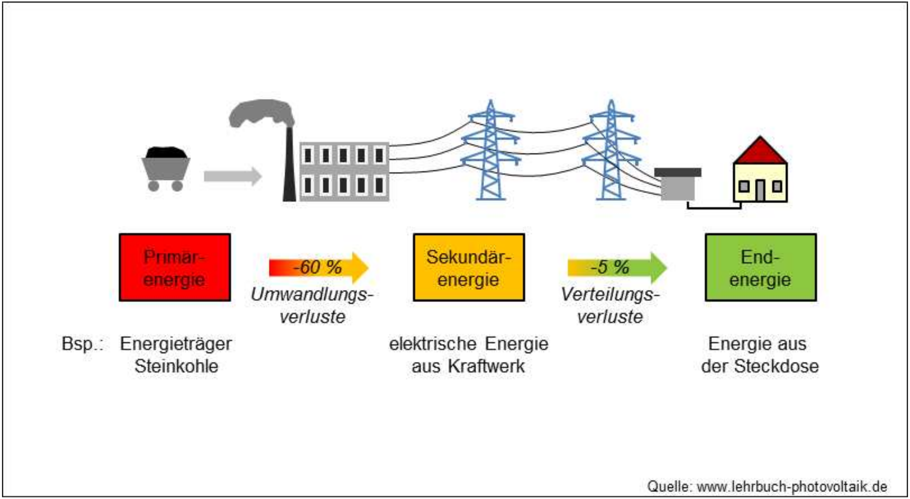
(Fig. based on [3, Tab. 1.3]; without shale gas)

Gross power generation* in Germany 2013 (overall $631\,\mathrm{TW\,h}^1 = 631 \cdot 10^9\,\mathrm{kW\,h}$, aus [4])

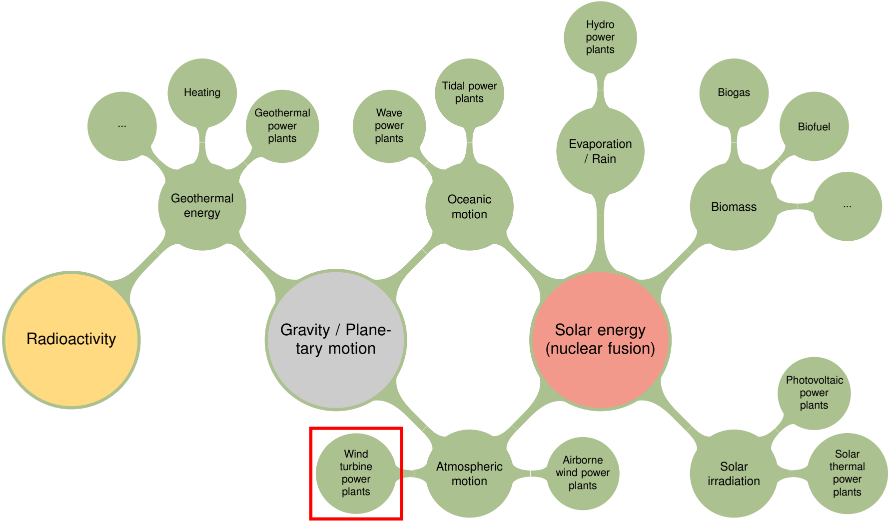


(* net power generation = gross power generation − energy consumption of power plant)

Exemplary electricity production with black coal



"Primary energy" for renewable energy systems



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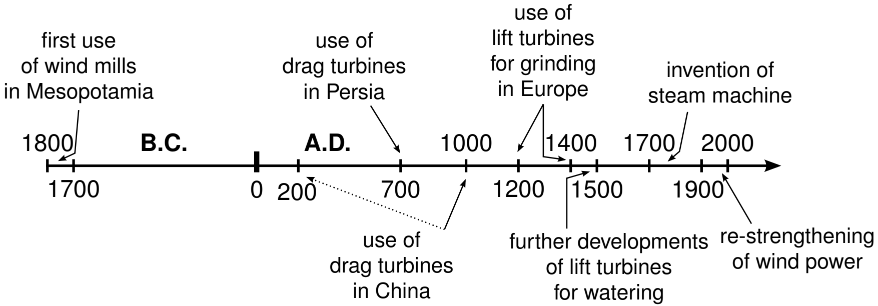
History of wind power systems



Modern wind turbines (for power production)

(http://www.siemens.com/)

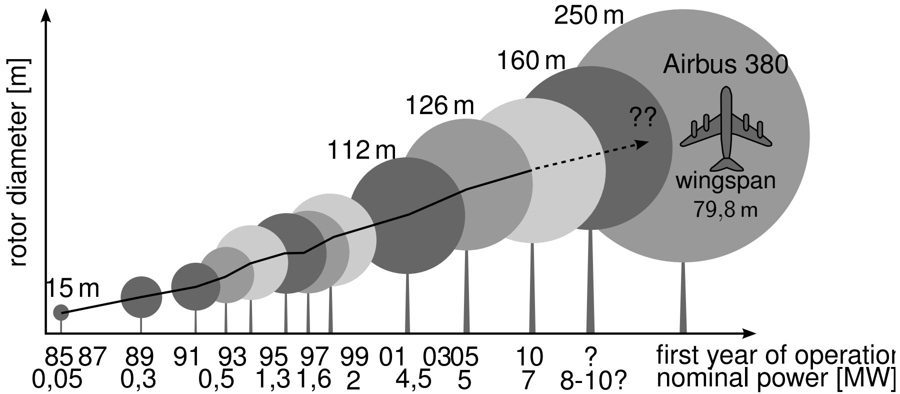
(http://www.ge.com/)

(http://www.enercon.de/)

Properties

- three rotor blades
- lift turbine
- windward (luv) rotor with horizontal axis
- typical generator topologies:
  - synchronous generator (SM) *without* gear ("direct drive")
  - double-fed induction generator (DFIG) *with* gear

Evolution of wind turbine size



(based on p. 17 in [5])

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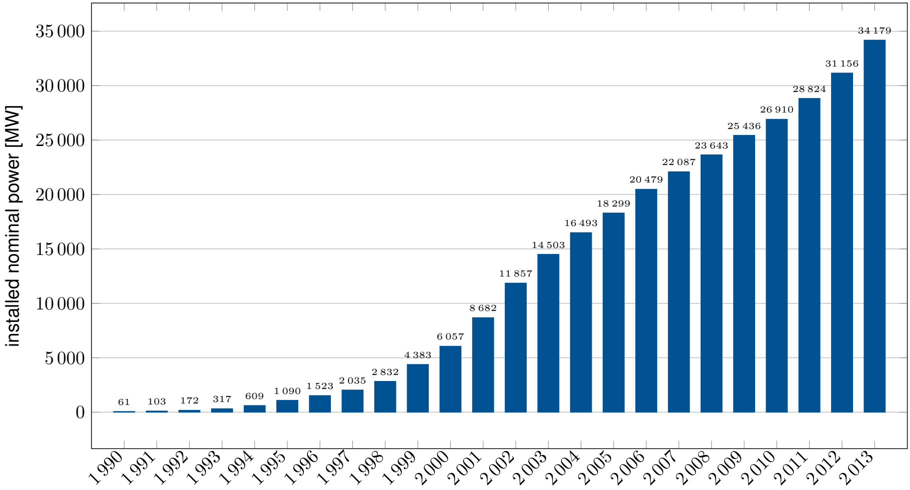
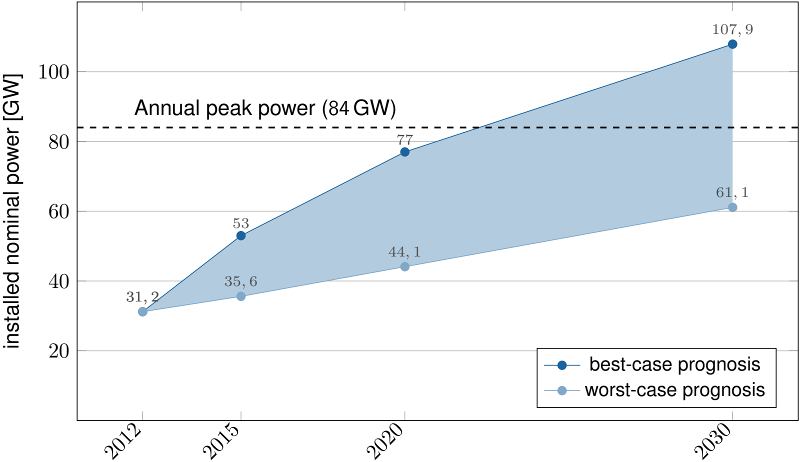
Installed nominal wind power in Germany 1990-2013



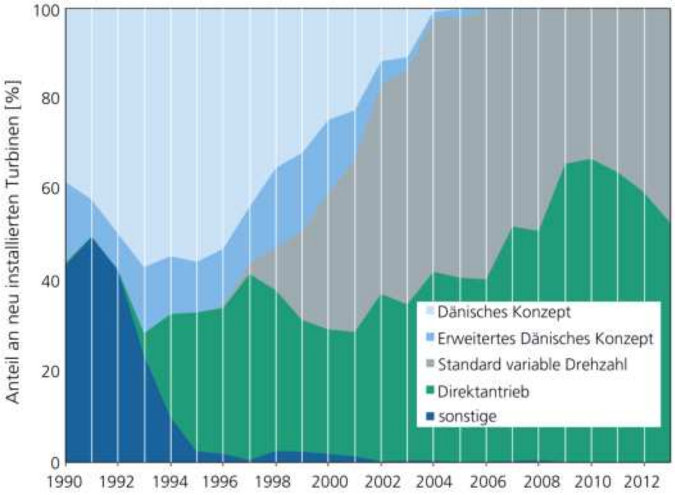
(based on Fig. 4 in [6])

Prognosis of installed nominal wind power in Germany 2030

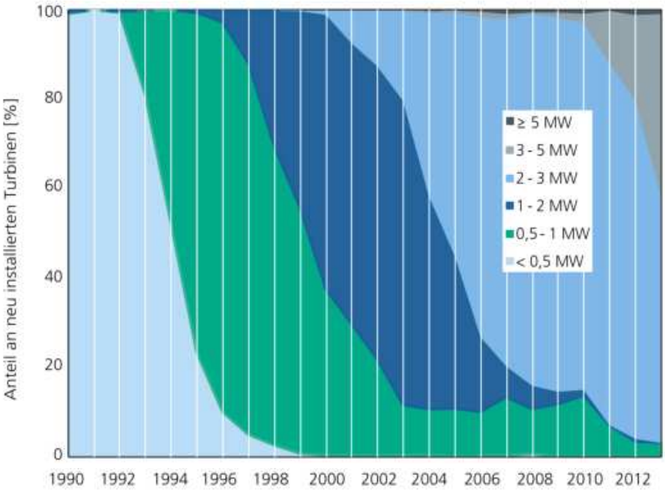


(Fig. based on p. 6 in [7])

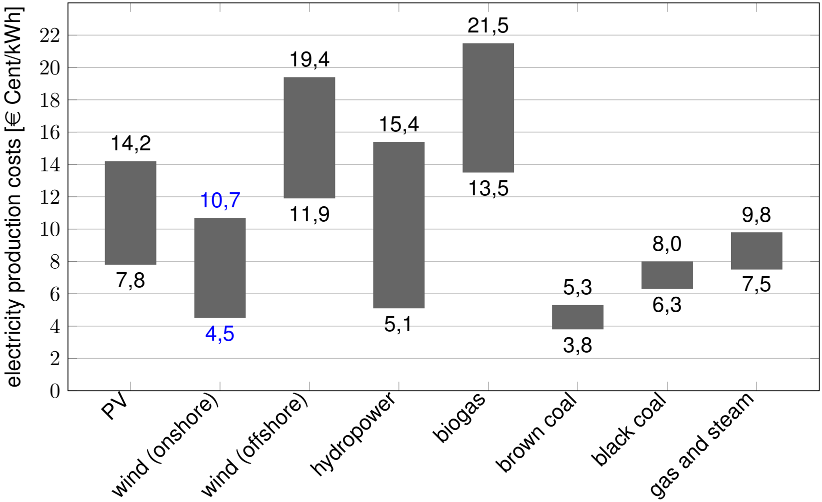
Percentage of installations after **generator topology** in Germany 1990-2013 (from [6])



Percentage of installations after **power size** in Germany 1990-2013 (from [6])



Electricity production costs in Germany 2013



(based on Fig. 1 in [8] and Tab. 4.12 (> 500 kW) in [9]).

Outline

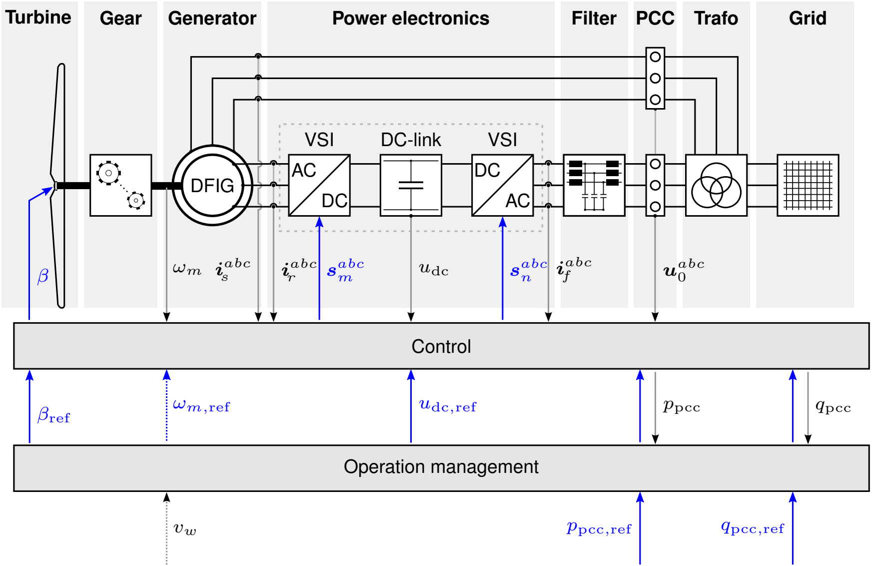
Outline

Core components: Inside a wind turbine

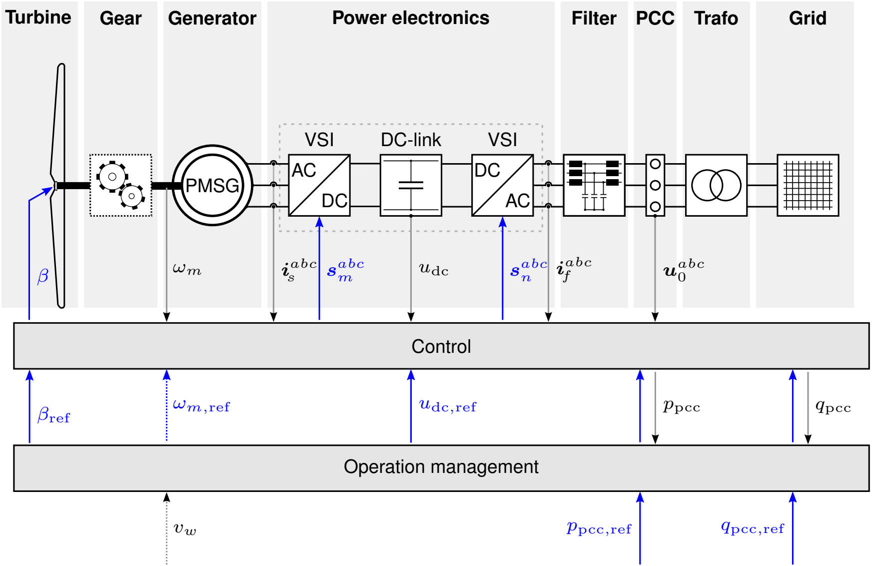
(http://www.youtube.com/watch?v=NG1uGt6qUfM; duration: 7:16 min)

Outline

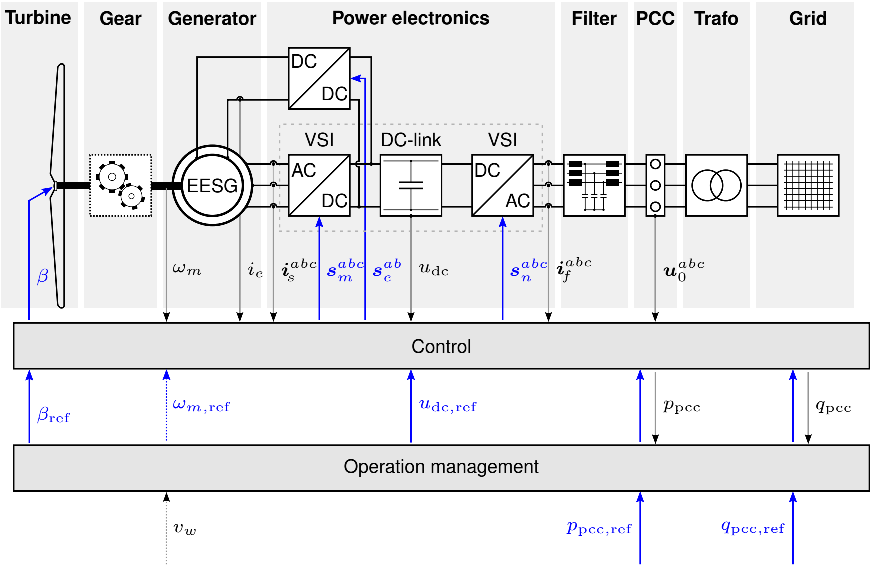
WTS with doubly-fed induction generator



WTS with **p**ermanent-**m**agnet **s**ynchronous **g**enerator



WTS with electrically-excited synchronous generator



Outline

Generator topologies

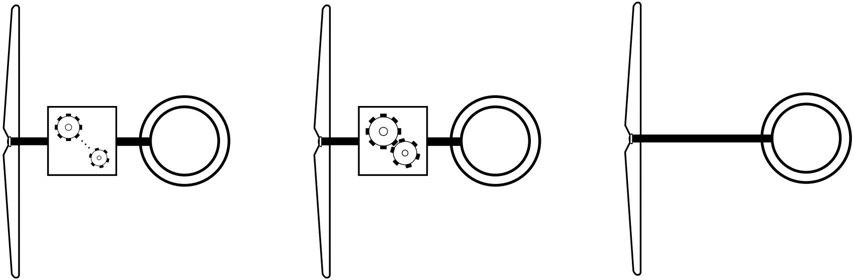
doubly-fed
induction generator
(DFIG, e.g. ABB)

electrically-excited
synchronous generator
(EESG, e.g. Enercon)

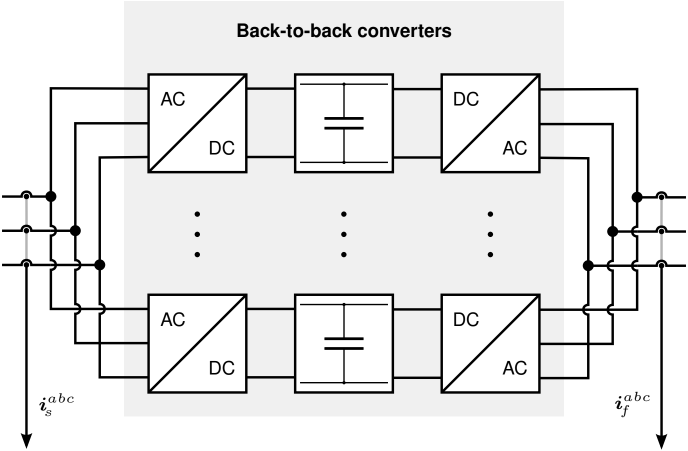
permanent-magnet
synchronous generator
(PMSG, e.g. Siemens)

Gear topologies

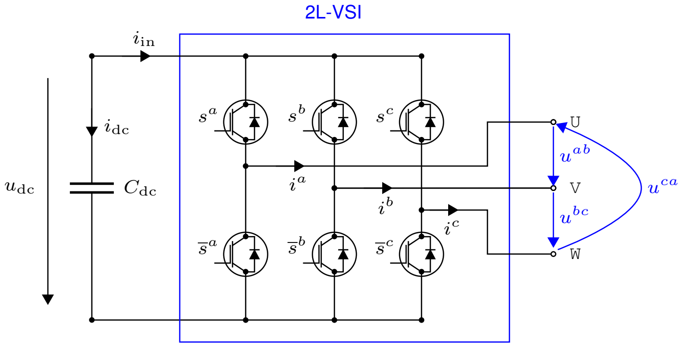
multi-stage gear | single-stage gear | direct drive



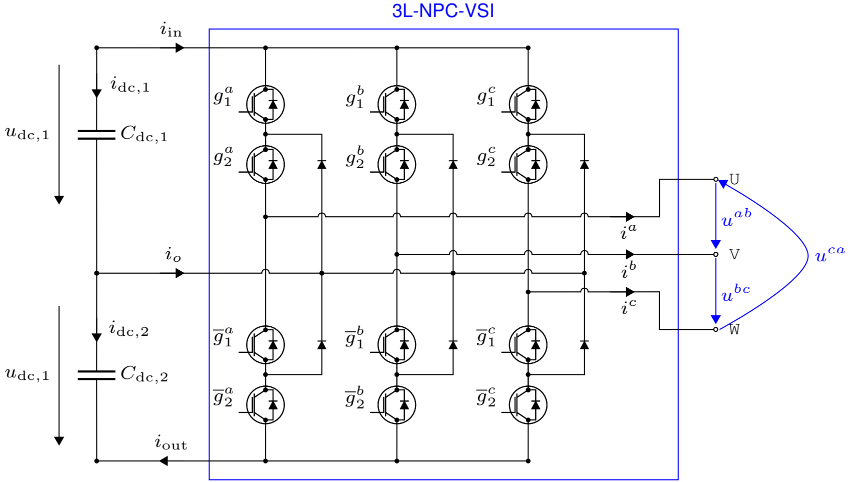
Parallel connection of back-to-back converters



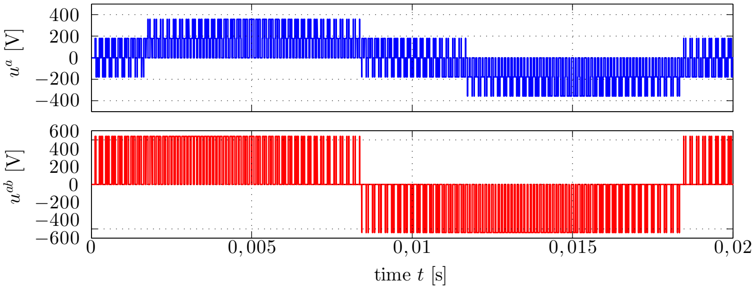
Converter topologies: Two-level voltage source inverter (2L-VSI)



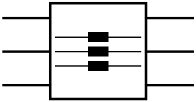
Three-level neutral-point-clamped voltage source inverter (3L-NPC-VSI)



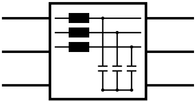
Filter topologies



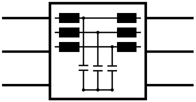
L-filter
(current control)



LC-filter
(voltage control)

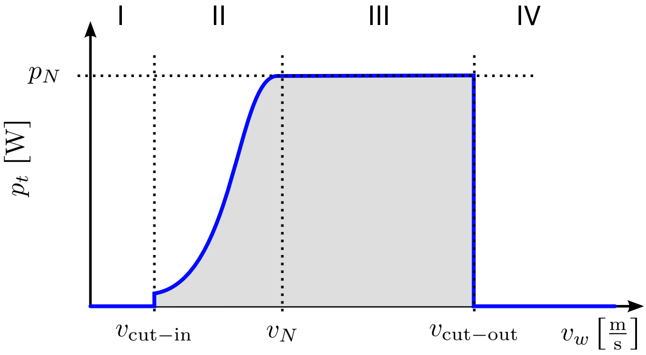


LCL-filter
(current control)



Outline

Operating regimes for different wind speeds



- Regime I: Stand still. No power output, i.e. $p_t = 0$.
- Regime II: Sub-nominal operation. Variable output power, i.e. $0 < p_t < p_n$ (Goal: Maximum power point tracking).
- Regime III: Nominal operation. Output of nominal power, i.e. $p_t = p_n$.
- Regime IV: Stand still (safety shut down), i.e. $p_t = 0$.

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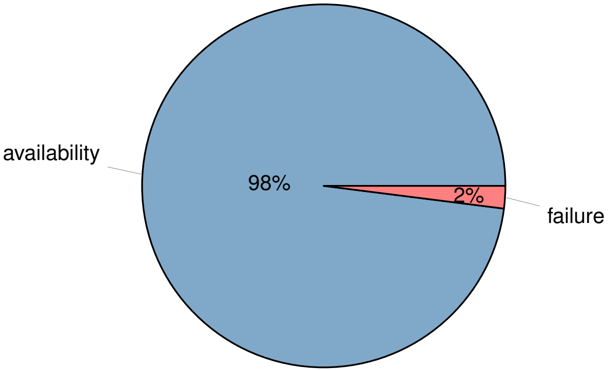
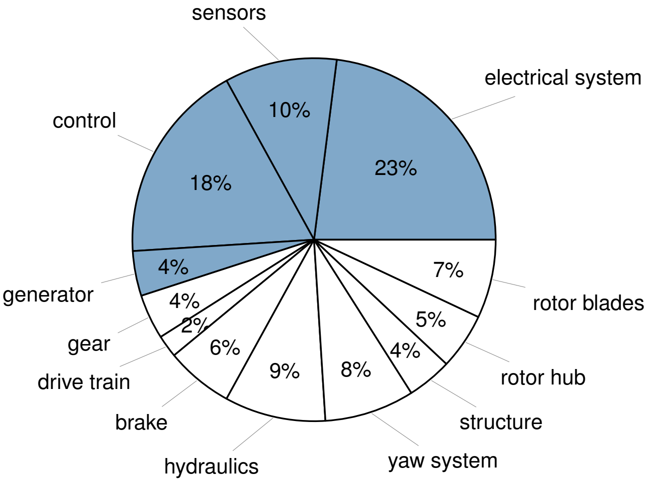
Availability (from a study with 1 500 WT, [10])



Average life span is 20 years (=7 400 days):

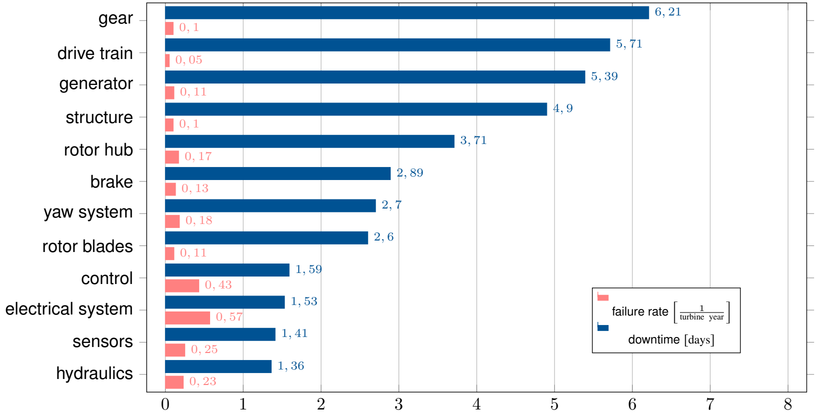
- Availability: 7 154 days
- Failure: 146 days (no production)

Share of failures of subsystems



(based on Fig. 2 in [10])

Failure rate and downtimes



(based on Fig. 2 in [11])

Average down time (over 20 years):

- electrical system: 18,9 days
- control: 16,7 days
- gear: 13,6 days

Seldom failure: Fire

(http://www.youtube.com/watch?v=0Chtr76jJyA; duration: 1:03 min)

Outline

Outline

2 Preliminaries

- Alternating current (AC) systems
  - One-phase systems
  - Three-phase systems
  - Interconnection of three-phase systems
  - Wiring of three-phase systems
  - Symmetrical three-phase systems
  - Examples: Symmetrical voltages and currents
- AC machines & space vector theory
  - AC machines: Examples
  - Space vector theory
  - Clarke transformation
  - Park transformation
- Power definitions
  - Classical power theory (sinusoidal signals)
  - Instantaneous power theory

Outline

Signals in one-phase systems

Definition 1 (Phase signal ($x \in \{u, i\}$))

$$x\colon \mathbb{R}_{\geqslant 0} \to \mathbb{R}, \quad t \mapsto x(t) := \hat{x}(t)\,\cos(\phi_x(t))$$

with *amplitude* $\hat{x}(\cdot) \in \mathcal{L}^{\infty}(\mathbb{R}_{\geqslant 0};\mathbb{R})$ and *phase angle* $\phi_x(\cdot) \in \mathcal{C}^{\mathrm{abs}}(\mathbb{R}_{\geqslant 0};\mathbb{R})$ (differentiable a.e.).

Definition 2 (Moving average, average rectified value, root mean square [sinusoidal signals with $\hat{x}, T > 0$ and $\phi_x = \frac{2\pi}{T}t$])

- *Moving average*: $\forall\, t \geqslant T > 0\colon\ \overline{X}(t) := \frac{1}{T}\int_{t-T}^{t} x(\tau)\,\mathrm{d}\tau\ \ [= 0\,]$
- *Average rectified value*: $\forall t \geqslant T > 0\colon\ \overline{X}_{\mathrm{dc}}(t) := \frac{1}{T}\int_{t-T}^{t} |x(\tau)|\,\mathrm{d}\tau\ \ [= \frac{2\hat{x}}{\pi}\,]$
- *Root mean square*: $\forall t \geqslant T > 0\colon\ X_{\mathrm{rms}}(t) := \sqrt{\frac{1}{T}\int_{t-T}^{t} x(\tau)^2\,\mathrm{d}\tau}\ \ [= \frac{\hat{x}}{\sqrt{2}}\,]$

Outline

Signals in three-phase systems

Definition 3 (Phase signals in vector notation ($x \in \{u, i, \psi, \ldots\}$))

$$\boldsymbol{x}^{abc} \colon \mathbb{R}_{\geqslant 0} \to \mathbb{R}^3, \quad t \mapsto \boldsymbol{x}^{abc}(t) := \begin{pmatrix} x^a(t) \\ x^b(t) \\ x^c(t) \end{pmatrix} := \begin{pmatrix} \hat{x}^a(t)\,\cos(\phi_x^a(t)) \\ \hat{x}^b(t)\,\cos(\phi_x^b(t)) \\ \hat{x}^c(t)\,\cos(\phi_x^c(t)) \end{pmatrix}$$

with *amplitudes* $\hat{x}^a(\cdot), \hat{x}^b(\cdot), \hat{x}^c(\cdot) \in \mathcal{L}^\infty(\mathbb{R}_{\geqslant 0}; \mathbb{R})$ and *phase angles* $\phi_x^a(\cdot), \phi_x^b(\cdot), \phi_x^c(\cdot) \in \mathcal{C}^{\mathrm{abs}}(\mathbb{R}_{\geqslant 0}; \mathbb{R})$ (differentiable a.e.).

Fact (Line-to-line signals)

$$\forall\, t \geqslant 0\colon \quad \begin{pmatrix} x^{ab}(t) \\ x^{bc}(t) \\ x^{ca}(t) \end{pmatrix} := \begin{pmatrix} x^a(t) - x^b(t) \\ x^b(t) - x^c(t) \\ x^c(t) - x^a(t) \end{pmatrix} = \underbrace{\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}}_{=:\, \boldsymbol{T}_V^\star, \quad \det(\boldsymbol{T}_V^\star) = 0} \boldsymbol{x}^{abc}(t)$$

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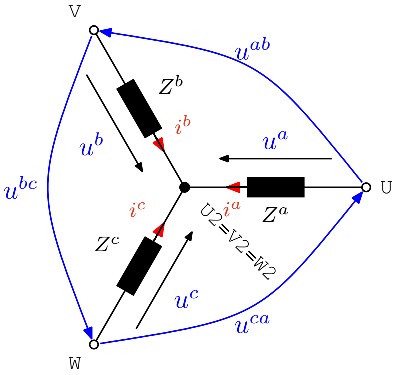
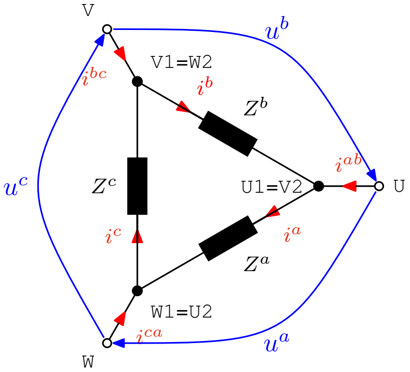
Interconnection of three-phase systems





Fact (star / Y connection)

- $i^a + i^b + i^c = 0$
- $u^{ab} + u^{bc} + u^{ca} = 0$
- $(u^a + u^b + u^c \neq 0)$

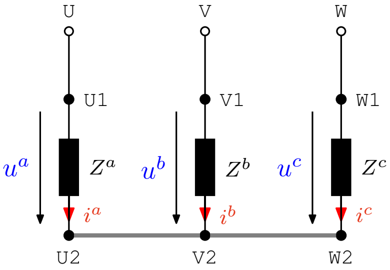
Fact (delta / △ connection)

- $i^{ab} + i^{bc} + i^{ca} = 0$
- $u^a + u^b + u^c = 0$
- $(i^a + i^b + i^c \neq 0)$

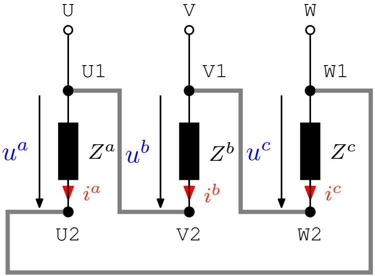
Outline

Wiring of three-phase systems (connector panel)

star connection (symbol $\curlyvee$)



delta connection (symbol $\triangle$)



Outline

Symmetrical three-phase systems

$$\boldsymbol{x}^{abc}\colon \mathbb{R}_{\geqslant 0} \to \mathbb{R}^3, \quad t \mapsto \boldsymbol{x}^{abc}(t) := \begin{pmatrix} x^a(t) \\ x^b(t) \\ x^c(t) \end{pmatrix} := \begin{pmatrix} \hat{x}^a(t)\ \cos(\phi_x^a(t)) \\ \hat{x}^b(t)\ \cos(\phi_x^b(t)) \\ \hat{x}^c(t)\ \cos(\phi_x^c(t)) \end{pmatrix}$$

Assumption 1 (Identical phase amplitudes)

$$\forall\, t \geqslant 0\colon \qquad \hat{x}(t) := \hat{x}^a(t) = \hat{x}^b(t) = \hat{x}^c(t)$$

Assumption 2 (Phase shift by $\frac{2}{3}\pi$, identical phase angle & offset)

$$\forall\, t \geqslant 0\colon \qquad \phi_x(t) = \phi_x^a(t) = \phi_x^b(t) + \tfrac{2}{3}\pi = \phi_x^c(t) + \tfrac{4}{3}\pi.$$

with phase angle $\phi_x(\cdot) \in \mathcal{C}^{\mathrm{abs}}(\mathbb{R}_{\geqslant 0}; \mathbb{R})$.

Fact (Zero sequence vanishes for symmetrical systems)

$$\forall\, t \geqslant 0\colon \qquad x^0(t) := x^a(t) + x^b(t) + x^c(t) \overset{\text{(A.1), (A.2)}}{=} 0$$

Outline

Examples: Symmetrical voltages and currents

Examples 1

Symmetrical phase voltages:

$$\forall\, t \geqslant 0: \quad \boldsymbol{u}^{abc}(t) := \begin{pmatrix} u^a(t) \\ u^b(t) \\ u^c(t) \end{pmatrix} = \hat{u}(t) \begin{pmatrix} \cos(\phi_u(t)) \\ \cos\left(\phi_u(t) - \frac{2}{3}\pi\right) \\ \cos\left(\phi_u(t) - \frac{4}{3}\pi\right) \end{pmatrix}$$

Symmetrical phase currents:

$$\forall\, t \geqslant 0: \quad \boldsymbol{i}^{abc}(t) := \begin{pmatrix} i^a(t) \\ i^b(t) \\ i^c(t) \end{pmatrix} = \hat{\imath}(t) \begin{pmatrix} \cos(\phi_i(t)) \\ \cos\left(\phi_i(t) - \frac{2}{3}\pi\right) \\ \cos\left(\phi_i(t) - \frac{4}{3}\pi\right) \end{pmatrix}$$

Definition 4 (Phase shift)

$$\forall\, t \geqslant 0: \qquad \varphi(t) := \phi_u(t) - \phi_i(t)$$

Outline

Outline

2 Preliminaries

- Alternating current (AC) systems
  - One-phase systems
  - Three-phase systems
  - Interconnection of three-phase systems
  - Wiring of three-phase systems
  - Symmetrical three-phase systems
  - Examples: Symmetrical voltages and currents
- AC machines & space vector theory
  - AC machines: Examples
  - Space vector theory
  - Clarke transformation
  - Park transformation
- Power definitions
  - Classical power theory (sinusoidal signals)
  - Instantaneous power theory

AC machines: Examples

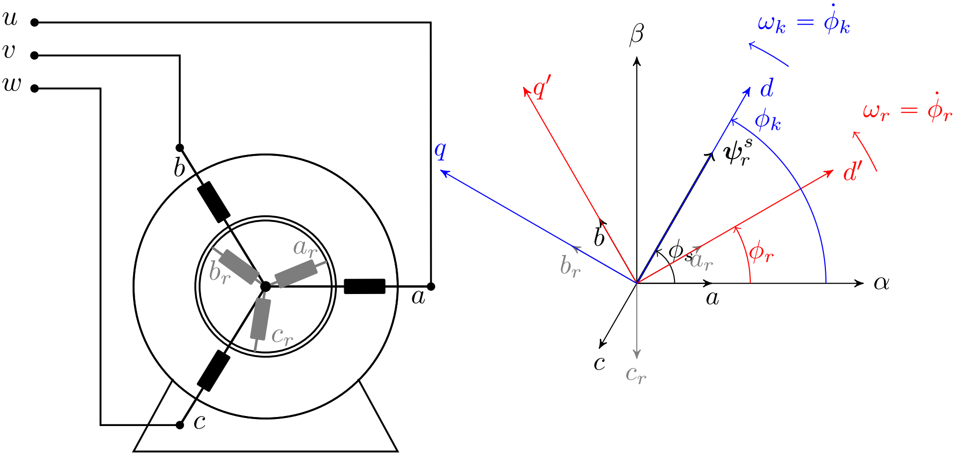
Induction machine (IM)	Synchronous machine (SM)
	
http://www.automation.siemens.com/bilddb/	http://www.automation.siemens.com/bilddb/

Induction machine (cutaway view)

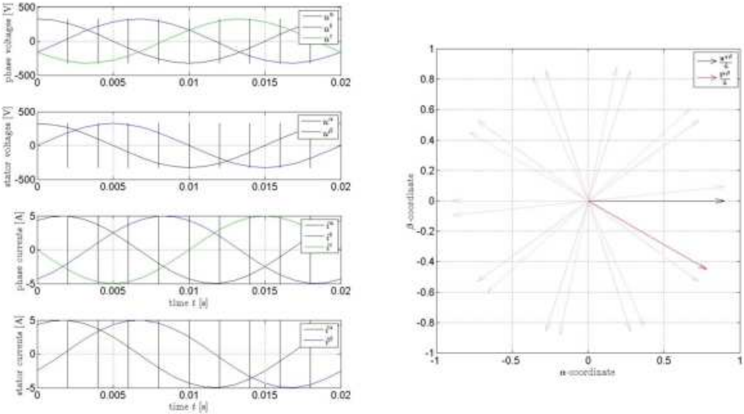
www.siemens.com

Outline

Space vector theory



Space vector theory (animation)



Outline

Clarke transformation $(a, b, c) \to (\alpha, \beta, 0)$

Definition 5 (Clarke transformation with $k \in \{2/3, \sqrt{2/3}\}$)

$$\boldsymbol{f}_C^\star : \mathbb{R}^3 \to \mathbb{R}^3, \quad \underbrace{\begin{pmatrix} x^a \\ x^b \\ x^c \end{pmatrix}}_{=:\boldsymbol{x}^{abc}} \mapsto \underbrace{\begin{pmatrix} x^\alpha \\ x^\beta \\ x^0 \end{pmatrix}}_{=:\boldsymbol{x}^{s,\star}} := \boldsymbol{f}_C(\boldsymbol{x}^{abc}) := \underbrace{k \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}}_{=:\boldsymbol{T}_C^\star \in \mathbb{R}^{3\times 3},\ \forall\, k \neq 0:\ \det(\boldsymbol{T}_C^\star) \neq 0} \begin{pmatrix} x^a \\ x^b \\ x^c \end{pmatrix}$$

$$(\boldsymbol{T}_C^\star)^{-1} = \frac{1}{k} \begin{bmatrix} \frac{2}{3} & 0 & \frac{\sqrt{2}}{3} \\ -\frac{1}{3} & \frac{1}{\sqrt{3}} & \frac{\sqrt{2}}{3} \\ -\frac{1}{3} & -\frac{1}{\sqrt{3}} & \frac{\sqrt{2}}{3} \end{bmatrix}, \quad \text{hence} \quad \boldsymbol{x}^{abc} = (\boldsymbol{f}_C^\star)^{-1}(\boldsymbol{x}^{s,\star}) = (\boldsymbol{T}_C^\star)^{-1} \boldsymbol{x}^{s,\star}.$$

Remark 1 (Choice of k)

$k = \frac{2}{3} \quad \Longrightarrow$ amplitude-correct transformation, i.e. $|x^a| = |x^\alpha|$.

$k = \sqrt{\frac{2}{3}} \quad \Longrightarrow$ power-correct transformation, i.e. $(\boldsymbol{u}^{abc})^\top \boldsymbol{i}^{abc} = (\boldsymbol{u}^s)^\top \boldsymbol{i}^s$.

Simplified Clarke transformation $(a, b, c) \to (\alpha, \beta)$

For **symmetrical systems**, i.e. $\boxed{x^a(t) + x^b(t) + x^c(t) = 0}$ for all $t \geqslant 0$:

$$\boldsymbol{f}_C : \mathbb{R}^3 \to \mathbb{R}^2, \quad \underbrace{\begin{pmatrix} x^a \\ x^b \\ x^c \end{pmatrix}}_{=:\boldsymbol{x}^{abc}} \mapsto \underbrace{\begin{pmatrix} x^\alpha \\ x^\beta \end{pmatrix}}_{=:\boldsymbol{x}^s} := \boldsymbol{f}_C(\boldsymbol{x}^{abc}) = \underbrace{k \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}}_{=:\boldsymbol{T}_C \in \mathbb{R}^{2\times 3}} \begin{pmatrix} x^a \\ x^b \\ x^c \end{pmatrix}$$

where

$$(\boldsymbol{T}_C)^{-1} := \frac{1}{k} \begin{bmatrix} \frac{2}{3} & 0 \\ -\frac{1}{3} & \frac{1}{\sqrt{3}} \\ -\frac{1}{3} & -\frac{1}{\sqrt{3}} \end{bmatrix}, \quad \text{hence} \quad \boldsymbol{x}^{abc} = (\boldsymbol{T}_C)^{-1} \boldsymbol{x}^s.$$

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Park transformation $(\alpha, \beta) \to (d, q)$

Definition 6 (Park transformation (simplified))

$\boldsymbol{f}_P : \mathbb{R}^2 \times \mathbb{R} \to \mathbb{R}^2,$

$$\Big(\underbrace{\begin{pmatrix} x^\alpha \\ x^\beta \end{pmatrix}}_{=:\boldsymbol{x}^s}, \phi\Big) \mapsto \underbrace{\begin{pmatrix} x^d \\ x^q \end{pmatrix}}_{=:\boldsymbol{x}^k} := \boldsymbol{f}_P(\boldsymbol{x}^s, \phi) = \underbrace{\begin{bmatrix} \cos(\phi) & -\sin(\phi) \\ \sin(\phi) & \cos(\phi) \end{bmatrix}}_{=:\boldsymbol{T}_P(\phi)\in\mathbb{R}^{2\times 2}, \forall\, \phi\in\mathbb{R}:\ \det(\boldsymbol{T}_P)\neq 0} \begin{pmatrix} x^\alpha \\ x^\beta \end{pmatrix}$$

Properties

- $\forall\, \phi_1, \phi_2 \in \mathbb{R}: \quad \boldsymbol{T}_P(\phi_1 + \phi_2) = \boldsymbol{T}_P(\phi_1) + \boldsymbol{T}_P(\phi_2)$
- $\forall\, \phi \in \mathbb{R}: \quad \boldsymbol{T}_P(\phi)^{-1} = \begin{bmatrix} \cos(\phi) & \sin(\phi) \\ -\sin(\phi) & \cos(\phi) \end{bmatrix} = \boldsymbol{T}_P(-\phi) = \boldsymbol{T}_P(\phi)^\top$
- $\boldsymbol{J} := \boldsymbol{T}_P(\frac{\pi}{2}) = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ and $\forall \phi \in \mathbb{R}: \ \boldsymbol{J}\boldsymbol{T}_P(\phi) = \boldsymbol{T}_P(\phi)\boldsymbol{J}$
- $\forall\, \phi(\cdot) \in \mathcal{C}^{\mathrm{abs}}(\mathbb{R}_{\geqslant 0}; \mathbb{R}): \quad \omega(\cdot) := \frac{\mathrm{d}}{\mathrm{d}t}\phi(\cdot) \ \wedge \ \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{T}_P(\phi(t)) = \omega(t)\boldsymbol{J}\boldsymbol{T}_P(\phi(t))$

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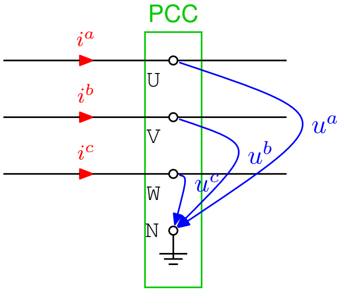
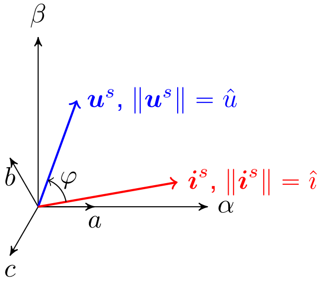
Classical power theory (sinusoidal signals)





Definition 7 (Active power [for $T, \hat{u}, \hat{\imath}, \varphi > 0$])

$$\forall\, t \geqslant T := \frac{2\pi}{\omega}: \qquad P_{3\sim}(t) := \frac{1}{T}\int_{t-T}^{t} \boldsymbol{u}^{abc}(\tau)^\top \boldsymbol{i}^{abc}(\tau)\,\mathrm{d}\tau \ \left[= \frac{3}{2}\hat{u}\hat{\imath}\cos(\varphi)\right]$$

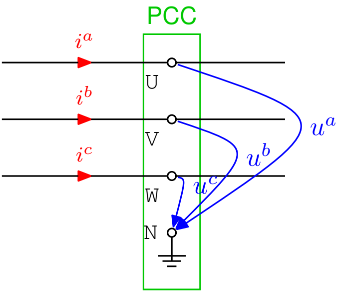
Definition 8 (Reactive power [for $T, \hat{u}, \hat{\imath}, \varphi > 0$])

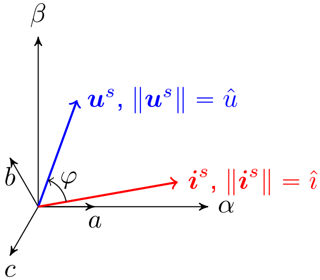
$$\forall\, t \geqslant T := \frac{2\pi}{\omega}: \qquad Q_{3\sim}(t) := \frac{1}{T}\int_{t-T}^{t} \boldsymbol{u}^{abc}(\tau)^\top \boldsymbol{i}^{abc}(\tau - \tfrac{T}{4})\,\mathrm{d}\tau \ \left[= \frac{3}{2}\hat{u}\hat{\imath}\sin(\varphi)\right]$$

Outline

2 Preliminaries

Instantaneous power theory





Definition 9 (Instantaneous active power)

$$\forall\, t \geqslant 0: \qquad p_{3\sim}(t) := \tfrac{3}{2}\boldsymbol{u}^s(t)^\top \boldsymbol{i}^s(t)\; \left[= \boldsymbol{u}^{abc}(t)^\top \boldsymbol{i}^{abc}(t) = \tfrac{3}{2}\hat{u}(t)\hat{\imath}(t)\cos(\varphi(t))\,\right]$$

Definition 10 (Instantaneous reactive power)

$$\forall\, t \geqslant 0: \qquad q_{3\sim}(t) := \tfrac{3}{2}\boldsymbol{u}^s(t)^\top \boldsymbol{J}\boldsymbol{i}^s(t)\; \left[= \tfrac{3}{2}\hat{u}(t)\hat{\imath}(t)\sin(\varphi(t))\,\right]$$

Outline

Outline

3 Modeling (part 1): Turbine, aerodynamics & power coefficient

- Example: Wind turbine systems with synchronous generator
- Power flow (simplified)
- Aerodynamics and power coefficient
  - Tip speed ratio and power coefficient
  - Power coefficient (without pitch system)
  - Power coefficient (with pitch system)
  - Aerodynamic torque (turbine torque)
- Dynamics of the mechanical system (simplified)
- Résumé: Modeling (part 1)

Example: Wind turbine systems with direct drive

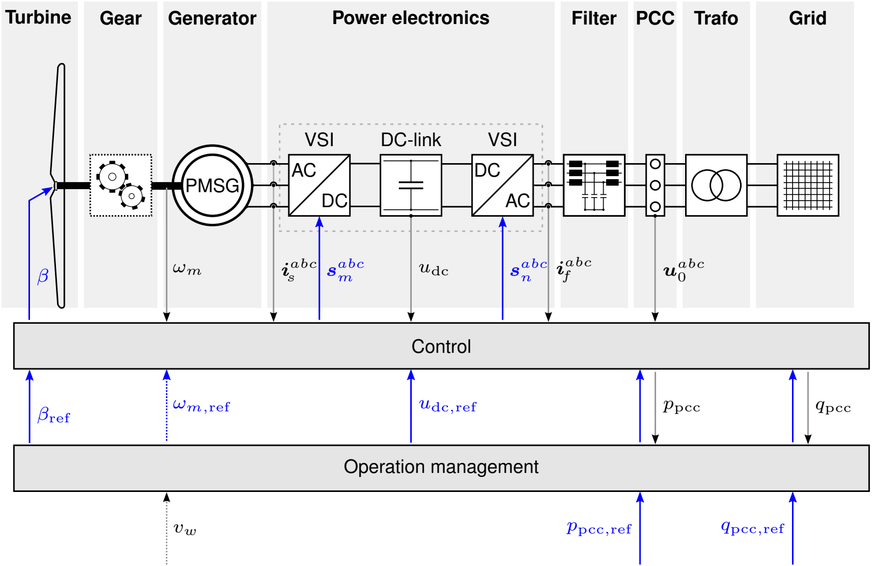
Wind turbine SWT-2.3-113

http://www.siemens.com/press/de/pressebilder/

permanent-magnet synchronous generator (PMSG)

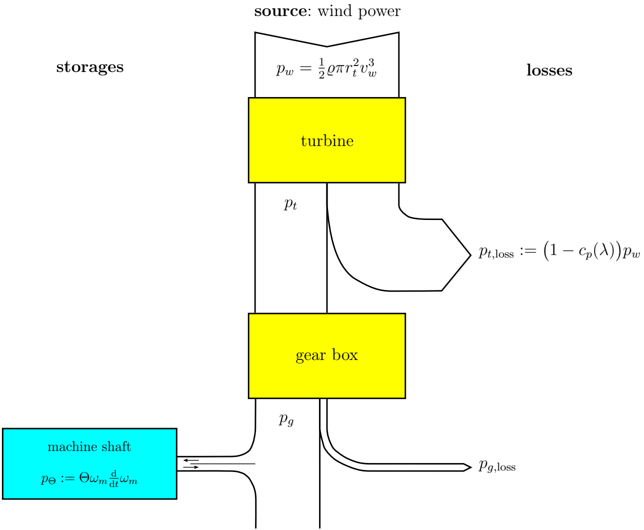
http://www.siemens.com/press/de/pressebilder/

Wind turbine systems with PMSG – core components

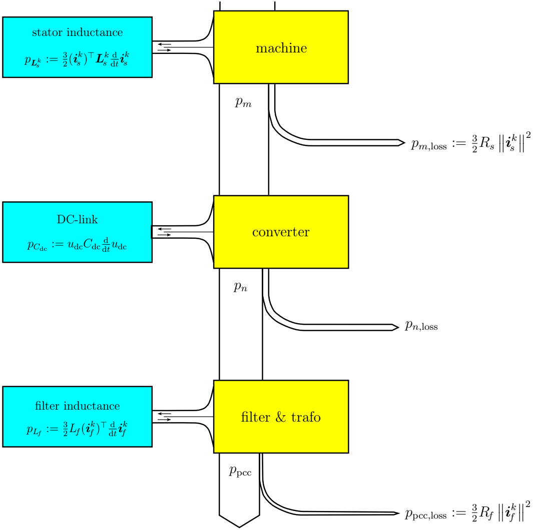


Outline

Power flow (part 1)



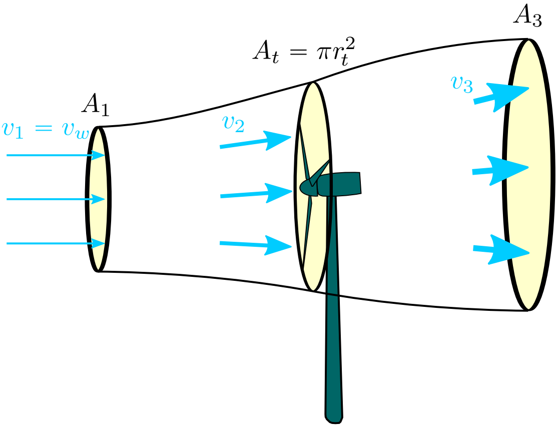
Power flow (part 2)



sink: point of common coupling (PCC)

Outline

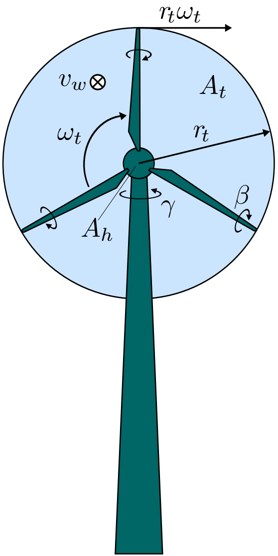
Wind power, turbine power and Betz limit



$$p_w(t) = \frac{1}{2}\varrho\pi r_t^2 v_w(t)^3 \;\Rightarrow\; p_t(t) = c_p(\cdot,\cdot)p_w(t) \leqslant \underbrace{c_{p,\mathrm{Betz}}}_{=16/27\approx 0{,}59} p_w(t) \quad (1)$$

Outline

Tip speed ratio and power coefficient



Tip speed ratio

$$\lambda := \lambda(\omega_m, v_w) := \frac{r_t \omega_m}{g_r v_w} \; [1], \quad \omega_m = g_r \omega_t. \qquad (2)$$

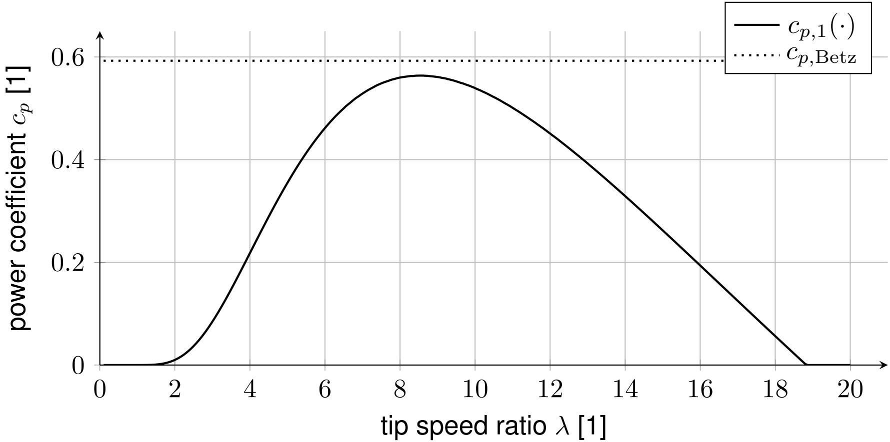
Power coefficient

$$c_p \colon \overline{\mathcal{D}} \to \mathbb{R}_{\geqslant 0}, \qquad (\beta, \lambda) \mapsto c_P(\beta, \lambda) :=$$
$$c_1 \big[c_2\, f(\beta,\lambda) - c_3 \beta - c_4 \beta^x - c_5 \big] e^{-c_6\, f(\beta,\lambda)}$$

where $\mathcal{D} := \{\, (\beta,\lambda) \in \mathbb{R}_{\geqslant 0} \times \mathbb{R}_{\geqslant 0} \mid c_P(\beta,\lambda) > 0 \,\}$ (3)

Outline

Power coefficient (without pitch system)



Turbine power (power capture)

$$p_t = c_{p,1}(\lambda) p_w(t) = c_{p,1}(\lambda)\,\frac{1}{2}\varrho\pi r_t^2 v_w(t)^3 \leqslant c_{p,\mathrm{Betz}}\,\frac{1}{2}\varrho\pi r_t^2 v_w(t)^3 \qquad (4)$$

Outline

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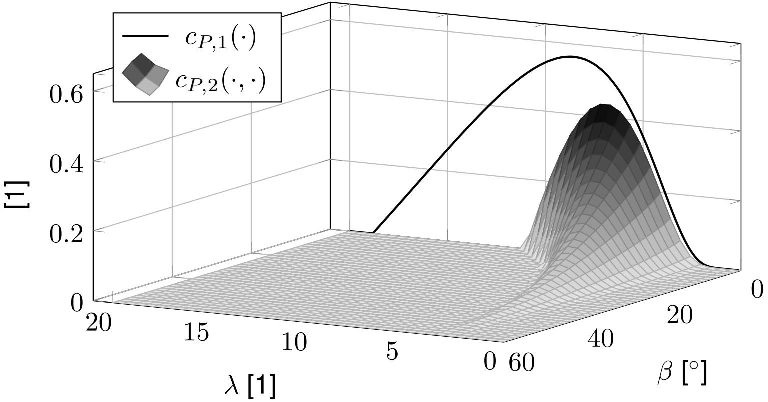
Power coefficient (with pitch system)



Turbine power (power capture)

$$p_t(t) = c_{p,2}(\lambda,\beta)p_w(t) = c_{p,2}(\lambda,\beta)\,\frac{1}{2}\varrho\pi r_t^2 v_w(t)^3 \leqslant c_{p,\mathrm{Betz}}\,\frac{1}{2}\varrho\pi r_t^2 v_w(t)^3 \tag{5}$$

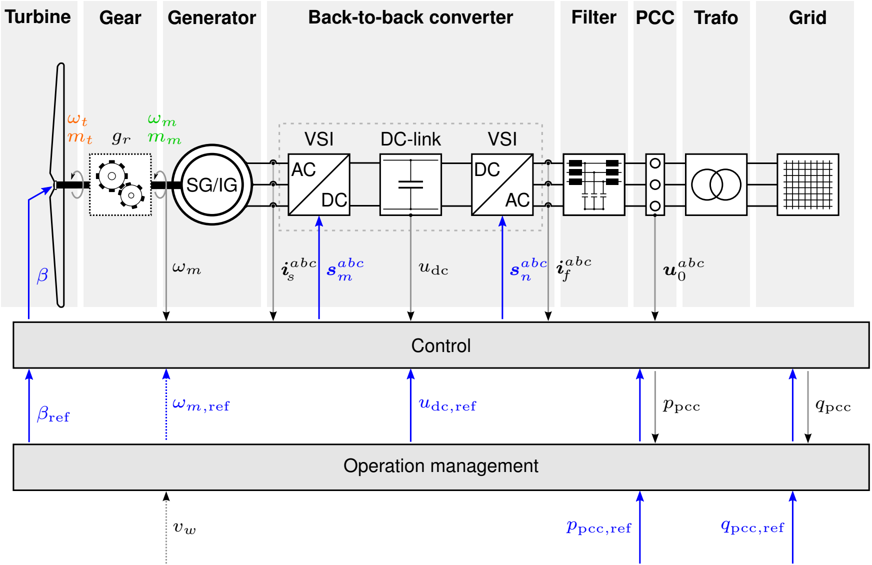
Outline

Aerodynamic torque (turbine torque)

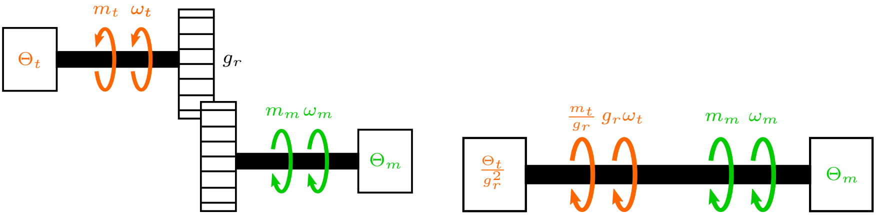
... discussion on whiteboard ...

Outline

Core components (recap.)



Effect of the gear ratio



Gear ratio

$$g_r := \frac{\omega_m}{\omega_t} \geqslant 1 \qquad \text{(for wind turbine systems)}$$

Energy and power balance

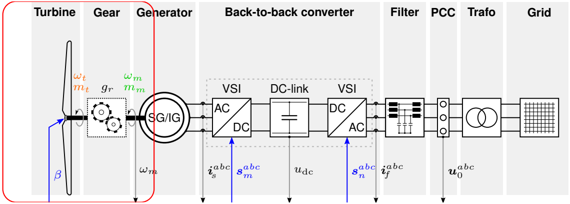
$$\forall\, t \geqslant 0: \quad \frac{1}{2}\left(\Theta_t \omega_t(t)^2 + \Theta_m \omega_m(t)^2\right)^2 = \text{ const. } \wedge \; m_t(t)\omega_t(t) = m_m(t)\omega_m(t)$$

Dynamics of the mechanical system (stiff coupling)

... discussion on whiteboard ...

Outline

Résumé: Modeling (part 1)



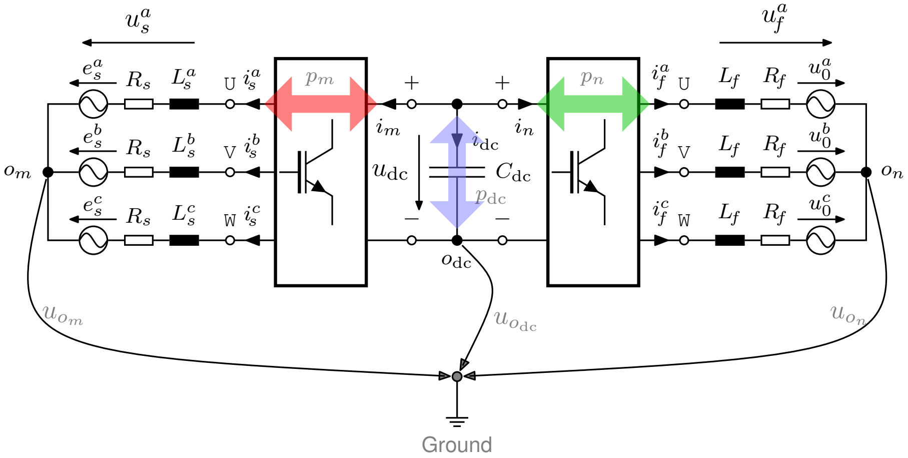
Facts (Wind power, turbine torque and mechanical system)

Wind power	$p_w(v_w) = \frac{1}{2}\varrho\pi r_t^2 v_w^3 \geqslant 0$
Tip speed ratio	$\lambda := \lambda(\omega_t,\, v_w) := \frac{r_t\omega_t}{v_w}, \qquad \omega_m = g_r\omega_t$
Power coefficient	$c_p(\beta,\lambda) \approx c_1\big[c_2\, f(\beta,\lambda) - c_3\beta - c_4\beta^x - c_5\big]e^{-c_6\, f(\beta,\lambda)}$
Turbine power	$p_t(\beta, v_w, \omega_t) = c_p(\beta, v_w, \omega_t)p_w(v_w)$
Turbine torque	$m_t(\beta, v_w, \omega_t) = \frac{p_t(\beta, v_w, \omega_t)}{\omega_t} \geqslant 0, \quad \forall\, \omega_t \geqslant 0$
Mech. dynamics	$\frac{\mathrm{d}}{\mathrm{d}t}\omega_m = \frac{1}{\Theta}\left(\frac{m_t(\beta, v_w, \omega_t)}{g_r} + m_m(?)\right), \quad \Theta := \Theta_m + \frac{\Theta_t}{g_r^2} > 0$

Outline

Outline

Electrical network of wind turbine system (overview)



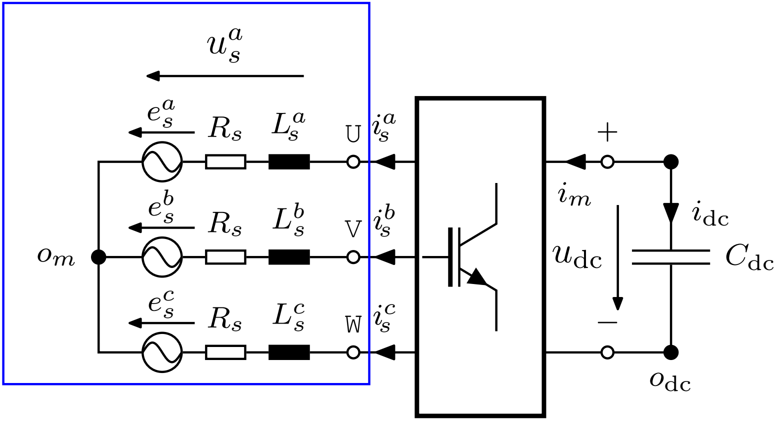
$\Longrightarrow$ Dynamics on machine and grid side (in (α, β)-CoSy) and of DC-link?

Outline

4 Modeling (part 2): Electrical components

- Electrical network of wind turbine system (overview)
- Generator dynamics (permanent-magnet synchronous generator)
- Grid-side dynamics (filter, grid voltage)
- Voltage source inverter (VSI)
  - Electrical network and output voltages
  - “Output space”: Voltage hexagon
  - Pulse width modulation (PWM)
- DC-link dynamics
- Résumé: Modeling (part 2)

Electrical network on machine side



$\Longrightarrow$ Generator dynamics in stationary reference frame (i.e. (α, β)-CoSy) ?

Generator dynamics in (α, β)-CoSy

... discussion on whiteboard ...

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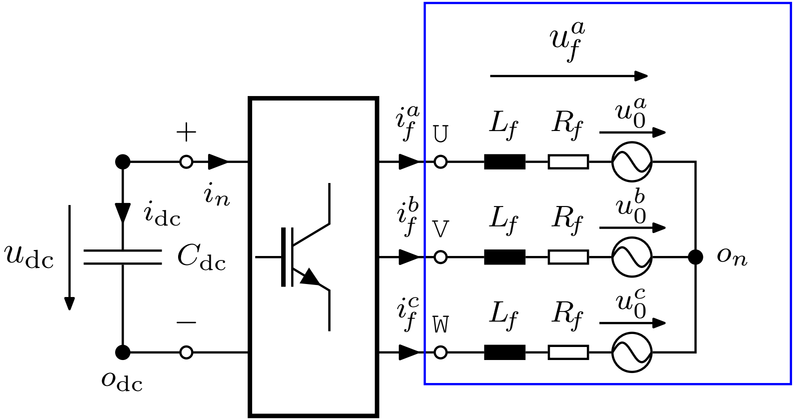
Electrical network on grid side



$\Longrightarrow$ Grid-side dynamics in stationary reference frame (i.e. (α, β)-CoSy) ?

Grid side dynamics in $(\alpha,\, \beta)$-CoSy

... discussion on whiteboard ...

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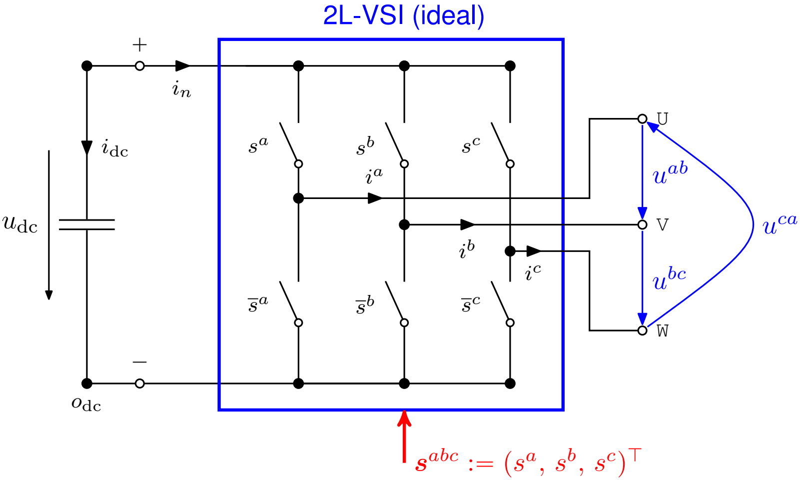
Electrical network



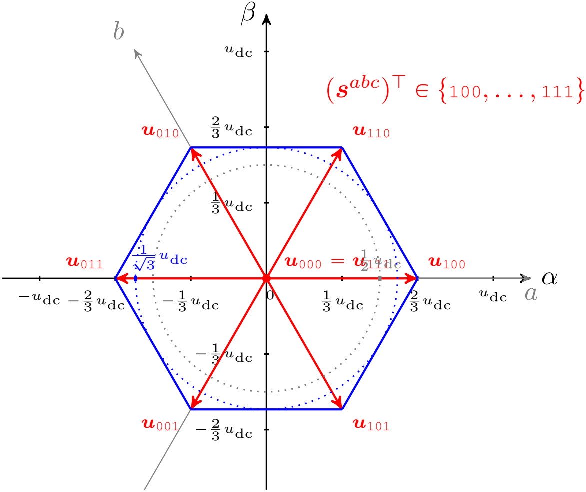
$\Longrightarrow$ Output voltages $\boldsymbol{u}^{abc}_{\mathrm{ltl}} = (u^{ab}, u^{bc}, u^{ca})^\top = f(\boldsymbol{s}^{abc}, u_{\mathrm{dc}})$?

Output voltages $\boldsymbol{u}_{\mathrm{ltl}}^{abc} = (u^{ab}, u^{bc}, u^{ca})^\top = f(\boldsymbol{s}^{abc}, u_{\mathrm{dc}})$

... discussion on whiteboard ...

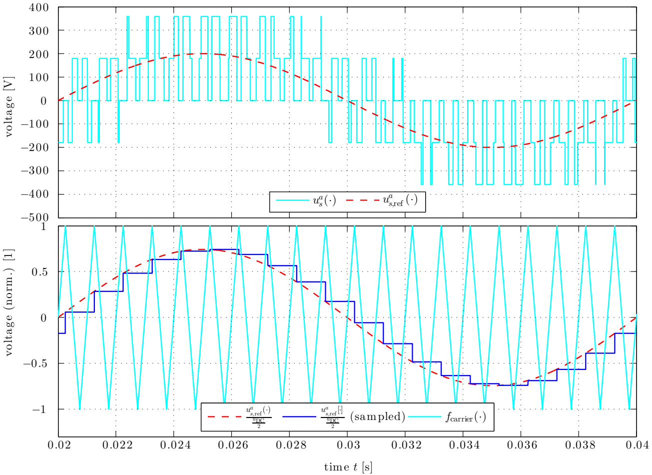
Outline

"Output space": Voltage hexagon



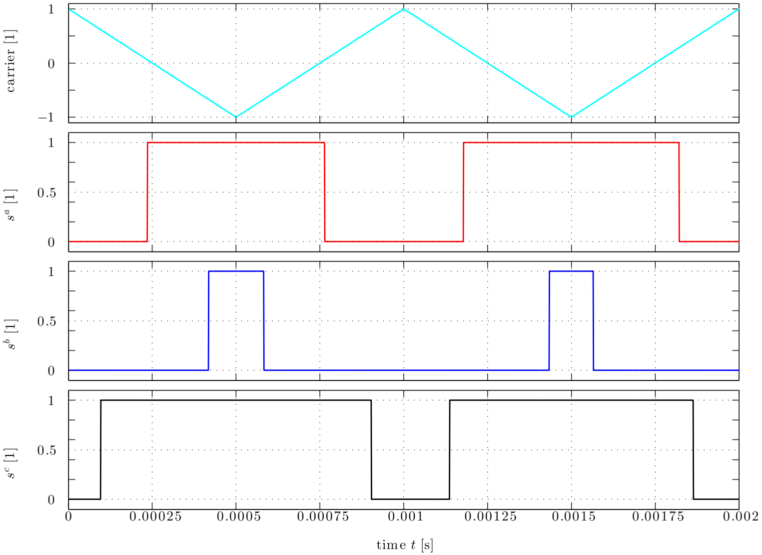
Outline

Pulse width modulation (PWM): Symmetrical PWM



$\Longrightarrow$ dead time $T_{\mathrm{dead}} = f(T_{\mathrm{pwm}})$?

Pulse width modulation (PWM): Symmetrical PWM



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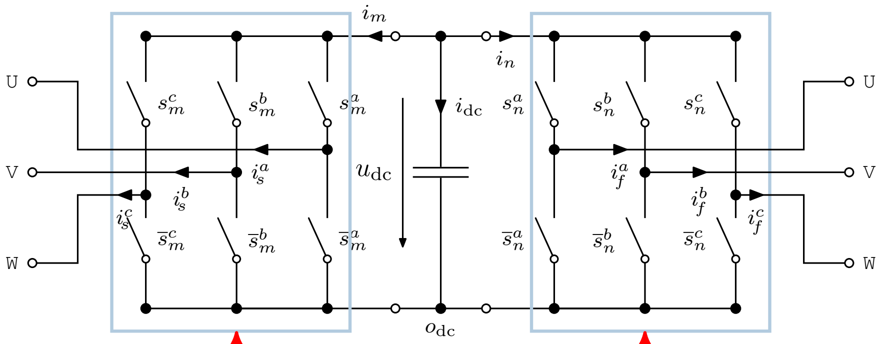
Electrical network of DC-link



$\boldsymbol{s}_m^{abc} = (s_m^a,\, s_m^b,\, s_m^c)^\top$ $\qquad$ $\boldsymbol{s}_n^{abc} = (s_n^a,\, s_n^b,\, s_n^c)^\top$

$\Longrightarrow$ DC-link dynamics $\frac{\mathrm{d}}{\mathrm{d}t}u_{\mathrm{dc}} = f(\boldsymbol{s}_m^{abc}, \boldsymbol{i}_s^{abc}, \boldsymbol{s}_n^{abc}, \boldsymbol{i}_f^{abc})$?

DC-link dynamics $\frac{\mathrm{d}}{\mathrm{d}t}u_{\mathrm{dc}} = f(\boldsymbol{s}_m^{abc}, \boldsymbol{i}_s^{abc}, \boldsymbol{s}_n^{abc}, \boldsymbol{i}_f^{abc})$

... discussion on whiteboard ...

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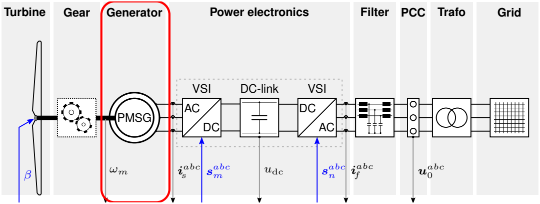
- Résumé: Modeling (part 2)

Résumé: Modeling (part 2) – Generator



Facts (Generator dynamics (in (α, β)-CoSy))

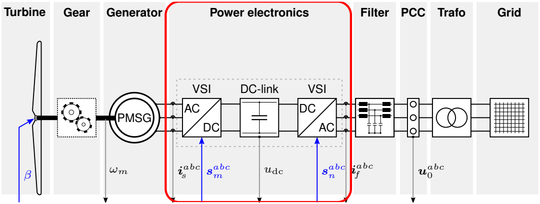
stator: $$\boldsymbol{u}_s^s = R_s \boldsymbol{i}_s^s + \frac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{\psi}_s^s$$

flux: $$\boldsymbol{\psi}_s^k = \underbrace{\begin{bmatrix} L_s^d & 0 \\ 0 & L_s^q \end{bmatrix}}_{=:\boldsymbol{L}_s^k \in \mathbb{R}^{2\times 2}} \boldsymbol{i}_s^k + \underbrace{\begin{pmatrix} \psi_{\mathrm{pm}} \\ 0 \end{pmatrix}}_{=:\boldsymbol{\psi}_{\mathrm{pm}}^k}$$

torque: $$m_m(\boldsymbol{i}_s^s, \boldsymbol{\psi}_s^s) = \frac{3}{2} p \,(\boldsymbol{i}_s^s)^\top \boldsymbol{J} \boldsymbol{\psi}_s^s .$$

mechanics: $$\frac{\mathrm{d}}{\mathrm{d}t} \omega_m = \frac{1}{\Theta} \left(\frac{m_T(\beta, v_w, \omega_t)}{g_r} + m_m(\boldsymbol{i}_s^s, \boldsymbol{\psi}_s^s) \right)$$

Résumé: Modeling (part 2) – Back-to-back converter



Facts (Back-to-back converter/VSI & DC-link (in (a, b, c)-CoSy))

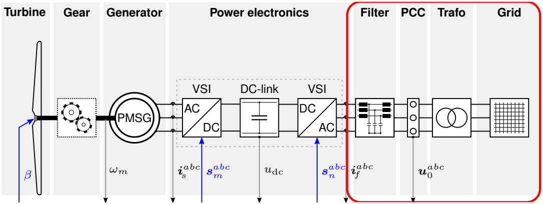
DC-link dynamics: $$\frac{\mathrm{d}}{\mathrm{d}t} u_{\mathrm{dc}}(t) = \frac{1}{C_{\mathrm{dc}}}\Big(- \boldsymbol{s}_m^{abc}(t)^\top \boldsymbol{i}_s^{abc}(t) - \boldsymbol{s}_n^{abc}(t)^\top \boldsymbol{i}_f^{abc}(t)\Big)$$

output voltage(s): $$\boldsymbol{u}_{s/f,\mathrm{ltl}}^{abc}(t) = u_{\mathrm{dc}}(t) \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \boldsymbol{s}_{m/n}^{abc}(t)$$

$$\overset{u^a+u^b+u^c=0}{\Longrightarrow} \qquad \boldsymbol{u}_{s/f}^{abc}(t) = \frac{u_{\mathrm{dc}}(t)}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \boldsymbol{s}_{m/n}^{abc}(t)$$

dead time: $$T_{\mathrm{dead}} \propto T_{\mathrm{pwm}}$$

Résumé: Modeling (part 2) – Filter, power & grid



Facts (Filter dynamics, power & grid voltage (in (α, β)-CoSy))

filter: $\boldsymbol{u}_f^s(t) = R_f \boldsymbol{i}_f^s(t) + L_f \frac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{i}_f^s(t) + \boldsymbol{u}_0^s(t)$

active power: $p_{\mathrm{pcc}}(t) = \frac{3}{2} \boldsymbol{u}_0^s(t)^\top \boldsymbol{i}_f^s(t)$

reactive power: $q_{\mathrm{pcc}}(t) = \frac{3}{2} \boldsymbol{u}_0^s(t)^\top \boldsymbol{J} \boldsymbol{i}_f^s(t)$

grid voltage: $\boldsymbol{u}_0^s(t) = \hat{u}_0 \begin{pmatrix} \cos(\phi_0(t)) \\ \sin(\phi_0(t)) \end{pmatrix}$

Outline

Outline

5 Control (part 1): Generator side

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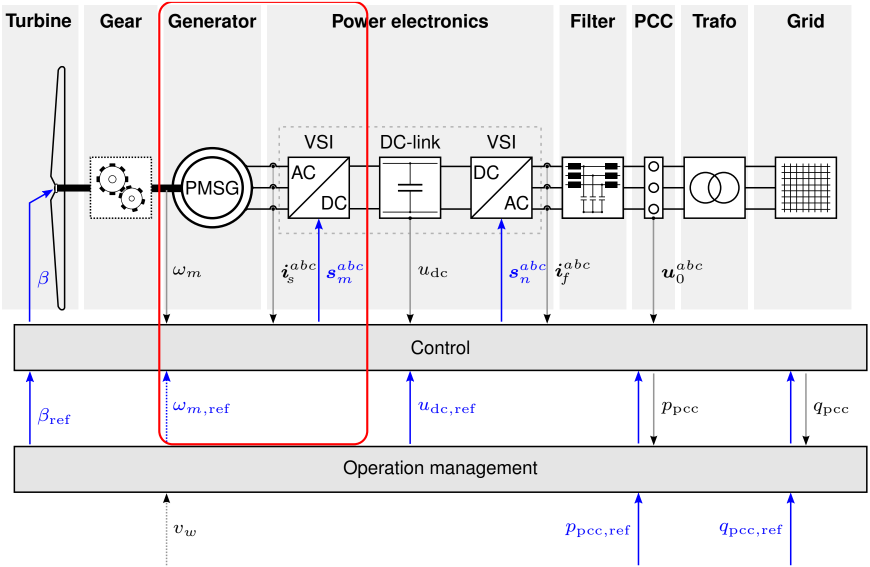
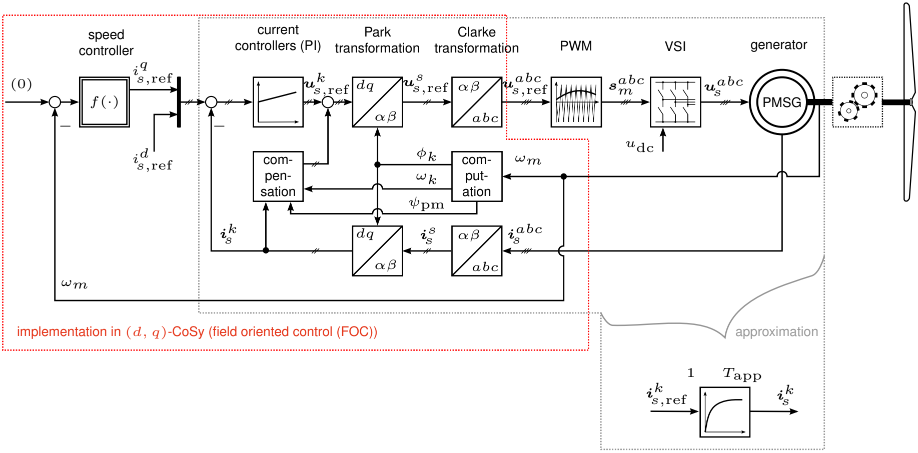
Generator side control: Relevant components



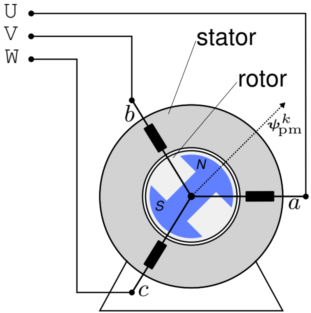
Overall control system on the generator side

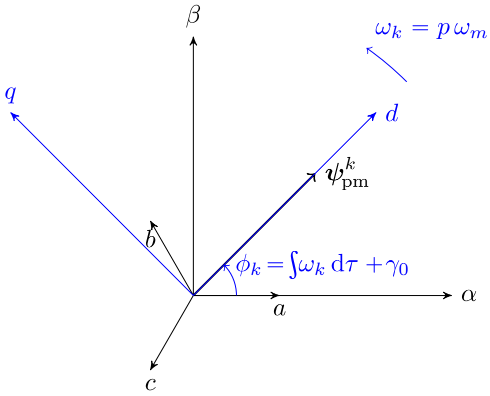


Outline

Outline

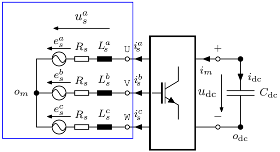
Field orientation: Basic idea (for $p = 1$)





Outline

Generator dynamics (recap.)



Facts (Generator dynamics (in (α, β)-CoSy))

$$\begin{aligned}
\text{stator:} \quad & \boldsymbol{u}_s^s &&= R_s \boldsymbol{i}_s^s + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_s^s \\
\text{flux:} \quad & \boldsymbol{\psi}_s^k &&= \underbrace{\begin{bmatrix} L_s^d & 0 \\ 0 & L_s^q \end{bmatrix}}_{=:\boldsymbol{L}_s^k \in \mathbb{R}^{2\times 2}} \boldsymbol{i}_s^k + \underbrace{\begin{pmatrix} \psi_{\mathrm{pm}} \\ 0 \end{pmatrix}}_{=:\boldsymbol{\psi}_{\mathrm{pm}}^k} \\
\text{torque:} \quad & m_m(\boldsymbol{i}_s^s, \boldsymbol{\psi}_s^s) &&= \frac{3}{2} p \, (\boldsymbol{i}_s^s)^\top \boldsymbol{J} \boldsymbol{\psi}_s^s . \\
\text{mechanics:} \quad & \frac{\mathrm{d}}{\mathrm{d}t}\omega_m &&= \frac{1}{\Theta}\left(\frac{m_T(\beta, v_w, \omega_t)}{g_r} + m_m(\boldsymbol{i}_s^s, \boldsymbol{\psi}_s^s) \right)
\end{aligned}$$

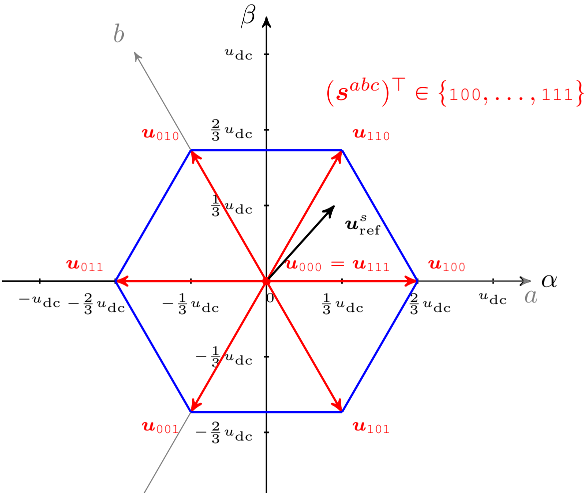
$\Longrightarrow$ Generator dynamics in (d, q)-CoSy,
i.e. $\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_s^k = \boldsymbol{f}(\boldsymbol{i}_s^k, \boldsymbol{\psi}_s^k)$ and $m_m = f(\boldsymbol{i}_s^k, \boldsymbol{\psi}_s^k)$?

Generator dynamics in field orientation/(d, q)-CoSy

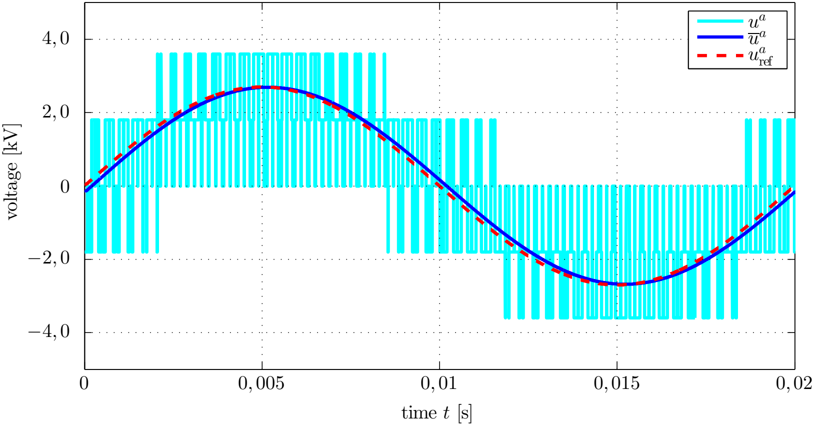
... discussion on whiteboard ...

Outline

“Output space”: Voltage hexagon (recap.)

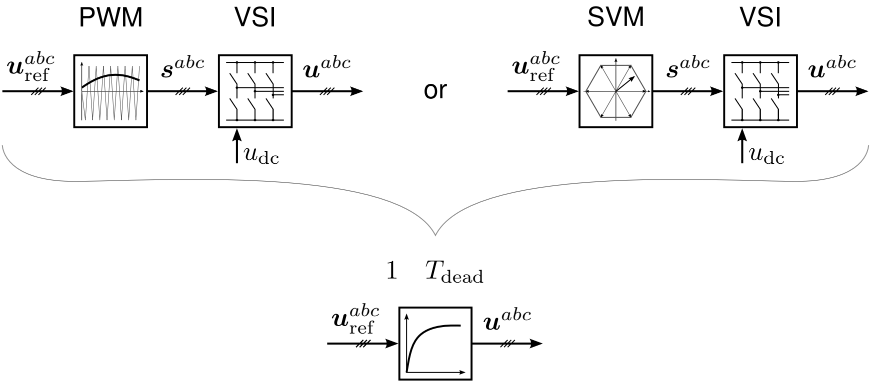


Delayed (average) voltage generation



$$\forall t \geqslant T_{\mathrm{dead}}: \qquad \boldsymbol{u}^{abc}(t) \approx \overline{\boldsymbol{u}}^{abc}(t) = \boldsymbol{u}^{abc}_{\mathrm{ref}}(t - T_{\mathrm{dead}})$$

VSI dynamics (approximation)



Fact (Delay depends on PWM (or space vector modulation))

$$T_{\mathrm{dead}} \propto T_{\mathrm{pwm}} \quad \Longrightarrow \quad F_{\mathrm{VSI}}(s) := \frac{\boldsymbol{u}^{abc}(s)}{\boldsymbol{u}_{\mathrm{ref}}^{abc}(s)} = e^{-sT_{\mathrm{dead}}} \approx \frac{1}{1 + sT_{\mathrm{dead}}}$$

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Current control (torque generation)

Model-based controller design (in field orientation)

$$\frac{\mathrm{d}}{\mathrm{d}t}\, i_s^d = \frac{1}{L_s^d}\left(u_s^d - R_s i_s^d + \omega_k L_s^q i_s^q\right)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\, i_s^q = \frac{1}{L_s^q}\left(u_s^q - R_s i_s^q - \omega_k L_s^d i_s^d - \omega_k \psi_{\mathrm{pm}}\right)$$

$$m_m = \frac{3}{2} p\left(\psi_{\mathrm{pm}} i_s^q + (L_s^d - L_s^q) i_s^d i_s^q\right)$$

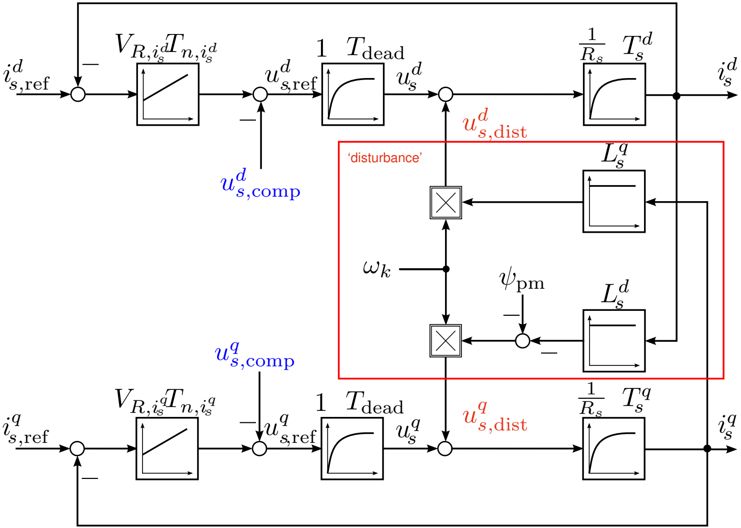
$$\frac{\mathrm{d}}{\mathrm{d}t}\omega_k = \frac{p}{\Theta_m + \frac{\Theta_t}{g_r^2}}\left(m_m(i_s^d, i_s^q) + \frac{m_t(\lambda, \beta)}{g_r}\right)$$

Next steps:

- Block diagram
- Disturbance compensation (feed forward)
- Controller design
- Approximation of torque dynamics

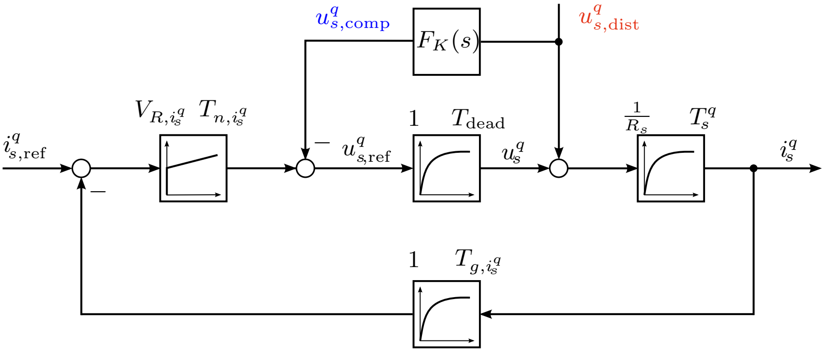
Outline

Current control loop (generator side)



Outline

Current controller design (q-component)



PI controller design (Magnitude Optimum) $\Longrightarrow$ fast set-point tracking

$$F_{R,i^q_s}(s) = V_{R,i^q_s}\frac{1+sT_{n,i^q_s}}{sT_{n,i^q_s}}, \quad V_{R,i^q_s} = \frac{T^q_s}{2\cdot 1/R_s \cdot T_{\mathrm{dead}}} \quad \wedge \quad T_{n,i^q_s} = T^q_s := \frac{L^q_s}{R_s}$$

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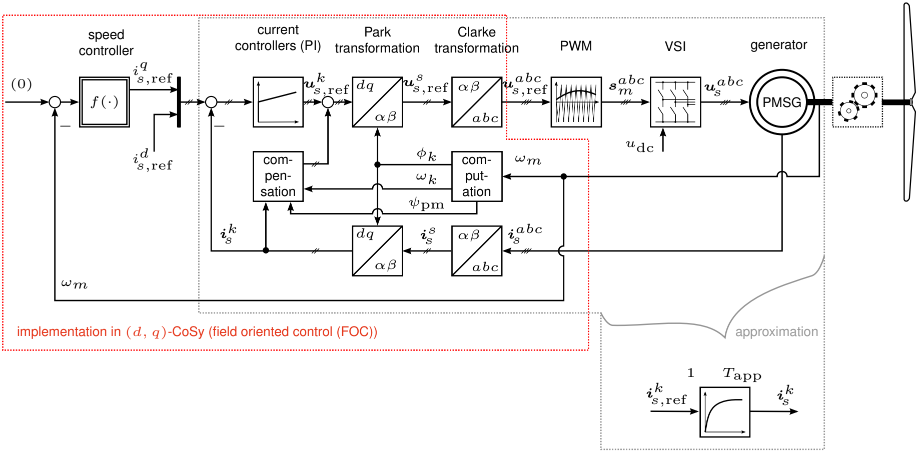
Approximation of current control loop

... discussion on whiteboard ...

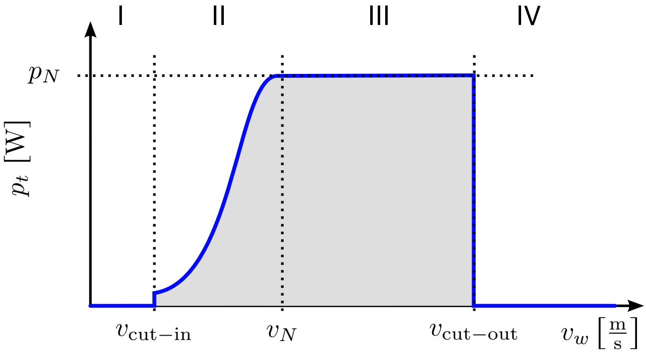
Outline

Overall control system on generator side (regime II)



Outline

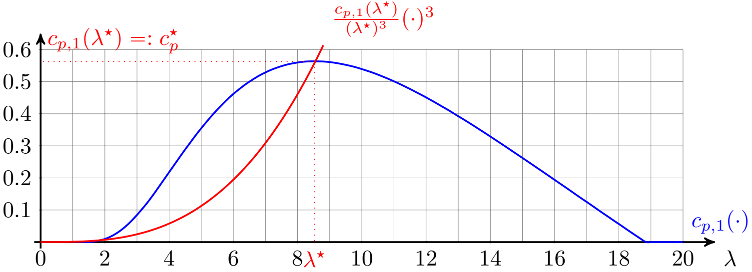
Operation regimes for different wind speeds



- Regime I: Stand still. No power output, i.e. $p_t = 0$.
- Regime II: Sub-nominal operation. Variable output power, i.e. $0 < p_t < p_n$ (Goal: Maximum power point tracking).
- Regime III: Nominal operation. Output of nominal power, i.e. $p_t = p_n$.
- Regime IV: Stand still (safety shut down), i.e. $p_t = 0$.

Outline

Control objective in regime II

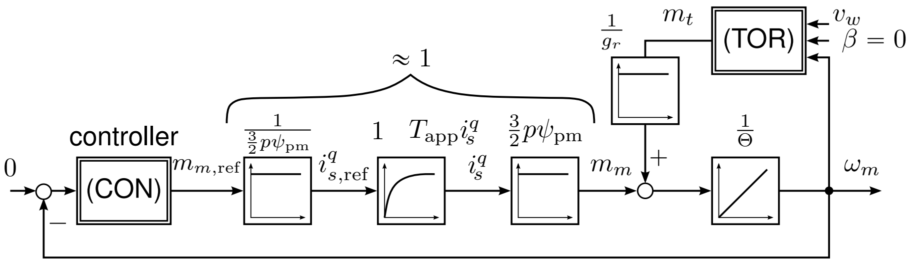


$$\frac{\mathrm{d}}{\mathrm{d}t}\omega_m = \frac{1}{\Theta}\left(\underbrace{c_0 \frac{c_{p,1}(\lambda)}{\lambda^3}\omega_m^2}_{=m_t/g_r} + m_{m,\mathrm{ref}}\right), \quad c_0 := \frac{\varrho r_t^5 \pi}{2 g_r^3} > 0 \;\wedge\; \Theta := \Theta_m + \frac{\Theta_t}{g_r^2}$$

$\Longrightarrow$ Control objective: $\lambda \to \lambda^\star$ (or $\omega_m \to \omega_m^\star$) for constant wind $v_w > 0$.

Outline

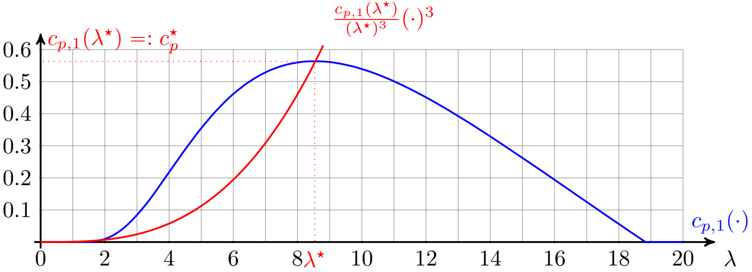
Speed control loop



turbine torque $\quad m_t(\lambda, \omega_m) = c_0 \frac{c_{p,1}(\lambda)}{\lambda^3}\omega_m^2 \quad$ where $\quad \lambda = \frac{r_t \omega_m}{g_r v_w} \quad$ (TOR)

generator torque: $\quad m_{m,\text{ref}} = -k_p^\star \omega_m^2 \approx m_m \quad$ where $\quad k_p^\star = c_0 \frac{c_{p,1}(\lambda^\star)}{(\lambda^\star)^3} \quad$ (CON)

Analysis of speed control loop



$$\frac{\mathrm{d}}{\mathrm{d}t}\omega_m = \frac{1}{\Theta}\left(\underbrace{c_0\frac{c_{p,1}(\lambda)}{\lambda^3}\omega_m^2}_{=m_t/g_r}\underbrace{-k_p^\star\omega_m^2}_{=m_{m,\mathrm{ref}}}\right) \quad \text{where} \quad k_P^\star = c_0\frac{c_{p,1}(\lambda^\star)}{(\lambda^\star)^3}$$

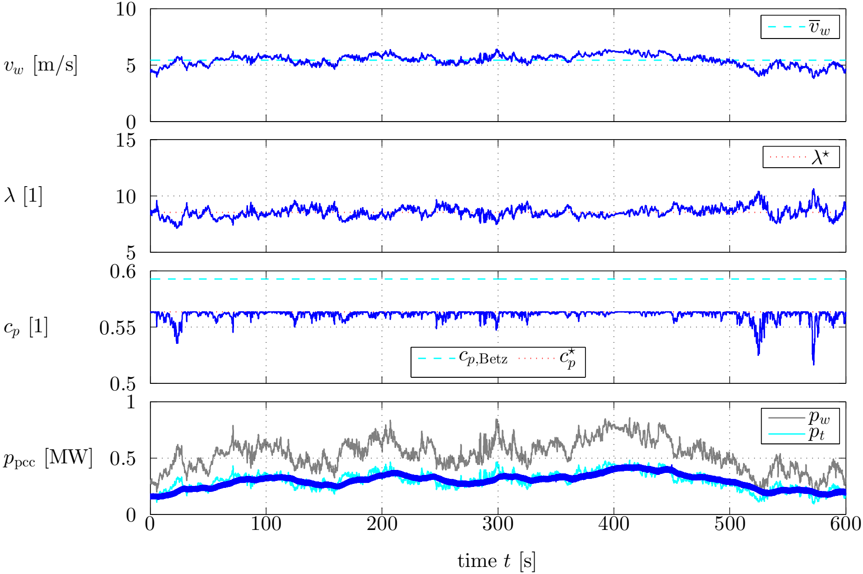
$\Longrightarrow \lambda \to \lambda^\star$ (or $\omega_m \to \omega_m^\star$) for all $\lambda \in (\lambda_{\min}, \lambda_{\max})$ and $v_w > 0$ (const.) ?

Analysis of speed control loop

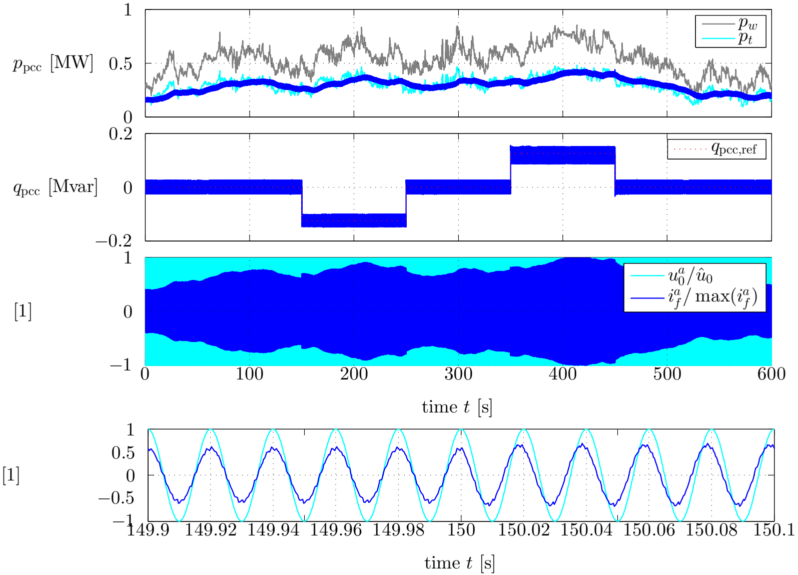
... discussion on whiteboard ...

Outline

Simulation results: Generator side control (1)

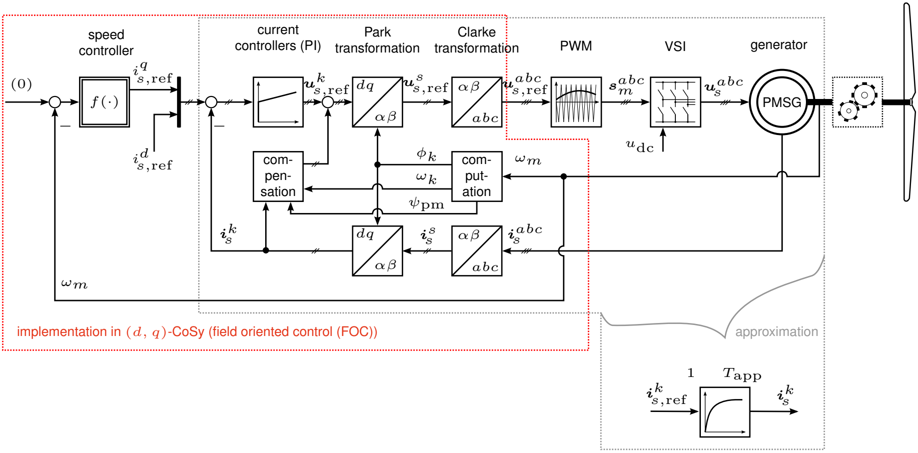


Simulation results: Generator side control (2)

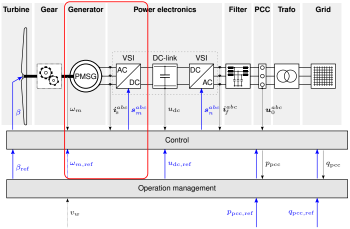


Outline

Résumé: Control (part 1) – Overall control system



Résumé: Control (part 1) – Generator side



Facts (Generator side control (for $L_s := L_s^q = L_s^d \implies T_s := \frac{L_s}{R_s}$))

current con.: $\frac{\boldsymbol{u}^k_{s,\mathrm{ref}}(s)}{\boldsymbol{i}^k_{s,\mathrm{ref}}(s) - \boldsymbol{i}^k_s(s)} = V_{R,\boldsymbol{i}^k_s} \frac{1+sT_{n,\boldsymbol{i}^k_s}}{sT_{n,\boldsymbol{i}^k_s}}, V_{R,\boldsymbol{i}^k_s} = \frac{T_s R_s}{2T_{\mathrm{dead}}} \wedge T_{n,\boldsymbol{i}^k_s} = T_s$

Dist. comp.: $\boldsymbol{u}^k_{s,\mathrm{comp}} = \mathcal{L}^{-1}\left\{\frac{1+s\,T_{\mathrm{dead}}}{1+sh}\right\}\begin{pmatrix} \omega_k L^q_s i^q_s \\ -\omega_k L^d_s i^d_s - \omega_k \psi_{\mathrm{pm}} \end{pmatrix}$

current dyn.: $\frac{\boldsymbol{i}^k_s(s)}{\boldsymbol{i}^k_{s,\mathrm{ref}}(s)} \approx \frac{1}{1+sT_{\mathrm{app}}}, \quad T_{\mathrm{app}} = 2T_{\mathrm{dead}} \ll 1$

torque gen.: $m_m \approx m_{m,\mathrm{ref}}, \quad$ (if $i^q_{s,\mathrm{ref}} = \frac{2m_{m,\mathrm{ref}}}{3p\psi_{\mathrm{pm}}} \wedge i^d_{s,\mathrm{ref}} = 0$)

speed con.: $m_{m,\mathrm{ref}} = -k^\star_p \omega^2_m \implies \lambda \to \lambda^\star$ (if $v_w > 0 \wedge \lambda > \lambda_{\min}$)

Outline

6 Control (part 2): Grid side

- Overview
- Voltage orientation (VOC)
  - Basic idea
  - Grid side dynamics in voltage orientation
  - Grid synchronization
- VSI dynamics (approximation, recap.)
- Current control (power control)
  - Current control loop
  - Current controller design
  - Approximation of current control loop
- DC-link voltage control (power balance)
  - DC-link dynamics
  - Linearization around equilibrium
  - “Structurally varying” system dynamics
  - Root loci of linearized system
  - Stability analysis (Hurwitz polynomial)
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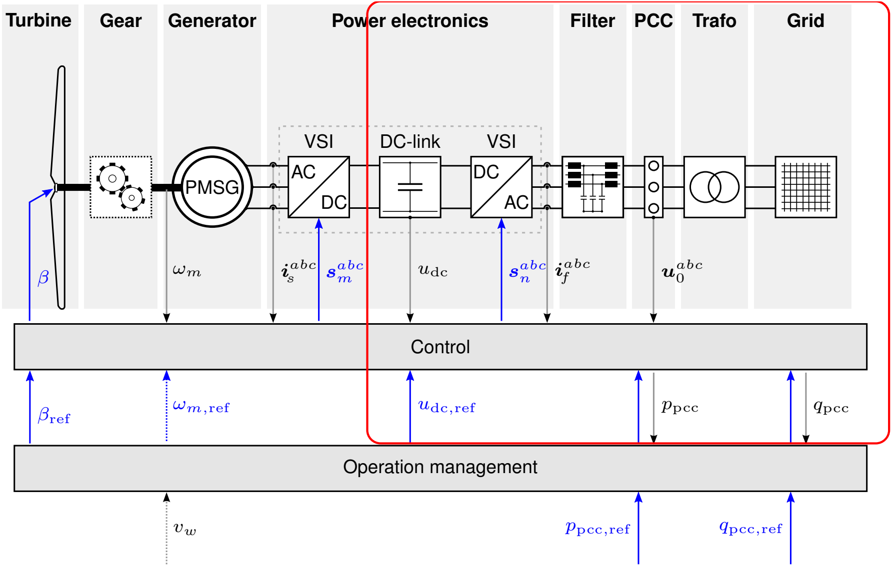
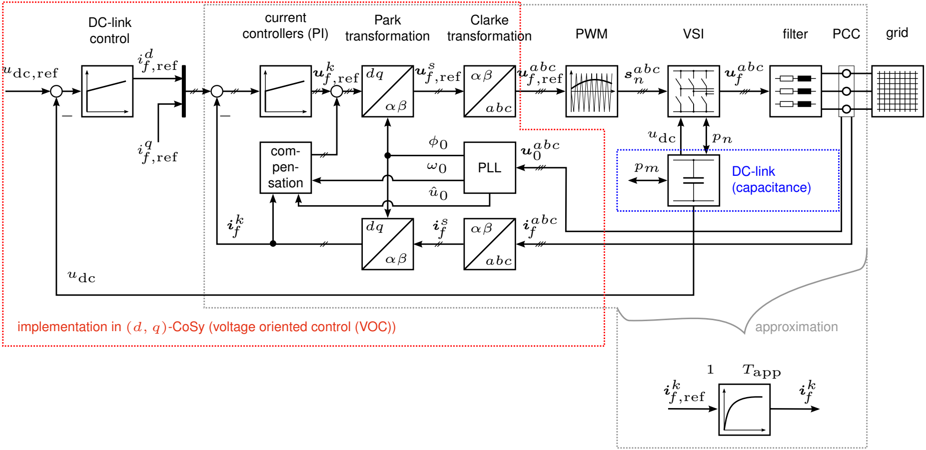
Grid side control: Relevant components



Overall control system on the grid side



Outline

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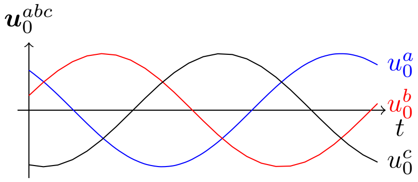
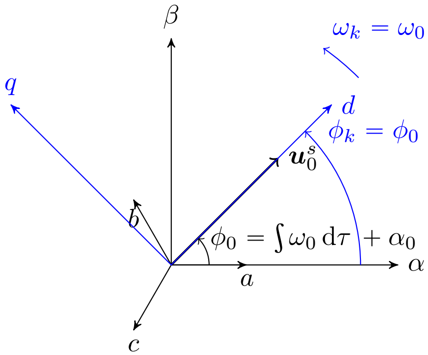
Voltage orientation: Basic idea (for symmetrical grid)

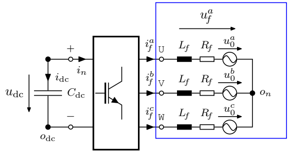




- $\boldsymbol{u}_0^k = \begin{pmatrix} \hat{u}_0 \\ 0 \end{pmatrix} = \boldsymbol{T}_P(\phi_0)^{-1}\boldsymbol{u}_0^s = \boldsymbol{T}_P(\phi_0)^{-1}\boldsymbol{T}_C\boldsymbol{u}_0^{abc}$
- determination of ϕ_0 (and of α_0, implicitely) via phase-locked loop

Outline

Grid side dynamics (recap.)



Facts (Filter dynamics, power & grid voltage (in (α, β)-CoSy))

filter:	$\boldsymbol{u}_f^s(t)$	$=$	$R_f \boldsymbol{i}_f^s(t) + L_f \frac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{i}_f^s(t) + \boldsymbol{u}_0^s(t)$
active power:	$p_{\mathrm{pcc}}(t)$	$=$	$\frac{3}{2} \boldsymbol{u}_0^s(t)^\top \boldsymbol{i}_f^s(t)$
reactive power:	$q_{\mathrm{pcc}}(t)$	$=$	$\frac{3}{2} \boldsymbol{u}_0^s(t)^\top \boldsymbol{J} \boldsymbol{i}_f^s(t)$
grid voltage:	$\boldsymbol{u}_0^s(t)$	$=$	$\hat{u}_0 \begin{pmatrix} \cos(\phi_0(t)) \\ \sin(\phi_0(t)) \end{pmatrix}$

$\Longrightarrow$ Grid side dynamics in (d, q)-CoSy,
i.e. $\frac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{i}_f^k = \boldsymbol{f}(\boldsymbol{i}_f^k, \boldsymbol{u}_0^k)$ and $p_{\mathrm{pcc}} \,\&\, q_{\mathrm{pcc}} = f(\boldsymbol{i}_f^k, \boldsymbol{u}_0^k)$?

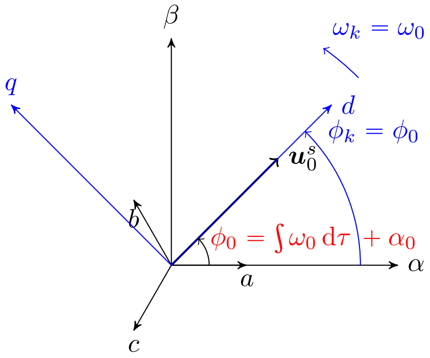
Grid side dynamics in voltage orientation/(d, q)-CoSy

... discussion on whiteboard ...

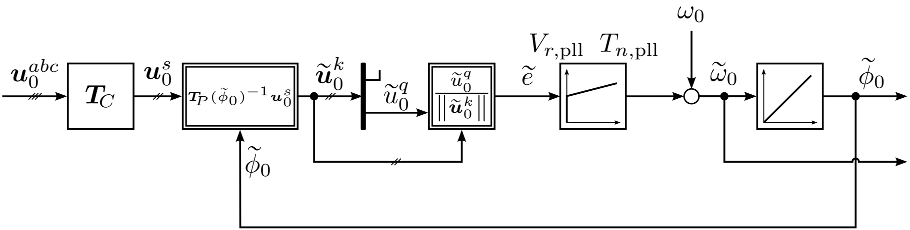
Outline

6 Control (part 2): Grid side

Grid synchronization (phase-locked loop)



Phase-locked loop (PLL): Block diagram



Goal:

$$\boxed{\lim_{t\to\infty} u_0^q(t) = 0 \quad \Longrightarrow \quad \lim_{t\to\infty} \left(\phi_0(t) - \tilde{\phi}_0(t)\right) = 0}$$

Use:

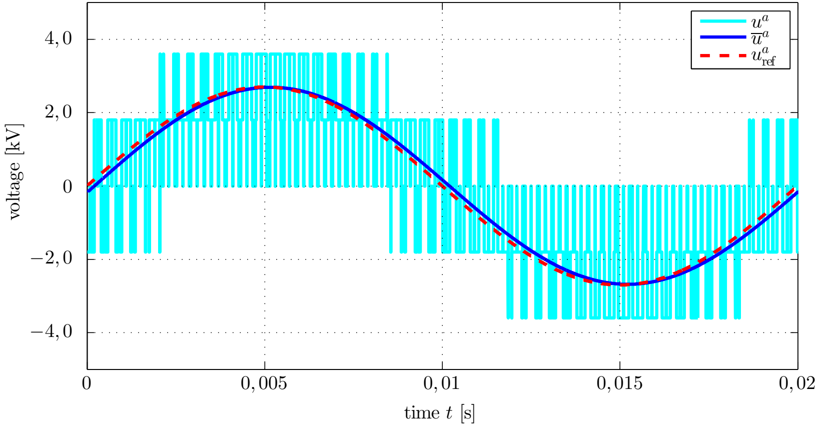
$\tilde{\phi}_0$ & $\tilde{\omega}_0$ for voltage orientation and disturbance compensation

Phase-locked loop (PLL): Analysis and design

... discussion on whiteboard ...

Outline

Delayed (average) voltage generation



Fact (Delay depends on PWM (or space vector modulation))

$$T_{\mathrm{dead}} \propto T_{\mathrm{pwm}} \quad \Longrightarrow \quad F_{\mathrm{VSI}}(s) := \frac{\boldsymbol{u}^{abc}(s)}{\boldsymbol{u}^{abc}_{\mathrm{ref}}(s)} = e^{-sT_{\mathrm{dead}}} \approx \frac{1}{1 + sT_{\mathrm{dead}}}$$

Outline

6 Control (part 2): Grid side

- Overview
- Voltage orientation (VOC)
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Current control (power control)

Model-based controller design (in voltage orientation)

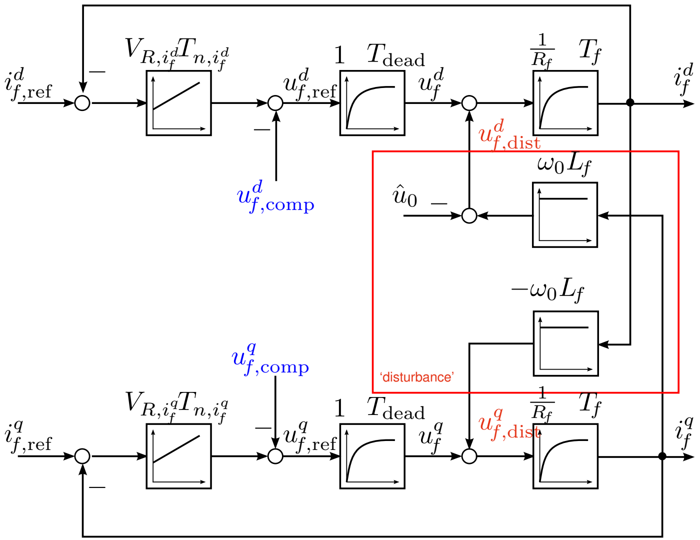
$$\frac{\mathrm{d}}{\mathrm{d}t}\, i_f^d = \frac{1}{L_f}\left(u_f^d - R_f i_f^d + \omega_0 L_f i_f^q - \hat{u}_0\right)$$
$$\frac{\mathrm{d}}{\mathrm{d}t}\, i_f^q = \frac{1}{L_f}\left(u_f^q - R_f i_f^q - \omega_0 L_f i_f^d\right)$$
$$p_{\mathrm{pcc}} = \frac{3}{2}\hat{u}_0 i_f^d \quad \& \quad q_{\mathrm{pcc}} = -\frac{3}{2}\hat{u}_0 i_f^q$$

Next steps:

- Block diagram
- Disturbance compensation (feed forward)
- Controller design

Outline

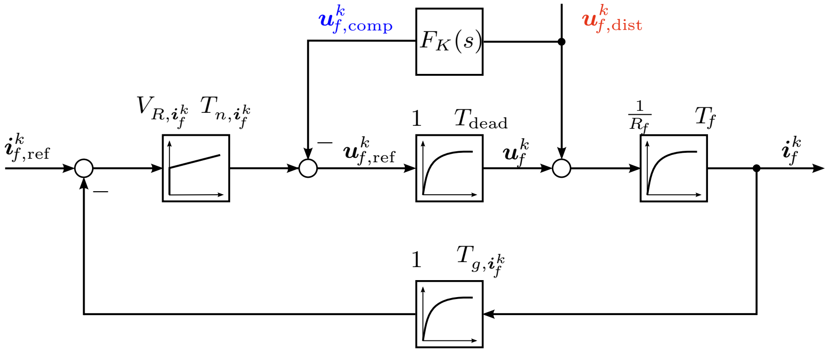
Current control loop (grid side)



Outline

6 Control (part 2): Grid side

Current controller design (recap.)



PI controller design (Magnitude Optimum) $\Longrightarrow$ fast set-point tracking

$$F_{R,\boldsymbol{i}_f^k}(s) = V_{R,\boldsymbol{i}_f^k}\frac{1+sT_{n,\boldsymbol{i}_f^k}}{sT_{n,\boldsymbol{i}_f^k}}, \quad V_{R,\boldsymbol{i}_f^k} = \frac{T_f}{2\cdot 1/R_f\cdot T_{\mathrm{dead}}} \quad \wedge \quad T_{n,\boldsymbol{i}_f^k} = T_f := \frac{L_f}{R_f}$$

Outline

6 Control (part 2): Grid side

Approximation of current control loop (recap.)

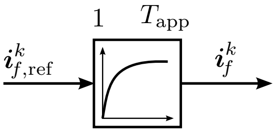
For (ideal ‘disturbance’ compensation)

$$\boldsymbol{u}_{f,\mathrm{comp}}^{k} = \mathcal{L}^{-1}\left\{\frac{1+s\,T_{\mathrm{dead}}}{1+sh}\right\}\begin{pmatrix}\omega_0 L_f i_f^q - \hat{u}_0 \\ -\omega_0 L_f i_f^d\end{pmatrix} \approx \boldsymbol{u}_{f,\mathrm{dist}}^{k}$$

we have

$$F_{CL,\boldsymbol{i}_f^k}(s) = \frac{\boldsymbol{i}_f^k(s)}{\boldsymbol{i}_{f,\mathrm{ref}}^k(s)} = \frac{1}{1+s2T_{\mathrm{dead}}+s^2 2T_{\mathrm{dead}}^2}$$

$$\approx \frac{1}{1+sT_{\mathrm{app}}} \qquad \text{where} \qquad T_{\mathrm{app}} := 2T_{\mathrm{dead}}$$



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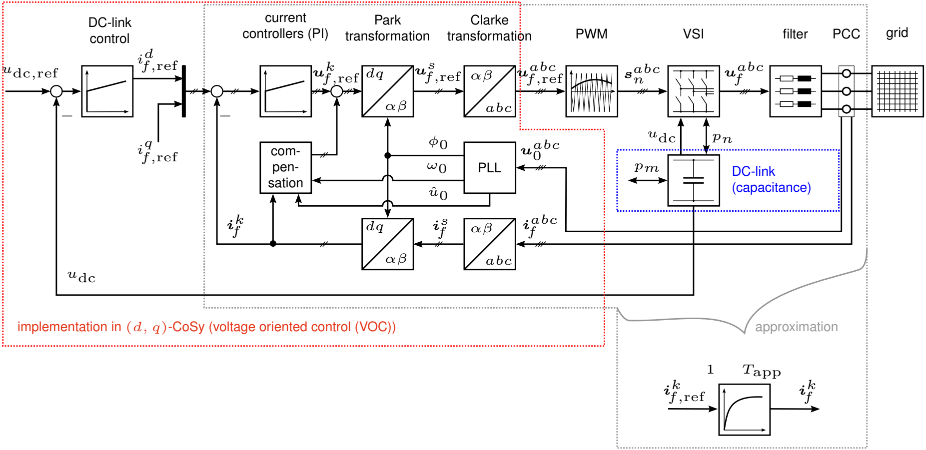
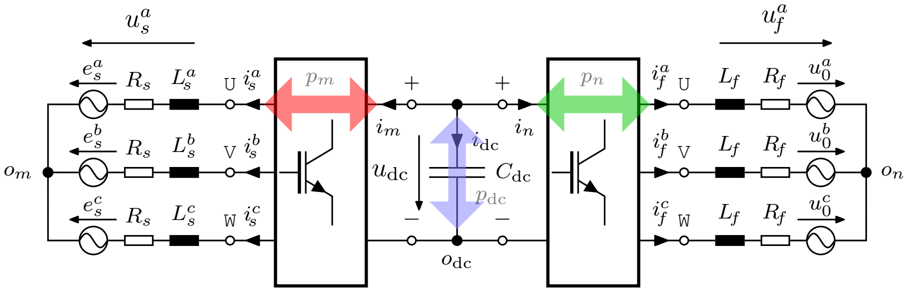
Overall system for DC-link voltage control



Outline

DC-link dynamics



- $p_{\mathrm{dc}} = u_{\mathrm{dc}} C_{\mathrm{dc}} \frac{\mathrm{d}}{\mathrm{d}t} u_{\mathrm{dc}} = -p_m - p_n \quad \Longrightarrow \quad \boxed{\frac{\mathrm{d}}{\mathrm{d}t} u_{\mathrm{dc}} = \frac{1}{u_{\mathrm{dc}} C_{\mathrm{dc}}} \big(-p_m - p_n \big)}$
- $p_m = \underbrace{\frac{3}{2} R_s \left\| \boldsymbol{i}_s^k \right\|^2}_{p_{m,\mathrm{loss}}} + \underbrace{\frac{3}{2} p \big(\psi_{\mathrm{pm}} i_s^q + (L_s^d - L_s^q) i_s^d i_s^q \big) \omega_m}_{p_{\mathrm{mech}} = m_m \omega_m} + \underbrace{\frac{3}{2} \frac{\mathrm{d}}{\mathrm{d}t} (\boldsymbol{i}_s^k)^\top \boldsymbol{L}_s^k \boldsymbol{i}_s^k}_{p_{\boldsymbol{L}_s^k}}$
- $p_n = \underbrace{\frac{3}{2} R_f \left\| \boldsymbol{i}_f^k \right\|^2}_{p_{\mathrm{pcc,loss}}} + \underbrace{\frac{3}{2} \frac{\mathrm{d}}{\mathrm{d}t} L_f (\boldsymbol{i}_f^k)^\top \boldsymbol{i}_f^k}_{p_{L_f}} + \underbrace{\frac{3}{2} \hat{u}_0 i_f^d}_{p_{\mathrm{pcc}}}$

Outline

6 Control (part 2): Grid side

Linearization around equilibrium

... discussion on whiteboard ...

Linearization around equilibrium (summary)

$$\frac{\mathrm{d}}{\mathrm{d}t}u_{\mathrm{dc}} = \frac{1}{C_{\mathrm{dc}}u_{\mathrm{dc}}}\left[-p_m - \frac{3}{2}\left(R_f\left\|\boldsymbol{i}_f^k\right\|^2 + L_f\left(\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_f^k\right)^\top \boldsymbol{i}_f^k + \hat{u}_0 i_f^d\right)\right]$$

$$\Longrightarrow \frac{\mathrm{d}}{\mathrm{d}t}\tilde{u}_{\mathrm{dc}} = -\frac{1}{C_{\mathrm{dc}}u_{\mathrm{dc}}^\star}\left[\tilde{p}_m + \frac{3}{2}\left(\left(\hat{u}_0 + 2R_f i_f^{d,\star}\right)\tilde{i}_f^d + L_f i_f^{d,\star}\frac{\mathrm{d}}{\mathrm{d}t}\tilde{i}_f^d\right) + \frac{3}{2}\left(2R_f i_f^{q,\star}\tilde{i}_f^q + L_f i_f^{d,\star}\frac{\mathrm{d}}{\mathrm{d}t}\tilde{i}_f^q\right)\right]$$

$$\circ\!\!-\!\!\bullet\; s\tilde{u}_{\mathrm{dc}}(s) = -\frac{1}{C_{\mathrm{dc}}u_{\mathrm{dc}}^\star}\left[\tilde{p}_m(s) + \frac{3}{2}\left(\left(\hat{u}_0 + 2R_f i_f^{d,\star}\right) + sL_f i_f^{d,\star}\right)\tilde{i}_f^d(s) + \frac{3}{2}\left(2R_f + sL_f\right)i_f^{q,\star}\tilde{i}_f^q(s)\right]$$

transfer function of linearized system:

$$\Longrightarrow \boxed{\frac{\tilde{u}_{\mathrm{dc}}(s)}{\tilde{i}_f^d(s)} = -V_S\frac{1+T_V s}{s}}$$ where $T_V := \frac{L_f i_f^{d,\star}}{\hat{u}_0 + 2R_f i_f^{d,\star}}$, $V_S := \frac{3}{2}\frac{\hat{u}_0 + 2R_f i_f^{d,\star}}{C_{\mathrm{dc}}u_{\mathrm{dc}}^\star}$

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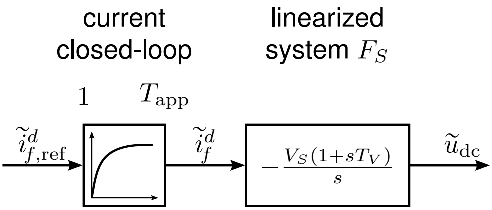
“Structurally varying” system dynamics



(S$_1$) $i_f^{d,\star} = 0 \implies T_V = 0 \implies \dfrac{\widetilde{u}_{\mathrm{dc}}(s)}{\widetilde{i}^{d}_{f,\mathrm{ref}}(s)} = \dfrac{V_S}{s(1+sT_{\mathrm{app}})}$ (IT$_1$)

(S$_2$) $i_f^{d,\star} > 0 \implies T_V > 0 \implies \dfrac{\widetilde{u}_{\mathrm{dc}}(s)}{\widetilde{i}^{d}_{f,\mathrm{ref}}(s)} = \dfrac{V_S(1+sT_V)}{s(1+sT_{\mathrm{app}})}$

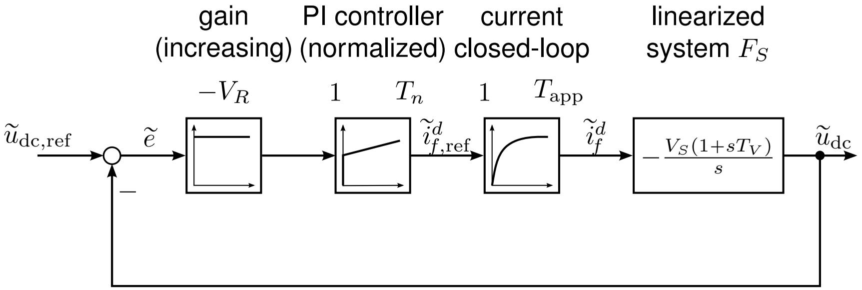
(IT$_1$ + PD, minimum phase)

(S$_3$) $i_f^{d,\star} < 0 \implies T_V < 0 \implies \dfrac{\widetilde{u}_{\mathrm{dc}}(s)}{\widetilde{i}^{d}_{f,\mathrm{ref}}(s)} = \dfrac{V_S(1-s|T_V|)}{s(1+sT_{\mathrm{app}})}$

(IT$_1$ + PD, **non-**minimum phase)

Outline

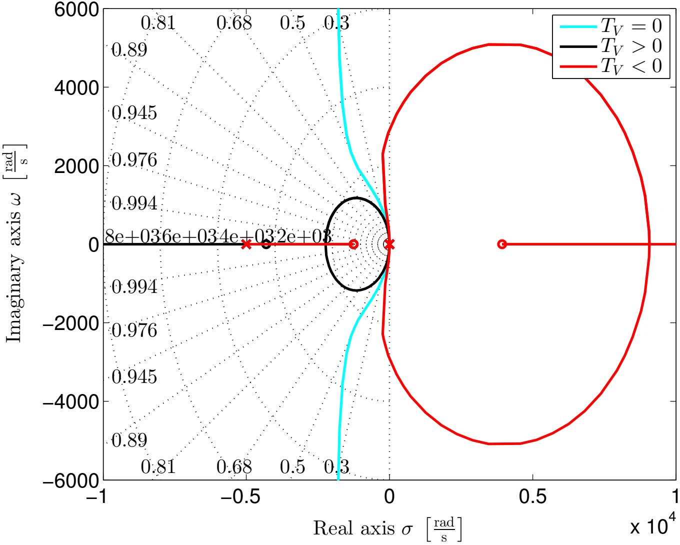
Root loci of linearized system



Open loop of linearized system

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

Root loci (depending on equilibrium)



Outline

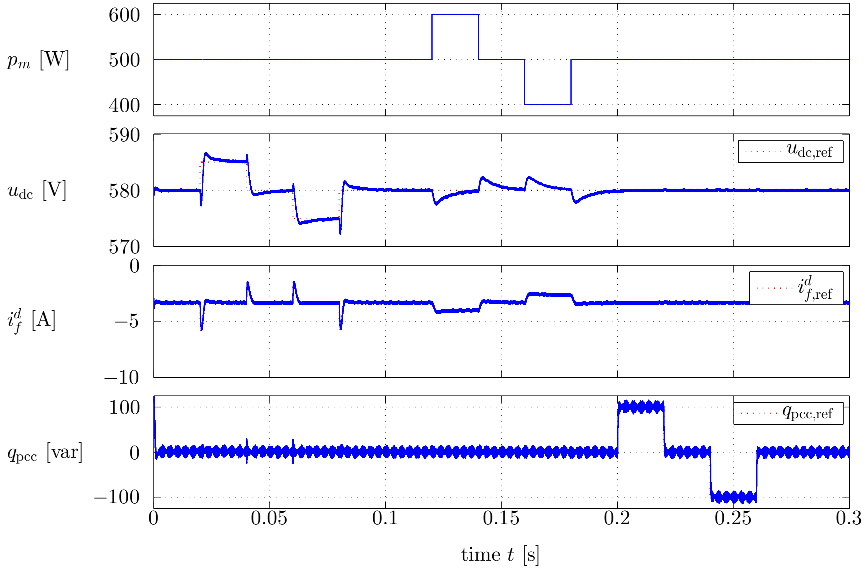
Stability analysis (Hurwitz polynomial)

... discussion on whiteboard ...

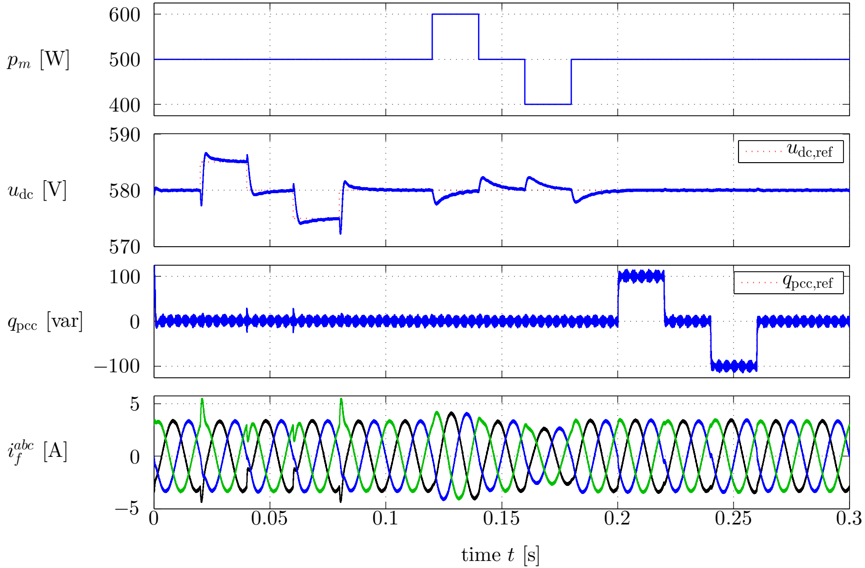
Outline

6 Control (part 2): Grid side

Simulation results (1): Grid-side control



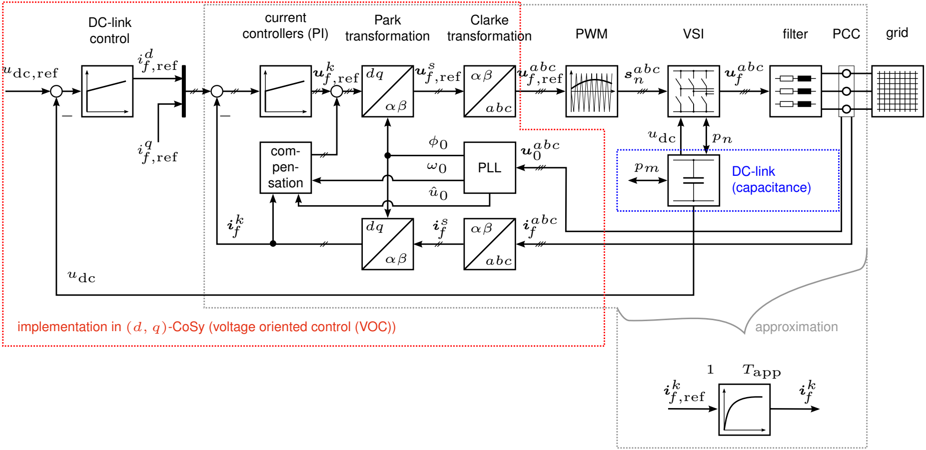
Simulation results (2): Grid-side control



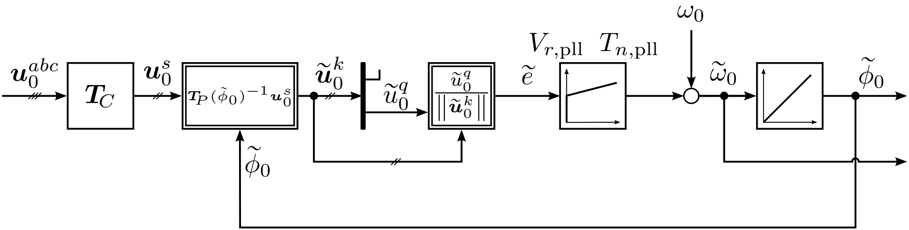
Outline

6 Control (part 2): Grid side

Résumé: Control (part 2) – Overall control system



Résumé: Control (part 2) – Grid side



Facts (Phase-locked loop (PLL))

PLL controller: $\frac{\omega_0(s)-\tilde{\omega}_0(s)}{\tilde{e}(s)} = V_{R,\mathrm{pll}} \frac{1+sT_{n,\mathrm{pll}}}{sT_{n,\mathrm{pll}}}$

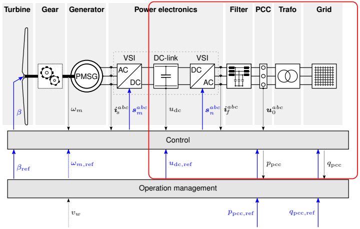
Small signal: $\sin(\phi_0 - \tilde{\phi}_0) =: \tilde{e} \approx \phi_0 - \tilde{\phi}_0,$ (for $\phi_0 - \tilde{\phi}_0 \ll 1$)

Control loop: $F_{CL,\mathrm{pll}}(s) = \frac{\tilde{\phi}_0(s)}{\phi_0(s)} = V_{r,\mathrm{pll}} \frac{1+s\,T_{n,\mathrm{pll}}}{1+s\,T_{n,\mathrm{pll}}+s^2\frac{T_{n,\mathrm{pll}}}{V_{r,\mathrm{pll}}}}$

Tuning: $\chi_{\mathrm{desired}}(s) = s^2T_p^2 + s2T_p + 1$ (e.g. pole placement)

$\Longrightarrow$ $V_{R,\mathrm{pll}} = \frac{2}{T_p} \quad \wedge \quad T_{n,\mathrm{pll}} = 2T_p, \qquad T_p \ll \frac{1}{f_0} = \frac{2\pi}{\omega_0}$

Résumé: Control (part 2) – Grid side



Facts (Grid side current/power control (for $T_f := L_f/R_f$))

current con.: $\frac{u^k_{f,\mathrm{ref}}(s)}{i^k_{f,\mathrm{ref}}(s) - i^k_f(s)} = V_{R,i^k_f} \frac{1+sT_{n,i^k_f}}{sT_{n,i^k_f}}, \; V_{R,i^k_f} = \frac{T_f R_f}{2T_{\mathrm{dead}}} \wedge T_{n,i^k_f} = T_f$

Dist. comp.: $u^k_{f,\mathrm{comp}} = \mathcal{L}^{-1}\left\{\frac{1+s\,T_{\mathrm{dead}}}{1+sh}\right\}\begin{pmatrix}\omega_0 L_f i^q_f - \hat{u}_0 \\ -\omega_0 L_f i^d_f\end{pmatrix}$

current dyn.: $\frac{i^k_f(s)}{i^k_{f,\mathrm{ref}}(s)} \approx \frac{1}{1+sT_{\mathrm{app}}}, \qquad T_{\mathrm{app}} = 2T_{\mathrm{dead}} \ll 1$

active pow.: $p_{\mathrm{pcc}} = \frac{3}{2}\hat{u}_0 i^d_f$ (p_{pcc} controlled via DC-link control)

react. pow.: $q_{\mathrm{pcc}} = -\frac{3}{2}\hat{u}_0 i^q_f$ (for q_{pcc} control set: $i^q_{f,\mathrm{ref}} = -\frac{2q_{\mathrm{pcc,ref}}}{3\hat{u}_0}$)

Résumé: Control (part 2) – Grid side

Facts (DC-link control (linearization, local results))

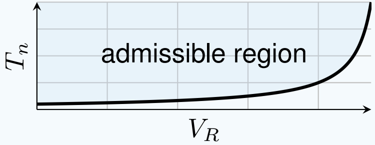
- Linearized system: $-V_S \frac{1+T_V s}{s}$, $T_V := \frac{L_f i_f^{d,\star}}{\hat{u}_0 + 2R_f i_f^{d,\star}} \wedge V_S := \frac{3}{2} \frac{\hat{u}_0 + 2R_f i_f^{d,\star}}{C_{\mathrm{dc}} u_{\mathrm{dc}}^\star}$
- Closed-loop system with PI controller $V_R \frac{1+sT_n}{sT_n}$

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

Sufficient conditions for **local** stability

(B$_1$) $0 < V_R < \frac{1}{|T_V| V_S}$

(B$_2$) $T_n > \frac{T_{\mathrm{app}}}{1 - V_R V_S |T_V|} + |T_V| > 0$



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

Outline

7 Operation management and outlook

- Operation management
  - Operation regimes (recap.)
  - Power coefficient without pitch system (recap.)
  - Regime II: Speed control loop
  - Regime III: Speed control loop with pitch control
- Power flow (recap.)
- Outlook: Future challenges

Outline

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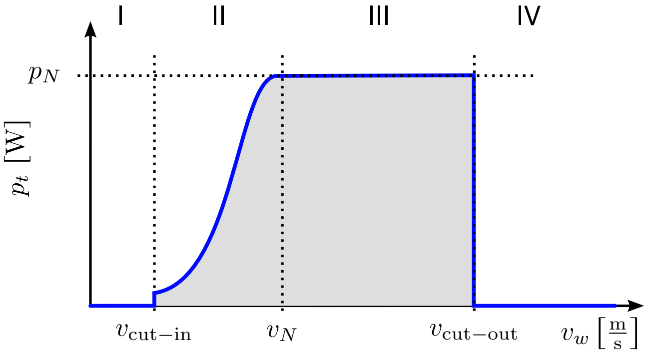
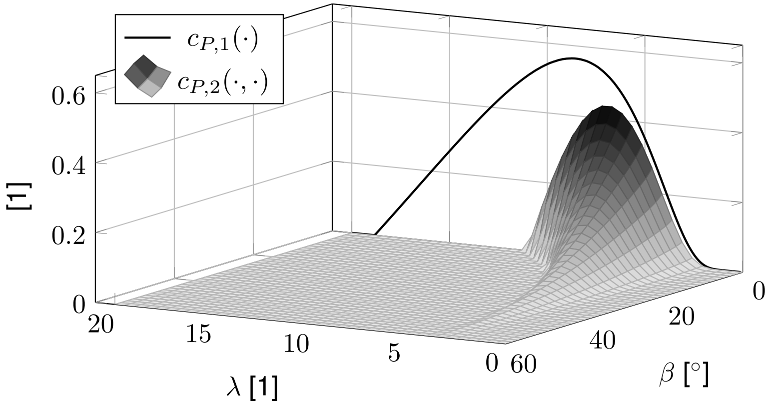
Operation regimes for different wind speeds (recap.)



- Regime I: Stand still. No power output, i.e. $p_t = 0$.
- Regime II: Sub-nominal operation. Variable output power, i.e. $0 < p_t < p_{\mathrm{nom}}$ (Goal: Maximum power point tracking).
- Regime III: Nominal operation. Output of nominal power, i.e. $p_t = p_{\mathrm{nom}}$.
- Regime IV: Stand still (safety shut down), i.e. $p_t = 0$.

Outline

Power coefficient without pitch system (recap.)



turbine power

$$p_t(t) = c_{p,2}(\lambda,\beta)p_w(t) = c_{p,2}(\lambda,\beta)\,\frac{1}{2}\varrho\pi r_t^2 v_w(t)^3 \leqslant c_{p,\mathrm{Betz}}\,\frac{1}{2}\varrho\pi r_t^2 v_w(t)^3 \tag{6}$$

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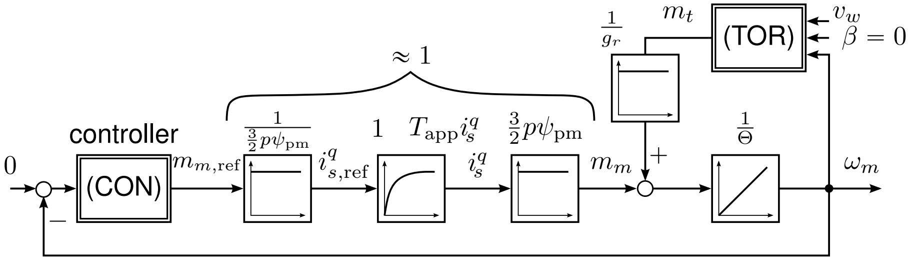
Regime II: Speed control loop

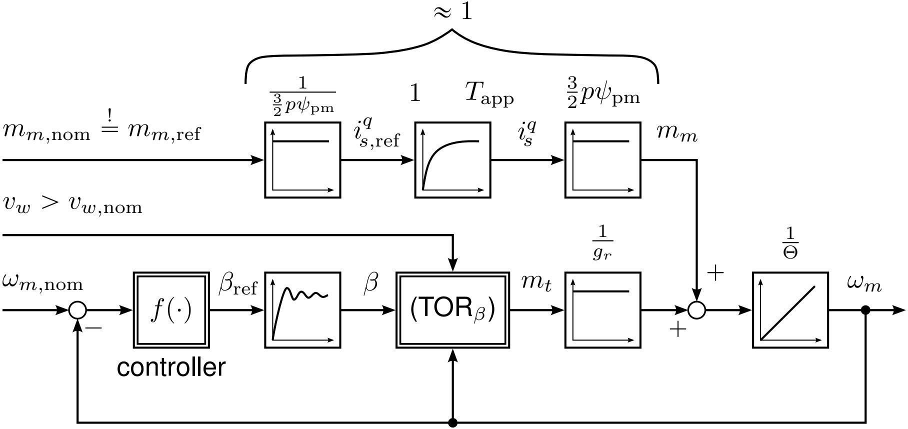


turbine torque: $m_t(v_w, 0, \omega_m) = c_0 \dfrac{c_P(v_w, 0)}{\lambda^3}\omega_m^2$ where $\lambda = \dfrac{r_t \omega_m}{g_r v_w}$ (TOR)

generator torque: $m_{m,\mathrm{ref}} = -k_p^\star \omega_m^2 \approx m_m$ where $k_p^\star = c_0 \dfrac{c_P(\lambda^\star, 0)}{(\lambda^\star)^3}$ (CON)

Outline

Regime III: Speed control loop with pitch control

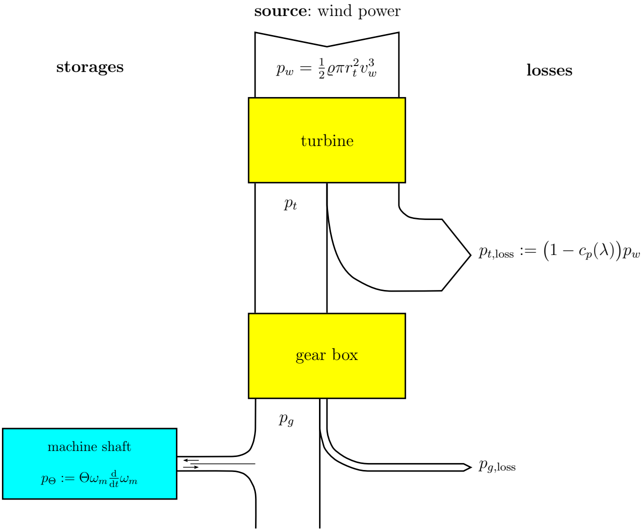


turbine torque: $m_t(v_w, \beta, \omega_m) = c_0 \dfrac{c_P(v_w, \beta)}{\lambda^3} \omega_m^2$ where $\lambda = \dfrac{r_t \omega_m}{g_r v_w}$

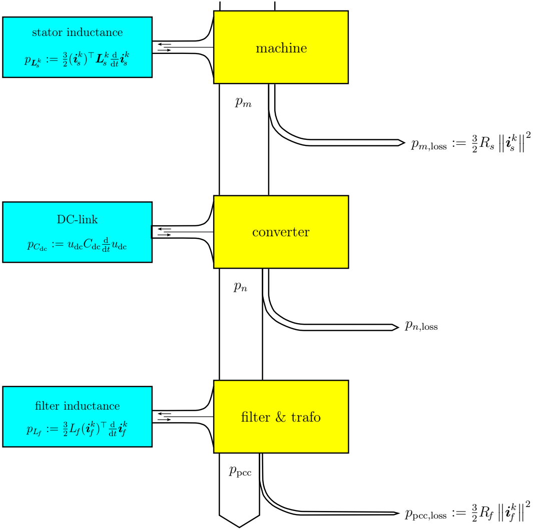
(TOR$_\beta$)

Outline

Power flow (part 1)



Power flow (part 2)



sink: point of common coupling (PCC)

Outline

Future challenges (see also [12])

- Reduction of levelized cost of energy (LCOE)
  $\Longrightarrow$ economical feasibility of the “Energiewende”?!
- Increase in reliability (in particular, of control system and power electronics)
  - Robustness
  - System analysis and simulation
  - Reduction of maintenance (condition monitoring / fault detection)
- Reliable grid integration
  - Plant safety,
  - Grid code requirements (e.g. LVRT, frequency/voltage support)
  - Decentralized generation (e.g. islanding mode/micro grid operation, etc.)
  - Wind farms (grid integration, wake effects, ...)
- New technologies/configurations
  - New generator topologies
  - New converter topologies (multi-level converters)
  - New gear topologies (“single-stage”)
  - Configurations without or smaller transformer
  - New semiconductors (SiC Mosfet, IGBT/IGCT press-pack, etc.)

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