# Modeling and control of electrical components in wind turbine systems

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# MSE Research group
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## Contact and further reading

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- 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])

# Outline

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1 Introduction and motivation
- Figures and facts
- Core components (electrical point of view)
- Availability and failures

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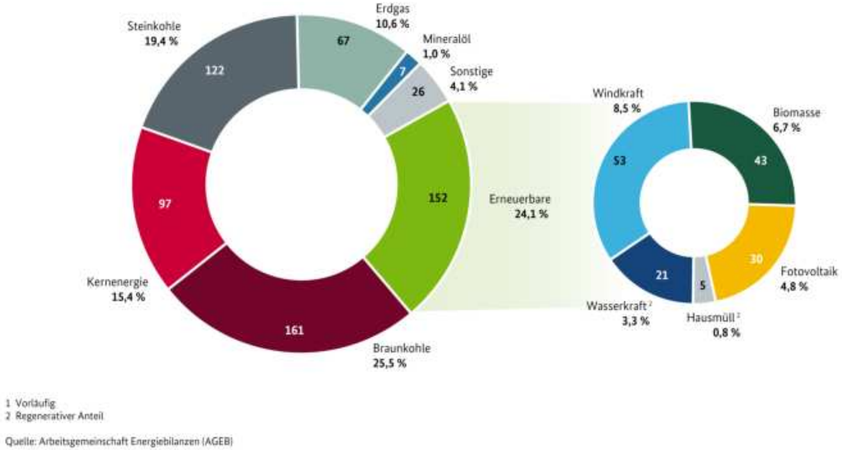
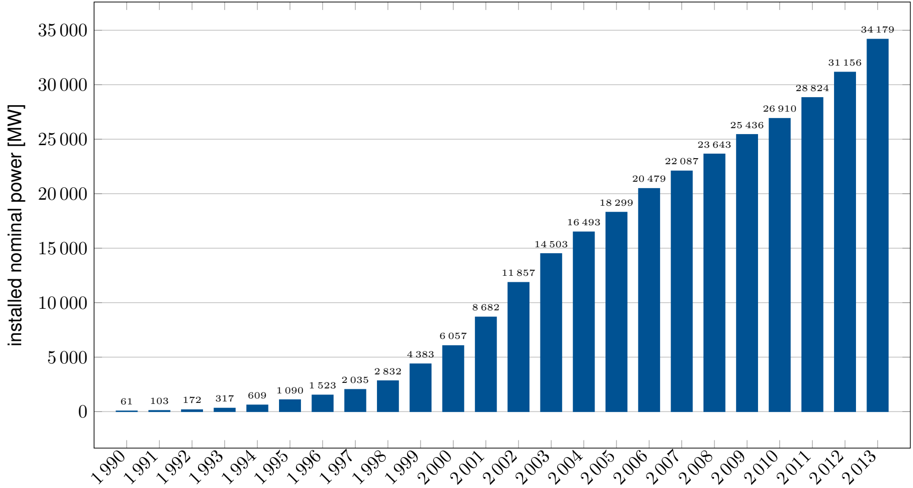
# Gross power generation⋆ in Germany 2013 (overall $631\,\mathrm{TW\,h}^1 = 631 \cdot 10^9\,\mathrm{kW\,h}$, aus [2])



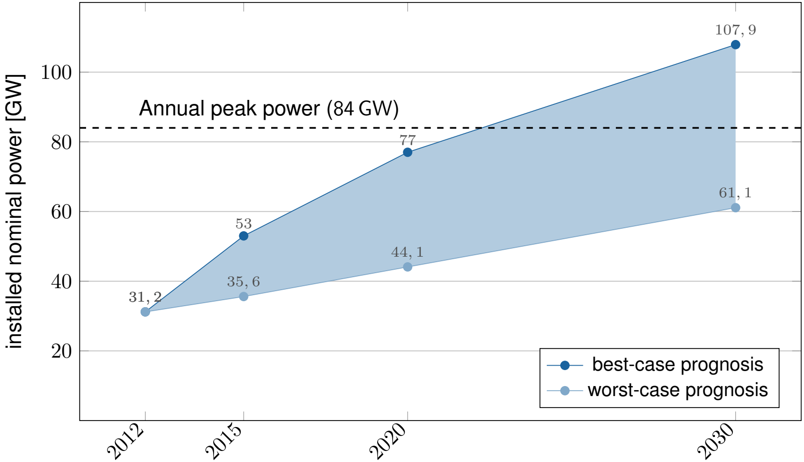

(⋆ net power generation = gross power generation − energy consumption of power plant)

# Installed nominal wind power in Germany 1990-2013



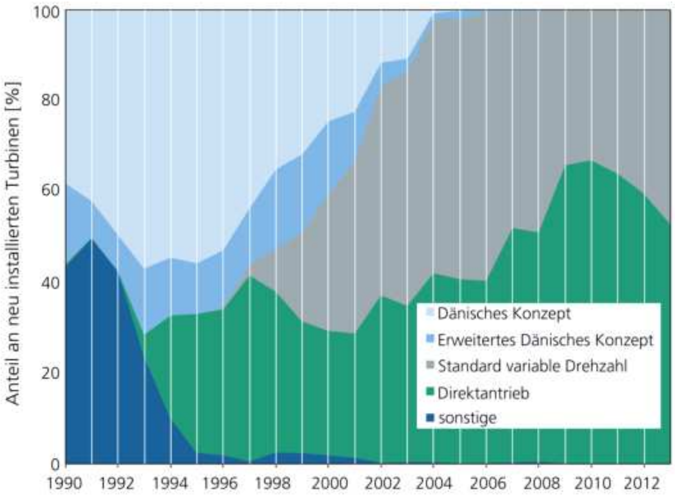

(based on Fig. 4 in [3])

# Prognosis of installed nominal wind power in Germany 2030

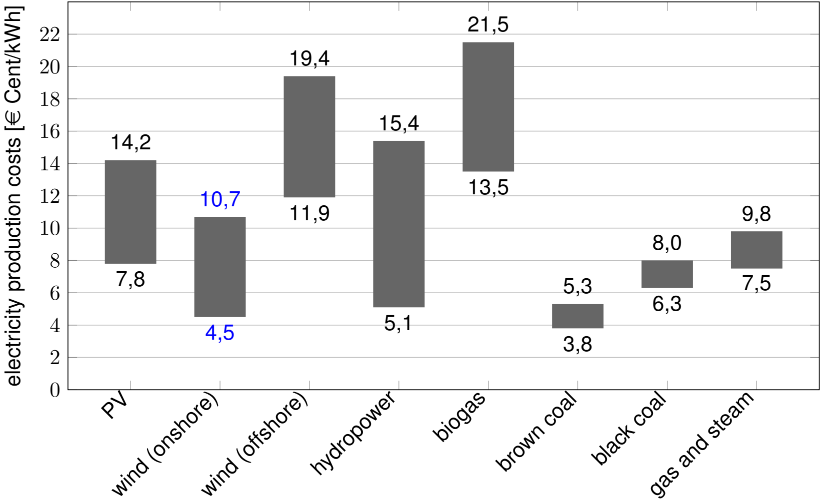



(Fig. based on p. 6 in [4])

# Percentage of installations after **generator topology** in Germany 1990-2013 (from [3])



# Electricity production costs in Germany 2013




(based on Fig. 1 in [5] and Tab. 4.12 (> 500 kW) in [6]).

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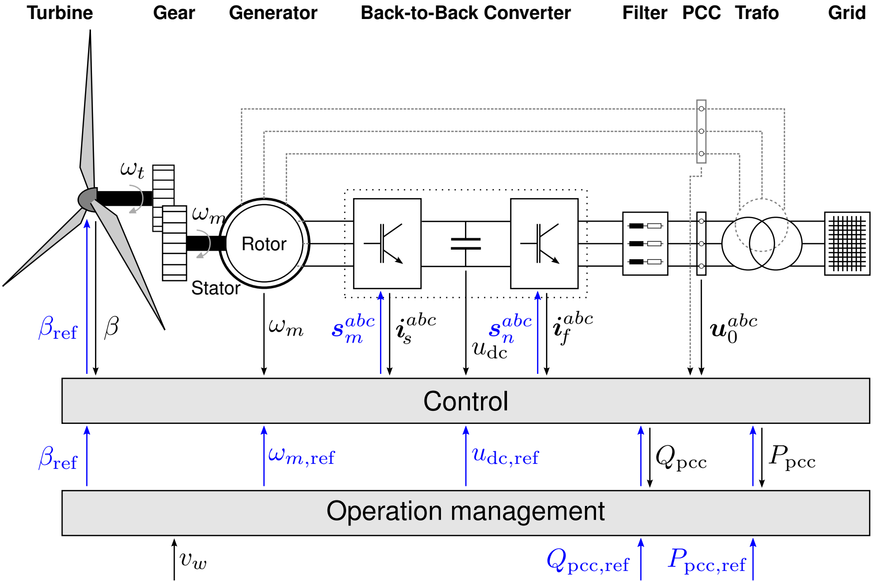
# Core components (electrical point of view)



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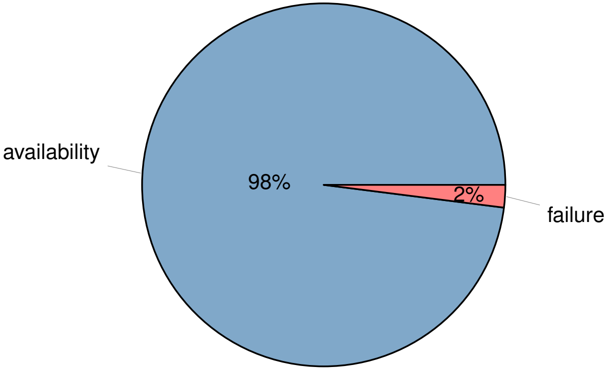
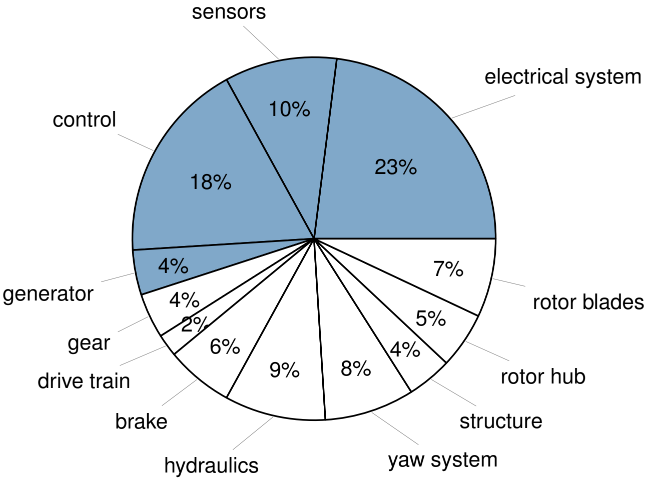
# Availability (from a study with 1 500 WT, [7])




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

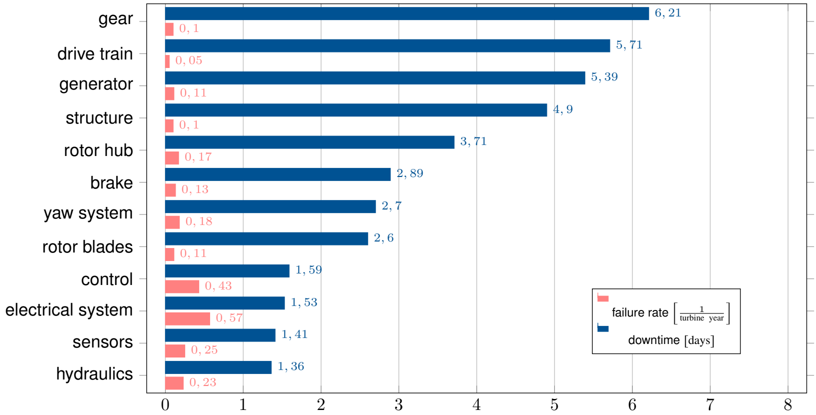
- Availability: 7 154 days
- Failure: 146 days (no production)

# Share of failures of subsystems




(based on Fig. 2 in [7])

# Failure rate and downtimes




(based on Fig. 2 in [8])

Average down time (over 20 years):

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

# Outline

## 2 Modeling

- Example: Wind turbine systems with direct drive
- Electrical network of wind turbine system (overview)
- Generator dynamics (permanent-magnet synchronous generator)
  - Electrical network on machine side (recap.)
  - AC machines
  - Space vector theory
- Voltage source inverter (VSI)
  - Electrical network
  - Voltage hexagon
  - Pulse width modulation (PWM)
  - Dynamics (approximation)
- Grid-side dynamics (filter, grid voltage)
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  - Grid voltage: Model in voltage orientation
- Summary: Electrical models in $(d, q)$-CoSy

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# Example: Wind turbine systems with direct drive

Wind turbine SWT-2.3-113

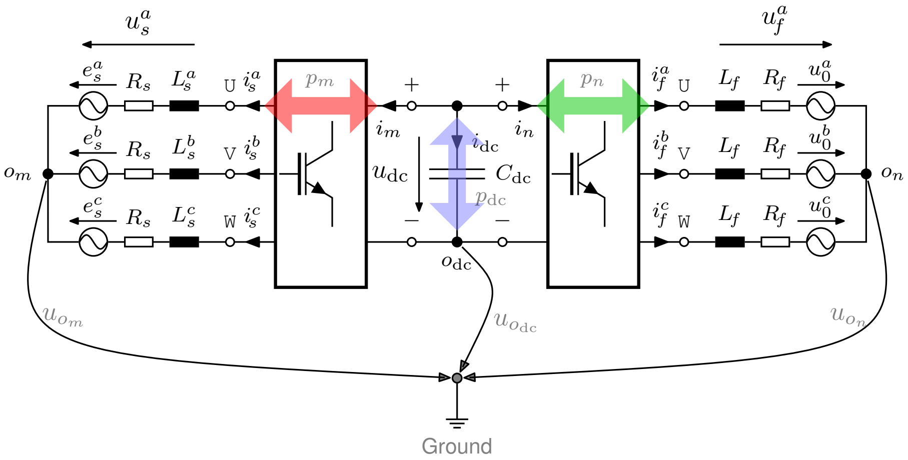
http://www.siemens.com/press/de/pressebilder/

direct drive
(permanent-magnet
synchronous generator (PMSG))

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

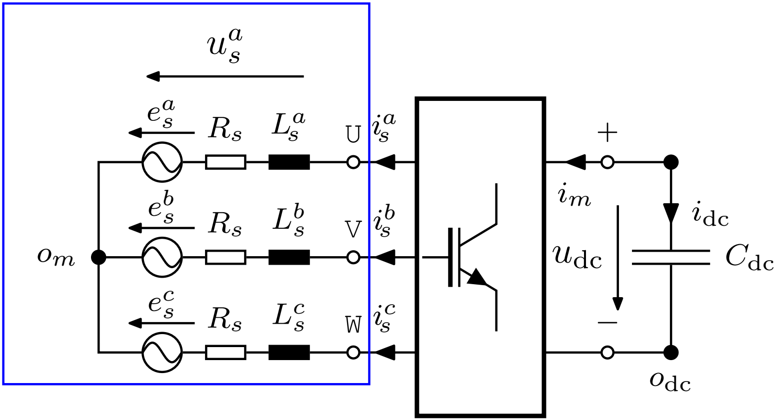
# Outline

# Electrical network of wind turbine system (overview)



# Outline

# Electrical network on machine side




$\Longrightarrow$ Generator dynamics in flux orientation (using rotating $(d, q)$-CoSy)

# AC machines

Induction machine (IM)

http://www.automation.siemens.com/bilddb/

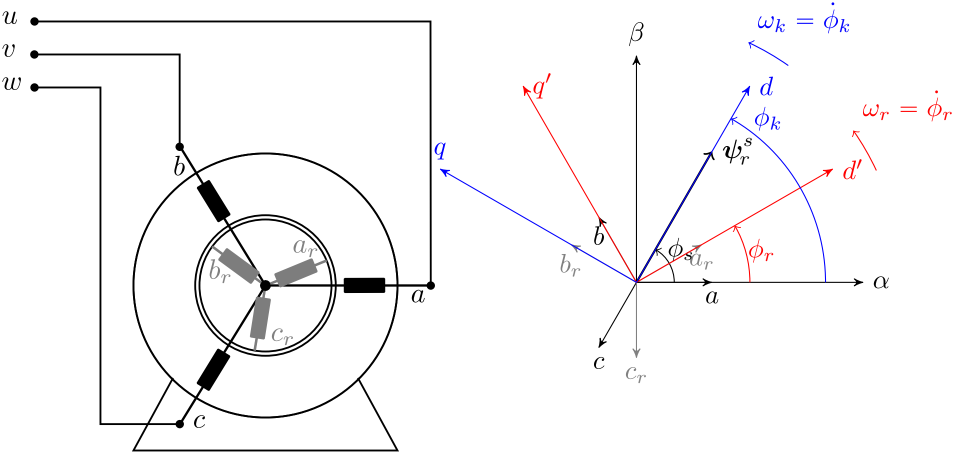
Synchronous machine (SM)

http://www.automation.siemens.com/bilddb/

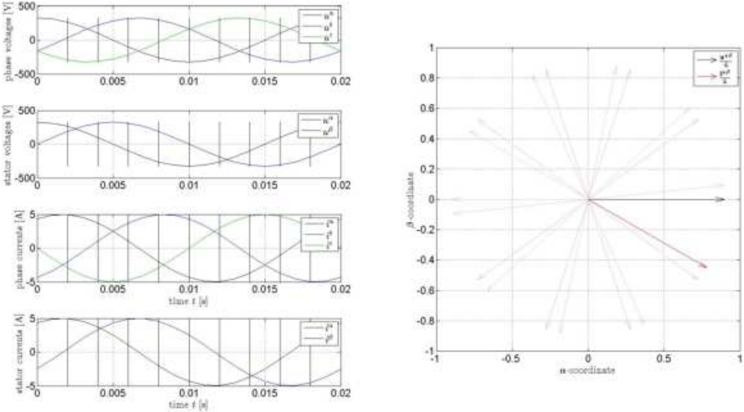
# Induction machine (cutaway view)

www.siemens.com

# Space vector theory: Flux orientation



# Space vector theory (animation)



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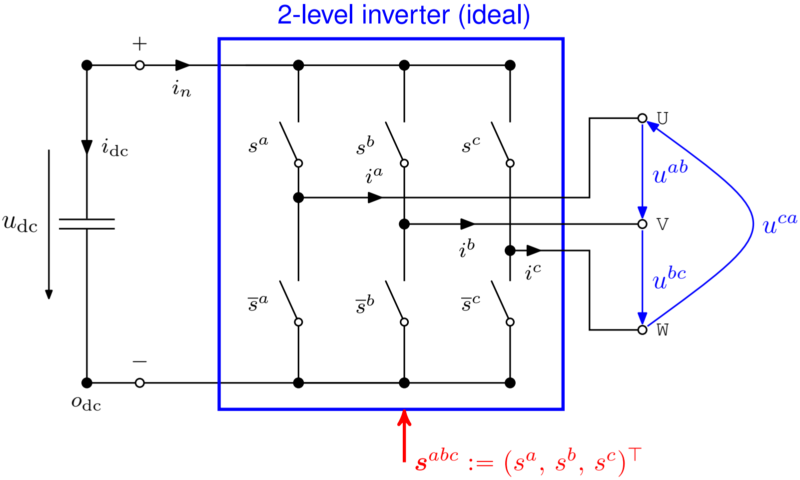
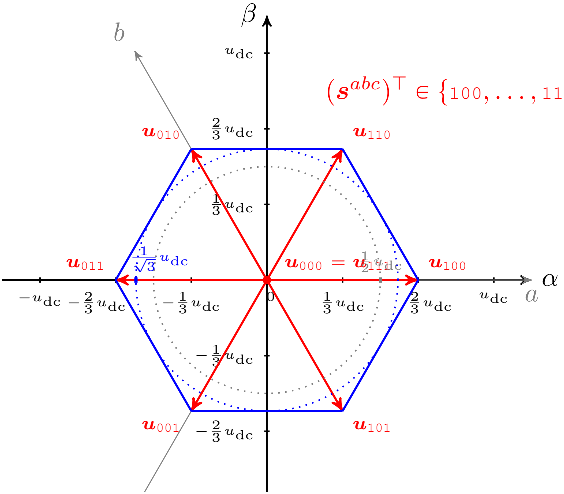
# VSI model: Electrical network

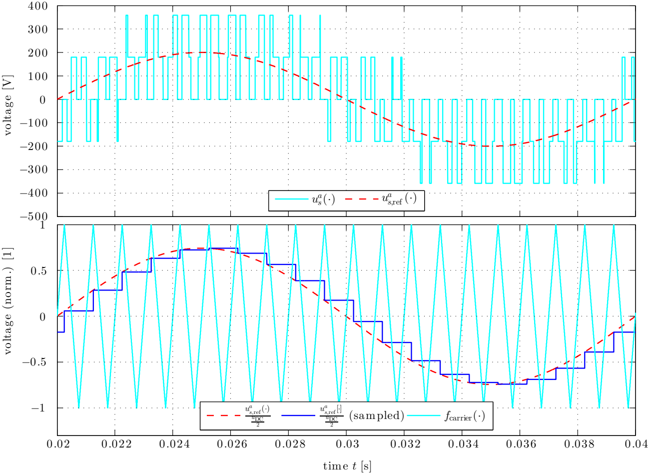



$\Longrightarrow$ output voltages $\boldsymbol{u}^{abc}_{\mathrm{ltl}} = (u^{ab}, u^{bc}, u^{ca})^\top = f(\boldsymbol{s}^{abc}, u_{\mathrm{dc}})$ ?

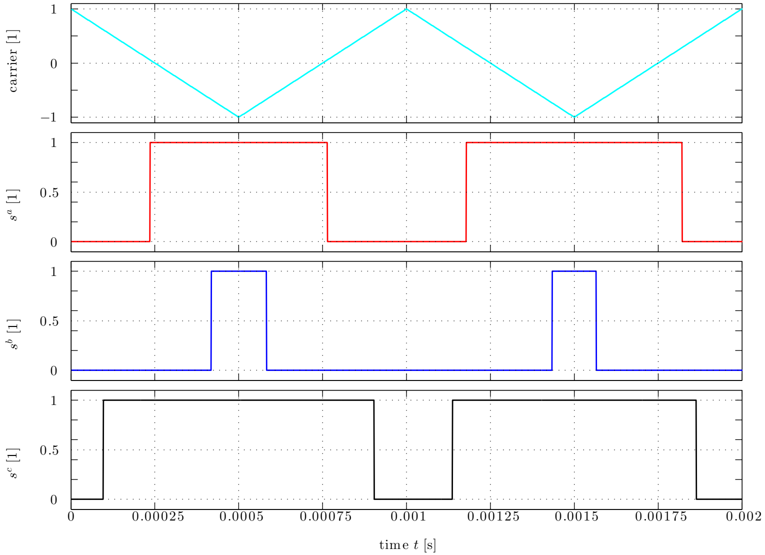
# VSI model: Voltage hexagon



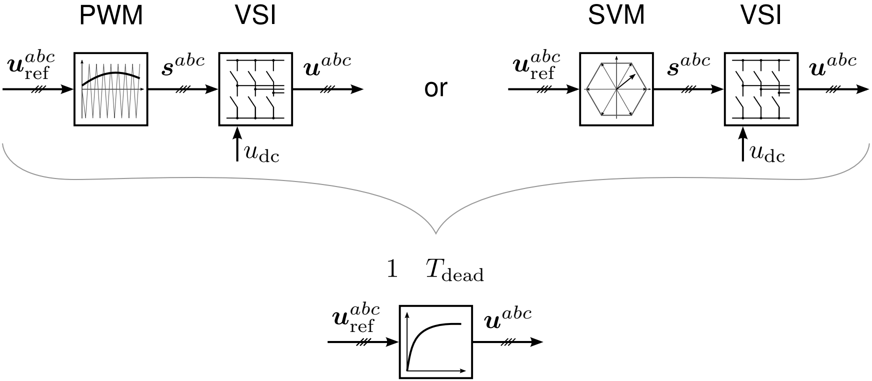
# Pulse width modulation (PWM): Symmetrical PWM



# Symmetrical PWM



# VSI model: Dynamics (approximation)



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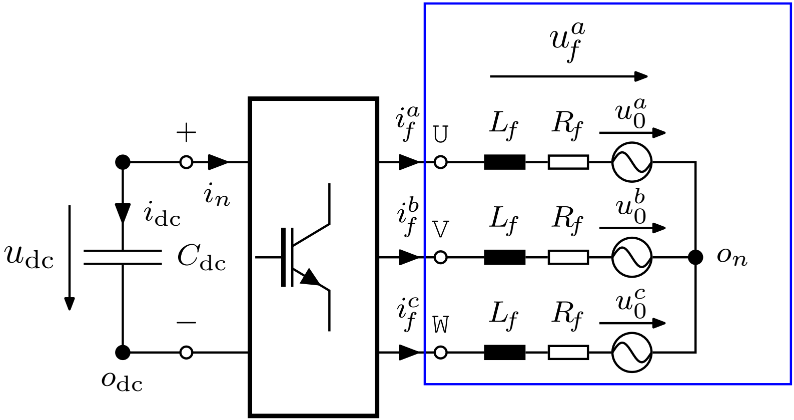
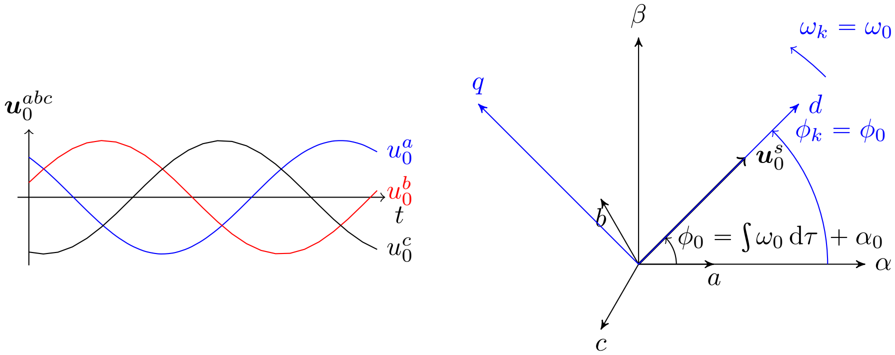
# Electrical network on grid side




$\Longrightarrow$ Grid-side dynamics in voltage orientation (using rotating $(d, q)$-CoSy)

# Grid voltage: Model in voltage orientation




$\Longrightarrow$ grid-side model in voltage orientation of $(d,\, q)$-CoSy?

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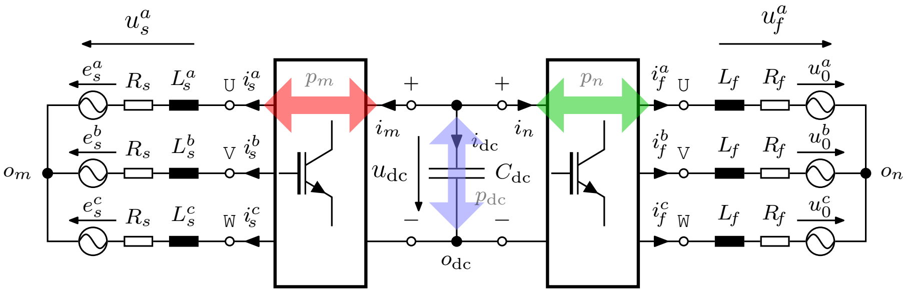
# Summary: Electrical models in $(d,\, q)$-CoSy




model in flux orientation (FOC)

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

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

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

model in voltage orientation (VOC)

$$\frac{\mathrm{d}}{\mathrm{dt}}\, i_f^d = \frac{1}{L_f}\big(u_f^d - R_f i_f^d + \omega_0 L_f i_f^q - \hat{u}_0\big)$$

$$\frac{\mathrm{d}}{\mathrm{dt}}\, i_f^q = \frac{1}{L_f}\big(u_f^q - R_f i_f^q - \omega_0 L_f i_f^d\big)$$

$$P_{\mathrm{pcc}} = \frac{3}{2}\hat{u}_0 i_f^d \quad \& \quad Q_{\mathrm{pcc}} = -\frac{3}{2}\hat{u}_0 i_f^q$$

# Outline

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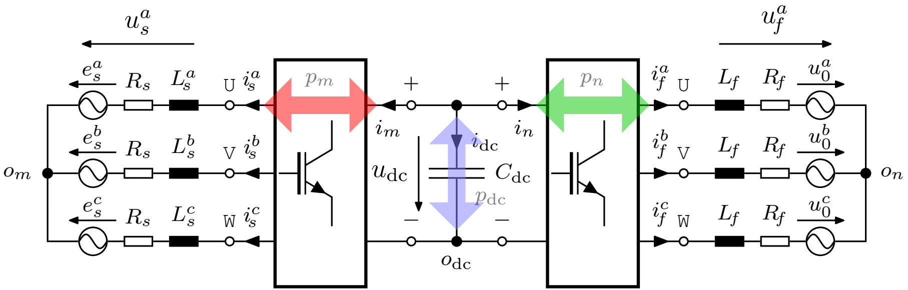
## 3 Control

- Control of machine/grid-side currents
  - Electrical model of wind turbine system
  - Model of voltage source inverter (VSI)
  - Generator current controller design
  - Grid-side current controller design
- Control of turbine speed
  - Power coefficient and turbine speed
  - Turbine speed controller
- Control of the DC-link voltage
  - Model of the DC-link
  - Overall system for DC-link voltage control
  - “Structurally varying” system dynamics
  - Root loci of linearized system

# Electrical model of wind turbine system




model in flux orientation (FOC)

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

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

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

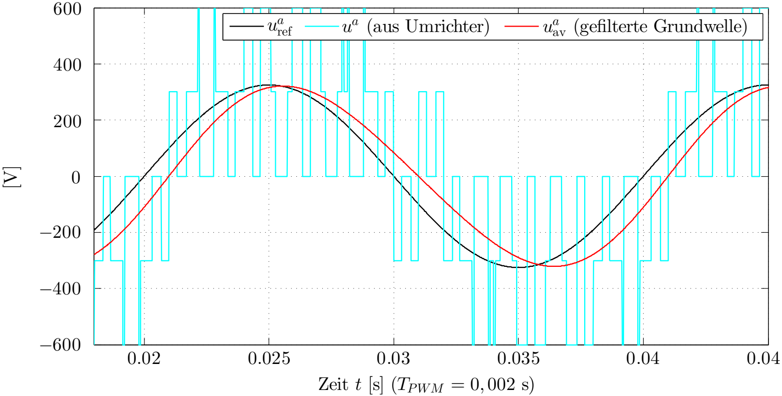
model in voltage orientation (VOC)

$$\frac{\mathrm{d}}{\mathrm{dt}} i_f^d = \frac{1}{L_f}\left(u_f^d - R_f i_f^d + \omega_0 L_f i_f^q - \hat{u}_0\right)$$

$$\frac{\mathrm{d}}{\mathrm{dt}} i_f^q = \frac{1}{L_f}\left(u_f^q - R_f i_f^q - \omega_0 L_f i_f^d\right)$$

$$P_{PCC} = \frac{3}{2}\hat{u}_0 i_f^d \quad \& \quad Q_{PCC} = -\frac{3}{2}\hat{u}_0 i_f^q$$

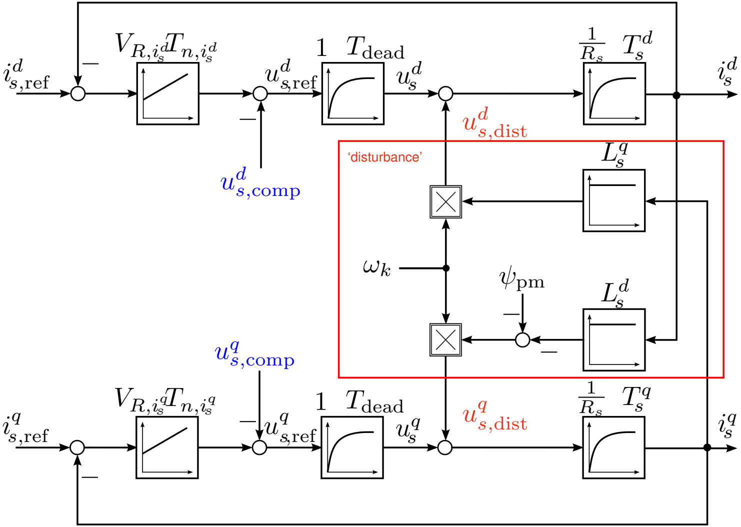
# Delayed voltage generation



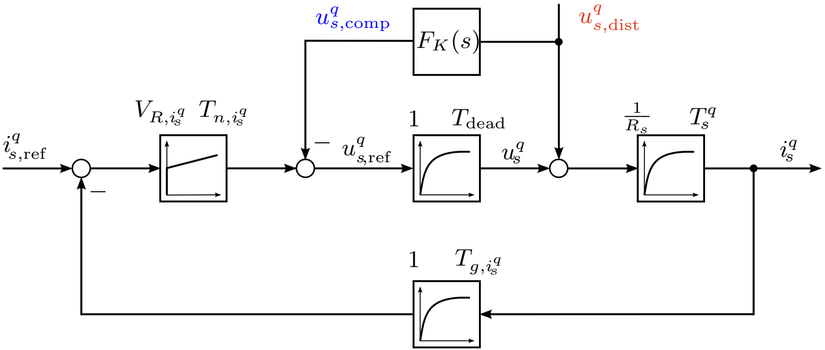

Delay depends on implemented PWM methods:

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

# Generator current closed-loop system



# Current controller design (ideal disturbance compensation)




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

$$F_{R,i^d_s}(s) = V_{R,i^d_s}\frac{1+sT_{n,i^d_s}}{sT_{n,i^d_s}} \quad \text{where} \quad V_{R,i^d_s} = \frac{T^d_s}{2\cdot 1/R_s \cdot T_{\mathrm{dead}}} \quad \text{and} \quad T_{n,i^d_s} = T^d_s$$

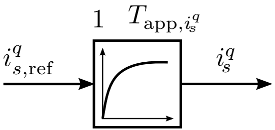
# Approximation of current closed-loop system

We have

$$F_{CL,i_s^q}(s) = \frac{i_s^q(s)}{i_{s,\mathrm{ref}}^q(s)} = \frac{1}{1 + s2T_{\mathrm{dead}} + s^2 2T_{\mathrm{dead}}^2}$$

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

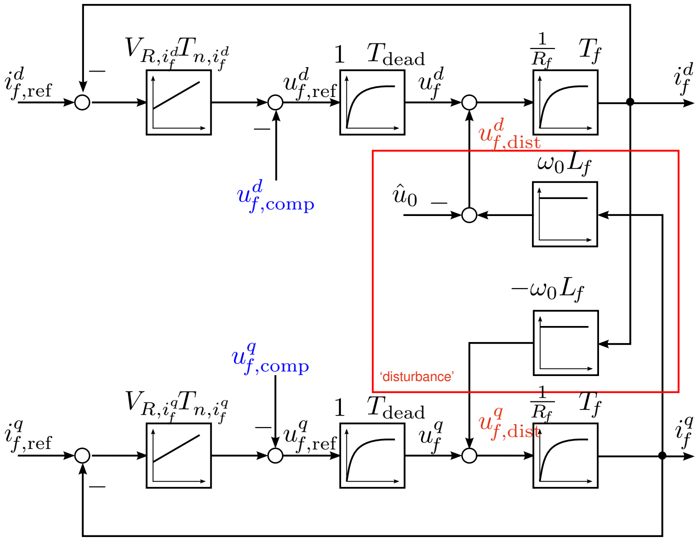
i.e.



Since $T_{\mathrm{dead}} \ll 1$ we may assume

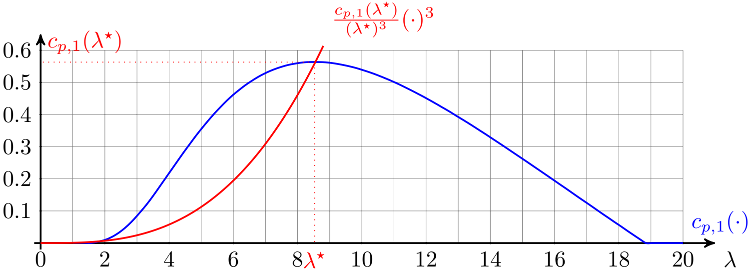
$$F_{CL,i_s^q}(s) = \frac{i_s^q(s)}{i_{s,\mathrm{ref}}^q(s)} \approx 1 \qquad \Longrightarrow \qquad \boxed{\forall\, t \geqslant 0:\ \ m_{m,\mathrm{ref}}(t) \approx m_m(t)}$$

# Grid-side current controller design



# Outline

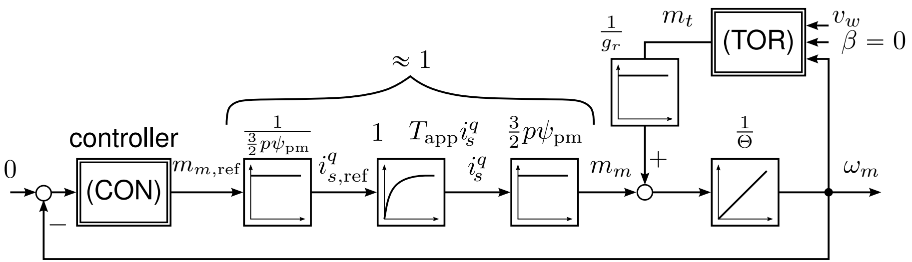
# Power coefficient and turbine speed




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

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

# Turbine speed controller

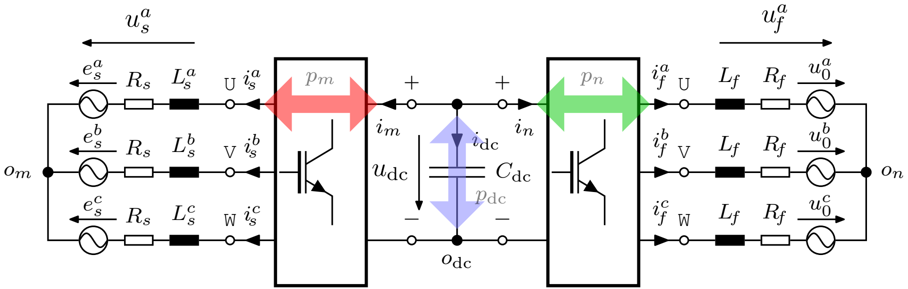



turbine torque $m_t(\lambda, \omega_m) = c_0 \frac{c_{p,1}(\lambda)}{\lambda^3} \omega_m^2$ where $\lambda = \frac{r_t \omega_m}{g_r v_w}$ (TOR)

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

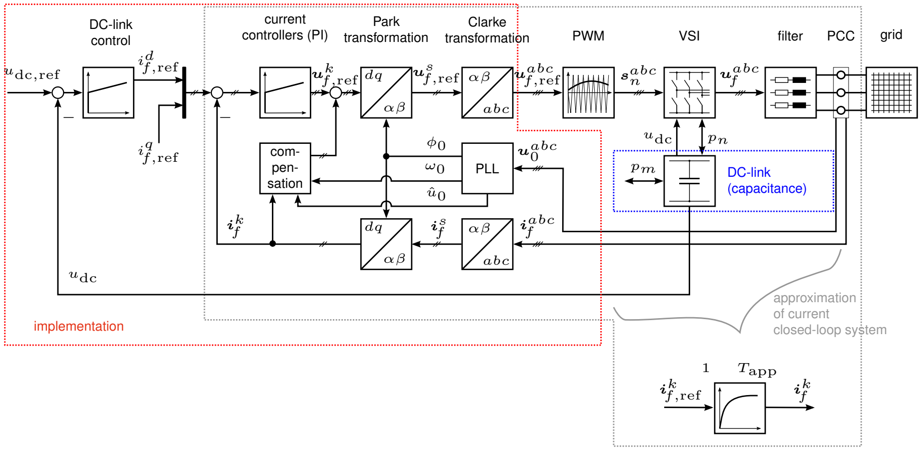
# Outline

# Model of the DC-link

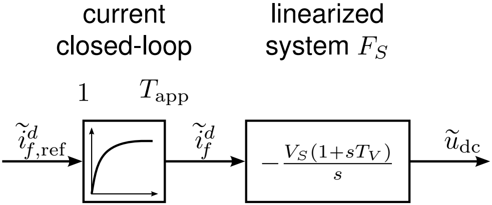



- $p_{dc} = u_{dc} C_{dc} \frac{d}{dt} u_{dc} = -p_m - p_n \quad \Longrightarrow \quad \boxed{\frac{d}{dt} u_{dc} = \frac{1}{u_{dc} C_{dc}} \big( -p_m - p_n \big)}$
- $p_m = \underbrace{\frac{3}{2} R_s \left\| \boldsymbol{i}_s^k \right\|^2}_{p_{V,R_s}} + \underbrace{\frac{3}{2} p \big( \psi_{pm} i_s^q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

# Overall system for DC-link voltage control



# "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$_1$)

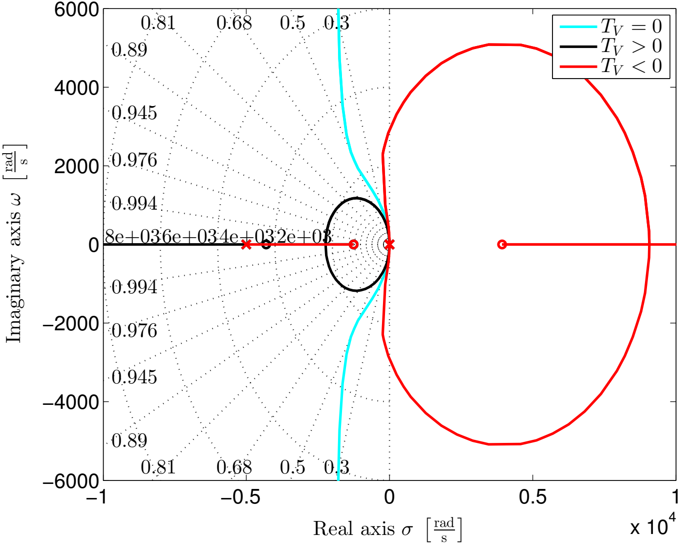
(S$_2$) $i_f^{d,\star} > 0 \implies T_V > 0 \implies \dfrac{\widetilde{u}_{\mathrm{dc}}(s)}{\widetilde{i}^{d}_{f,\mathrm{ref}}(s)} = \dfrac{V_S(1+sT_V)}{s(1+sT_{\mathrm{app}})}$

(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)

# Root loci (depending on equilibrium)



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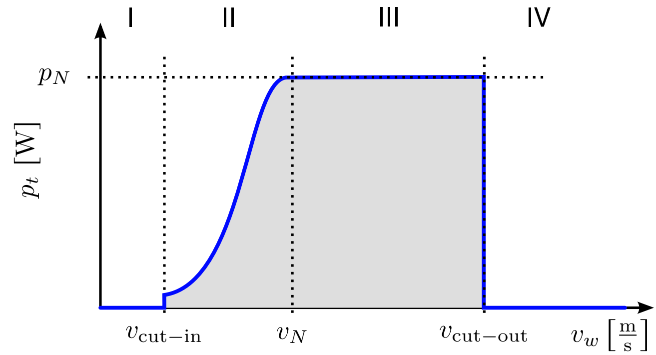
4 Operation management and power flow

- Operation regimes
- Regime II: Speed control loop
- Regime III: Speed control loop with pitch control
- Power flow

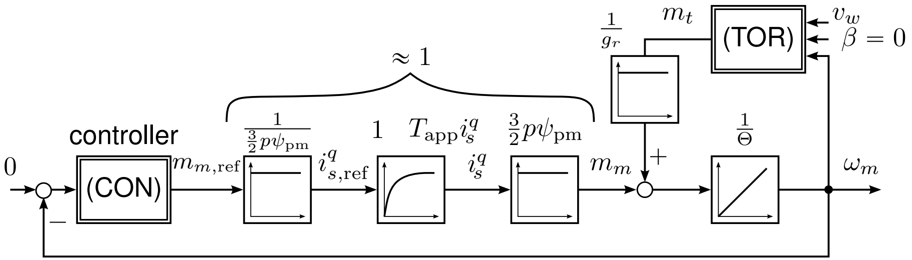
# Operation regimes for different wind speeds




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

# Outline

# Regime II: Speed control loop

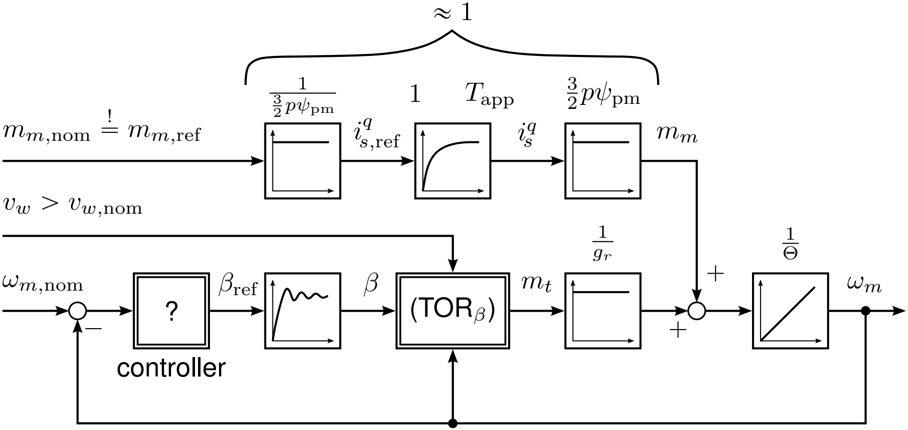



turbine torque: $m_t(v_w, 0, \omega_m) = c_0 \frac{c_P(v_w, 0)}{\lambda^3} \omega_m^2$ where $\lambda = \frac{r_t \omega_m}{g_r v_w}$ (TOR)

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

# Outline

# Regime III: Speed control loop with pitch control



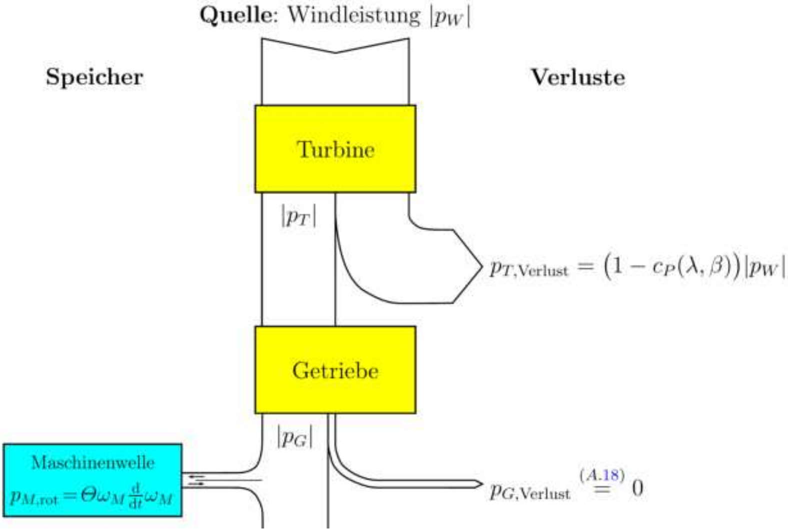

turbine torque: $m_t(v_w, \beta, \omega_m) = c_0 \dfrac{c_P(v_w, \beta)}{\lambda^3} \omega_m^2$ where $\lambda = \dfrac{r_t \omega_m}{g_r v_w}$ $(\mathrm{TOR}_\beta)$

# Outline

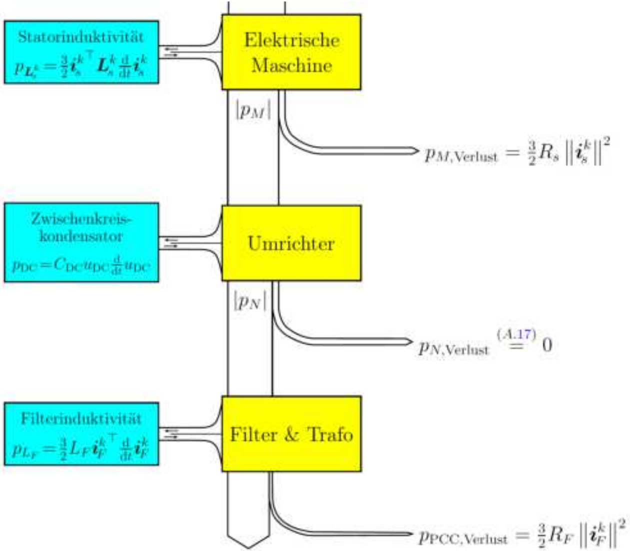
4 Operation management and power flow

- Operation regimes
- Regime II: Speed control loop
- Regime III: Speed control loop with pitch control
- Power flow

# Power flow (part 1)



# Power flow (part 2)



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