Non-ideal feedforward torque control of wind turbines: Impacts on annual energy production & gross earnings

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Abstract. We discuss non-ideal torque control in wind turbine systems. Most high-level controllers generate a reference torque which is then sent to the underlying electrical drive system (generator + inverter) of the wind turbine system to steer the turbine/generator to its optimal operation point (depending on the wind speed). The energy production heavily depends on the mechanical power (i.e. the product of rotational speed and generator torque). However, since torque sensors in the MW range are not available or extremely expensive, the underlying torque control system is implemented as feedforward control and, therefore, is inherently sensitive to parameter variations/uncertainties. Based on real wind data and a wind turbine system model, we discuss causes and impacts of non-ideal feedforward torque control on the energy production and the annual gross earnings.

Notation
\( \mathbb{N}, \mathbb{R} \): natural and real numbers.
\( \mathbf{x} := (x_1, \ldots, x_n)^\top \in \mathbb{R}^n \): column vector, \( n \in \mathbb{N} \) where ‘\( \top \)’ and ‘:=’ mean ‘transposed’ and ‘is defined as’.
\( \alpha \overset{(#1)}{=} \beta \): Equivalence of \( \alpha \) and \( \beta \) follows by invoking Eq. (#1) and Eq. (#2).
\( \mathbf{x} [X]^n \): physical quantity \( \mathbf{x} \in \mathbb{R}^n \), each of the \( n \) elements has SI-unit \( X \).

1. Motivation and introduction
Onshore wind turbine systems (WTS) are already today a competitive alternative to classical power generation with respect to the levelized costs of electricity (LCOE) [1]. The major part of the overall costs of wind power is fixed by the initial investment costs. So, a crucial factor to reduce the LCOE is to maximize the energy production (per year or lifetime). One reason for a non-optimal energy production is non-ideal torque control. Since WTS are not equipped with a torque sensor, the underlying “torque control loop” is implemented as feedforward control being severely sensitive to parameter variations/uncertainties, see Fig. 1. Hence, the machine torque \( m_M \text{[Nm]} \) might differ from the required (reference) torque \( m_M,\text{ref} \text{[Nm]} \) and affect annual power production and gross earnings.

Many high-level control strategies assume that (i) the actual torque equals the demanded torque instantaneously (neglecting the dynamics of the electrical system, see [2], [3]) and accurately (neglecting possible deviations between demanded and actual torque) or assume that (ii) the machine torque is proportional to the difference between synchronous speed and machine speed (which only holds in steady state, see [4]). Torque deviations violate this assumption and
directly affect the power production of modern WTS. Hence, for benchmark tests, faults leading to torque deviations are considered to have a medium to high impact on the power production (see [5]). Other phenomena which influence the power production such as the pitch-control dynamics or erroneous pitch- and yaw-control, etc. (see [5]) are not investigated. This work only studies the influence of non-ideal torque control on the annual energy production under the assumption that all other systems/components work perfectly.

After a brief description of the feedforward torque control in state of the art wind turbines in Sect. 2, the effects of non-ideal torque control and its modelling for the simulation are described in Sect. 3. Finally in Sect. 4 simulation results illustrate the impact of non-ideal torque control on annual energy production and gross earnings for different scenarios including different (varying) wind speeds and parameter uncertainties.

2. Electrical machines in wind turbine systems

According to [6] the most common generator (machine) topologies in WTS in Germany are

- the electrically excited synchronous generator (EESG) with generator torque (including anisotropy and cross coupling, without damper windings, see [7, Ch. 6], [8, Ch. 16])

\[ m_{M,\text{EESG}}(t) = \frac{3}{2}p \left[ \psi_e(i_e(t))i_s^d(t) + \left( L_s^d - L_s^q \right)i_s^q(t)i_s^d(t) + M\left( i_s^q(t)^2 - i_s^d(t)^2 \right) \right], \]

- the permanent magnet synchronous generator (PMSG) with generator torque (including anisotropy and cross coupling, see [2], [8, Ch. 16])

\[ m_{M,\text{PMSG}}(t) = \frac{3}{2}p \left[ \psi_{PM}i_s^q(t) + \left( L_s^q - L_s^d \right)i_s^d(t)i_s^q(t) + M\left( i_s^q(t)^2 - i_s^d(t)^2 \right) \right], \]

- and the doubly-fed induction generator (DFIG) with generator torque (see [8, Ch. 13], [9])

\[ m_{M,\text{DFIG}}(t) = \frac{3}{2}pL_M\left( i_s^d(t)i_s^q(t) - i_s^q(t)i_s^d(t) \right). \]

The machine torques (1)-(3) may depend on the number of pole pairs \( p \) [1], excitation flux linkage \( \psi_e \) [Vs], excitation current \( i_e \) [A], flux linkage \( \psi_{PM} \) [Vs] of the permanent magnet, stator \( d \)-current \( i_s^d \) [A], stator \( q \)-current \( i_s^q \) [A], machine \( d \)-inductance \( L_s^d \) [Vs/A], machine \( q \)-inductance \( L_s^q \) [Vs/A], coupling inductance \( M \) [Vs/A] between \( d \)- and \( q \)-axis, coupling inductance \( L_M \) [Vs/A] between rotor and stator. Note that all inductances may depend nonlinearly on the respective currents. The underlying current feedback control system can be approximated as first order lag systems (see [2]) with time constant \( T \_{s/r/e}^{d/q} \) [s]

\[ F_{CL}(s) = \frac{i_{s/r/e}^{d/q}(s)}{i_{s/r/e,\text{ref}}^{d/q}(s)} = \frac{1}{1 + sT \_{s/r/e}^{d/q}} \]

(and, hence, in steady state: \( i_{s/r/e}^{d/q} = i_{s/r/e,\text{ref}}^{d/q} \))

and achieves steady state accuracy. However, since no torque sensors are installed, only feedforward control of the generator torque is feasible (see Fig. 1). For (most) torque controller designs in state-of-the-art wind turbine systems, it is assumed that the actual machine torque equals the reference torque, i.e. \( m_M = m_{M,\text{ref}} \), because the electrical system is much faster than the mechanical system of the turbine (see [2], [10, Ch. 8]). Equations (1)-(3) show that the generator torques depend on machine parameters, flux linkages and currents. To achieve an accurate torque feedforward control their exact values are needed. Parameter uncertainties and/or measurement errors will lead to a deteriorated (wrong) current reference computation (see Fig. 1) and, hence, actual and reference torque will differ, i.e. \( m_M \neq m_{M,\text{ref}} \). The torque feedforward control system is not capable to compensate for parameter uncertainties.

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In this paper, only the effects during energy production are considered (i.e. \( m_M \neq 0 \)) and the occurring torque deviations \( m_M = \gamma m_{M,\text{ref}} \) are modelled by a simple multiplication with the deviation factor \( \gamma \) [1]. For simplicity, we only consider a constant factor \( \gamma \). Moreover, for the upcoming analysis, we impose the following assumptions.

**Assumption (A.1)** The actual machine torque \( m_M \) [Nm] (a non-linear function of flux linkage and machine currents) and reference torque \( m_{M,\text{ref}} \) [Nm] differ by a constant deviation factor \( \gamma \), i.e.

\[
\forall \gamma \in (0, \gamma_{\text{max}}) \forall t \geq 0: \quad m_M(t) = \gamma m_{M,\text{ref}}(t). \quad (5)
\]

**Assumption (A.2)** The pitch control system is ideal (e.g. no dynamics and deviations), i.e.

\[
\beta(t) = \beta_{\text{ref}}(t), \quad \forall t \geq 0,
\]

with pitch angle \( \beta[^\circ] \) and its reference value \( \beta_{\text{ref}}[^\circ] \).

**Assumption (A.3)** All losses in the wind turbine systems are neglected; e.g. friction (in the mechanical drive train), iron and copper losses in the electrical machine and conducting and switching losses in the converters are not considered.

3. Operation, modeling and control of WTS with non-ideal torque control

In this section, the principles of wind turbine operation are explained, a simple turbine model is introduced and the control objectives and control methods for the different operation regimes are revisited. Finally, the impact of non-ideal torque control is discussed.

3.1. Regimes of operation.

Depending on the actual wind speed \( v_W \) [m/s], the wind turbine system will operate in one of the four regimes of operation (see Fig. 2). For too less or too much wind (i.e. \( v_W < v_{\text{cut-in}} \) in regime I and \( v_{\text{cut-out}} \leq v_W \) in regime IV, resp.), the wind turbine is (usually) at standstill or in idle speed: The turbine angular velocity is zero, i.e. \( \omega_T = 0 \) rad/s or the machine torque is zero, i.e. \( m_M = 0 \) Nm, hence the turbine power is \( p_T = 0 \) W.

In regime II, the wind speed is below the nominal wind speed \( v_{\text{nom}} \) [m/s] but at least the (minimum) cut-in wind speed \( v_{\text{cut-in}} \) [m/s]. Due to the time-varying nature of the wind speed \( v_W(\cdot) \), the turbine output power will vary between zero and nominal power \( p_{T,\text{nom}} \) [W], i.e. \( 0 \leq p_T < p_{T,\text{nom}} \). The goal is to extract as much wind power as possible, i.e. maximum power point tracking (MPPT) which is achieved by an underlying speed controller (see Sec. 3.3.2).

1 Note that the factor is actually a function of several possibly changing parameters and states; e.g. \( \gamma = f(q, L^s, L^q, M, \psi, \psi') \) for an EESM, see (1). Commonly, various faults in electrical machines cause a decreased (average) torque [11].

2 Some companies use more sophisticated control methods for high winds, e.g. see patent [12] of REpower Systems for a reduced power production above \( v_{\text{cut-out}} \) instead of a shut down.
Figure 2: Operation regimes of a WTS:

- Regime I: Standstill (too less wind), i.e. \( p_T = 0 \),
- Regime II: Variable power, i.e. \( 0 \leq p_T < p_{T,\text{nom}} \) (Goal: Maximum power point tracking),
- Regime III: Nominal power, i.e. \( p_T = p_{T,\text{nom}} \),
- Regime IV: Standstill (too much wind), i.e. \( p_T = 0 \).

In regime III, the wind speed is at least the nominal wind speed but lower than the (maximum) cut-out wind speed \( v_{\text{cut-out}} \) [m/s], i.e. \( v_{\text{nom}} \leq v_W < v_{\text{cut-out}} \), and the torque \( m_T \) of the electrical machine is kept constant at its nominal value (by constant feedforward torque control and ideal pitch control, see Assumption (A.2)). The nominal output power is generated, i.e. \( p_T = p_{T,\text{nom}} \) (see Sec. 3.3.3).

3.2. Simplified wind turbine model (see [2], [10, Ch. 8] or [13])

The wind power is given by

\[
p_W(t) = \frac{1}{2} \rho \pi r_T^2 v_W(t)^3 \quad \text{[W]} \tag{7}
\]

with air density \( \rho \) [kg/m\(^3\)], turbine radius \( r_T \) [m], and wind speed \( v_W \). The extractable power can be approximated by introducing a power coefficient \( c_P(\lambda, \beta) \) [1] which is a function of the tip speed ratio \( \lambda := \frac{r_T \omega_T}{v_W} \) [1] (depending on turbine radius \( r_T \), turbine rotational speed \( \omega_T \) and wind speed \( v_W \)) and the pitch angle \( \beta \). The (mechanical) turbine power

\[
p_T(\lambda, \beta, v_W) = c_P(\lambda, \beta) p_W(t), \tag{8}
\]

is limited by the Betz limit with \( p_T(\lambda, \beta, v_W) \leq \frac{16}{27} p_W(t) \), see [14]. From turbine power (8), the turbine torque

\[
m_T(\lambda, \beta, \omega_T) = \frac{p_T(\lambda, \beta, v_W)}{\omega_T} \tag{7} \quad \begin{aligned}
&= \frac{1}{2} \rho \pi r_T^2 v_W^3 \frac{c_P(\lambda, \beta)}{\omega_T} \\
&= \frac{1}{2} \rho \pi r_T^2 \frac{c_P(\lambda, \beta)}{\lambda^3} \omega_T^2 \quad \text{[Nm]} \tag{9}
\end{aligned}
\]

can be approximated as function of the turbine rotational speed \( \omega_T \) [rad/s]. Note that (9) is only a reasonable model for positive wind speeds and angular speeds [15] (for \( \omega_T = 0 \), (9) gives a zero torque which is physically not reasonable).

For the drive train another assumption is imposed.

**Assumption (A.4)** The mechanical coupling in the shaft is stiff and the (ideal) gear box has gear ratio \( g_r \geq 1 \).

Considering Assumption (A.3) and Assumption (A.4), the simplified dynamics of the mechanical drive train of the wind turbine system can be modeled by [2], [9]

\[
\frac{d}{dt} \omega_M(t) = \frac{1}{\Theta} \left( \frac{m_T(\lambda, \beta, \omega_T)}{g_r} + m_M(t) \right) \tag{10}
\]

with machine angular velocity \( \omega_M = g_r \omega_T \) [rad/s], (total) inertia \( \Theta \) [kgm\(^2\)], turbine torque \( m_T \) and machine torque \( m_M \).

3.3. Wind turbine control methods for the different regimes

In the following the control methods for all four regimes (see Fig. 2) of the turbine are presented.
3.3.1. Regime I and IV: In regime I and IV, torque control is not active and no power is produced, i.e. \(p_T = 0\) W (see Sec. 3.1). Hence, an analysis of the impact of non-ideal torque control on the power production is not meaningful.

3.3.2. Regime II: We consider the MPPT strategy proposed in [10, Ch. 8] or [13] which ensures a tip speed ratio in the steady state (i.e. \(\lambda_{\text{opt}}\)) given by

\[
\lambda = \frac{\rho \pi r_5^5 \rho \pi r_3 \gamma}{g_r^2} \left( \frac{\lambda_{\text{opt}}}{\lambda_{\text{opt}}} \right)^3 \omega_M(t)^2, \quad k_p := \frac{1}{2} \frac{\rho \pi r_5^5}{g_r^3} \frac{c_P(\lambda_{\text{opt}}, \beta_{\text{opt}})}{(\lambda_{\text{opt}})^3}
\]

has been proposed (for details on stability of the closed-loop system dynamics, see [2], [10, Ch. 8] or [13]). Note that the closed-loop system (10), (11) reaches its equilibrium if and only if

\[
\forall t \geq 0: \quad m_M(t) = -\frac{m_T(\lambda(t), \beta(t), \omega_T(t))}{g_r}.
\]

Analyzing (10), (11) in steady state (i.e. \(\frac{d}{dt} \omega_M = 0\)) gives

\[
0 = \frac{m_T(\lambda, \beta, \omega_T)}{g_r} + m_M = \frac{m_T(\lambda, \beta, \omega_T)}{g_r} + \gamma m_M_{\text{ref}}(t) = \frac{1}{2} \frac{\rho \pi r_5^5}{g_r^3} \left( \frac{c_P(\lambda, \beta)}{\lambda^3} - \gamma \frac{c_P(\lambda_{\text{opt}}, \beta_{\text{opt}})}{(\lambda_{\text{opt}})^3} \right) \omega_M^2
\]

which shows, that for \(\lambda = \lambda_{\text{opt}}, \beta = \beta_{\text{opt}}, \text{ and } \gamma = 1\) (ideal torque control), the wind turbine system operates at its maximum power point (MPP, see Fig. 3), i.e. \((\lambda, c_P(\lambda, \beta)) = (\lambda_{\text{opt}}, c_{P,\text{opt}}) = (\lambda_{\gamma=1.0}, c_{P,\gamma=1.0})\).

Discussion of the impacts of non-ideal torque control What happens for non-ideal torque control, i.e. \(\gamma \neq 1\) in (13)? Clearly, assuming that the closed-loop system (10), (11) remains stable, it will not converge to the MPP. The impact of \(\gamma \neq 1\) on the power coefficient is illustrated in Fig. 3: For \(\gamma > 1\), the equilibrium is shifted to the left and, for \(\gamma < 1\), it is shifted to the right of the MPP. In general, the attained (steady state) tip speed ratio will differ from its optimal value, i.e. \(\lambda^* \neq \lambda_{\text{opt}}\), and, hence, the wind turbine operates with a reduced power coefficient, i.e. \(c_{P,\gamma \neq 1}^* < c_{P,\gamma=1.0}^*\) (see Fig. 3). A more detailed analysis of the dynamical behavior of the closed-loop system (10), (11) can be found in [2].

Concluding, for regime II and non-ideal torque control, the turbine power \(p_T\) is decreased and (in steady state) given by

\[
p_T = \frac{1}{2} \rho \pi r_T^2 c_{P,\gamma \neq 1}^* v_W^3 < \frac{1}{2} \rho \pi r_T^2 c_{P,\gamma=1.0}^* v_W^3.
\]

Remark 3.1. The presented state-of-the-art control strategy in regime II can also be extended by inertia compensation to achieve faster closed-loop system dynamics (see [10, Ch. 8]). However, this will not affect our analysis of the impact of non-ideal torque control on MPPT.
3.3.3. Regime III: In regime III, the control objective is to limit the extracted power to its rated value. The rotational machine speed $\omega_M = g_r \omega_T$ is limited to its nominal value $\omega_M,\text{nom} = g_r \omega_T,\text{nom}$ \text{[rad/s]} by adequate pitching of the turbine blades. Hence, the responsibility for speed control is now passed to the pitch control system, whereas the machine torque is kept constant at its rated value $m_M = m_M,\text{nom} = \frac{m_T,\text{nom}}{g_r}$. So, it ensures that the nominal power

$$p_{T,\text{nom}} = \omega_T,\text{nom} m_T,\text{nom} = \omega_M,\text{nom} m_M,\text{nom}$$

is extracted (see [10, Ch. 8]). Figure 4b illustrates the control strategy for regime III.

**Discussion of the impact of non-ideal torque control** What influence on the power production is to be expected for $\gamma \neq 1$? First note that, in steady state and in view of Assumption (A.2) (ideal pitch control system), the rotational speed is kept constant at its nominal value, i.e.

$$\omega_T = \omega_T,\text{nom} \iff \omega_M = \omega_M,\text{nom}. \tag{16}$$

Moreover, control strategy in regime III guarantees

$$m_{M,\text{ref}} = -m_{M,\text{nom}}, \tag{17}$$

which gives in steady state the following deviation from the nominal turbine power

$$p_T = \gamma p_{T,\text{nom}} = \omega_T,\text{nom} m_T,\text{nom} = -\gamma \omega_M,\text{nom} m_{M,\text{ref}} = \gamma \omega_M,\text{nom} m_M,\text{nom} \implies p_T = \gamma p_{T,\text{nom}}. \tag{18}$$
Remark 3.2. There exists also a slightly different approach to control the turbine power (see [10, Ch. 8]): The pitch controller still keeps the rotational speed at its nominal value. Due to the slow dynamics of the pitch control system, the actual rotational speed might differ from its nominal value. To keep the turbine power output constant at its nominal value, the reference machine torque $m_{M, ref}(t) = \frac{p_{T,nom}}{g \omega_{T,meas}(t)}$ is adjusted online based on the actual measurement of the turbine rotational speed $\omega_{T,meas} [\text{rad/s}]$. Nevertheless, this control method is also affected by non-ideal torque control.

3.4. Other control strategies
A few control strategies in the literature are able to overcome the problems of non-ideal torque control (although not explicitly addressing the problem). In [16], a torque observer for a permanent magnet synchronous generator is designed using current measurements. Another torque observer is proposed in [17] for condition monitoring. If exact knowledge of the power curve/coefficient of the turbine is available, deviations in turbine speed due to non-ideal torque control can be compensated for in region II (see [18]). Another option for region II is to use the measured or estimated value of the wind speed to compute and adjust the actual machine/turbine reference speed online (see [15, 19, 20]). In [21], the use of a turbine-mounted LIDAR system can improve the power output in regime II. In [22] a nonlinear torque controller for regime III is proposed which utilizes the actual value of the electrical output power and the rotational speed of the turbine. Most of the approaches are still sensitive to parameter uncertainties and variations. Next, we will discuss the impact of non-ideal torque control on the power output and the corresponding annual losses in the gross earnings for a turbine operator.

4. Simulation results
For the upcoming simulations, the variable-speed pitch-controlled 2 MW wind turbine system presented in [2] is considered. To compute the annual energy production of the wind turbine system, real one-year wind speed measurements with a time resolution of 10 min from FINO1 are used. System, controller and financial data are collected in Tab. 1.

4.1. Computation of annual power and energy
For the computation of the turbine power in regimes II and III, the steady state formulas (14) and (18) for the turbine power are evaluated. For regime I and IV, we set $p_T = 0$.

Hence, the generated energy in each operation regime $k \in \{I, II, III, IV\}$ can be computed for every 10 min by multiplying the respective turbine power $p_T$ with weighting factor $k^\alpha \in \{0, 1\}$ and time interval 600 s. A year can be divided into $n \in \{1, \ldots, 52560\}$ time intervals of $10 \text{min} = 600 \text{s}$ length each. Depending on the actual wind speed $v_W[n]$, turbine power $p_T[n]$ and energy $E_T[n] [\text{Wh}]$ are calculated for all $n \in \{1, \ldots, 52560\}$ as follows (iteration over all $n$):

- **Regime I** (if $0 \leq v_W[n] < v_{cut-in}$ then $k^I[n] = 1$, else $k^I[n] = 0$):
  $$P^I_T[n] = 0 \text{ W} \implies E^I_T[n] := p^I_T[n] \cdot k^I[n] \cdot 600 \text{ s} = 0 \text{ W h}; \quad (19)$$

- **Regime II** (if $v_{cut-in} \leq v_W[n] < v_{nom}$ then $k^{II}[n] = 1$, else $k^{II}[n] = 0$):
  $$p^{II}_T[n] = c_\rho \cdot c_{\alpha} \cdot \frac{1}{2} \rho \pi r_T^2 v_W[n]^3 \implies E^{II}_T[n] := p^{II}_T[n] \cdot k^{II}[n] \cdot 600 \text{ s}; \quad (20)$$

- **Regime III** (if $v_{nom} \leq v_W[n] < v_{cut-out}$ then $k^{III}[n] = 1$, else $k^{III}[n] = 0$):
  $$p^{III}_T = \gamma \cdot p_{T,nom} \implies E^{III}_T[n] := p^{III}_T \cdot k^{III}[n] \cdot 600 \text{ s}; \quad (21)$$

- **Regime IV** (if $v_{cut-out} \leq v_W[n]$ then $k^{IV}[n] = 1$, else $k^{IV}[n] = 0$):
  $$p^{IV}_T = 0 \text{ W} \implies E^{IV}_T[n] := p^{IV}_T \cdot k^{IV}[n] \cdot 600 \text{ s} = 0 \text{ W h}. \quad (22)$$
Table 1: System, controller and financial data.

| Description       | Symbols & values (with unit) |
|-------------------|-----------------------------|
| **System data**   |                             |
| rotor radius      | $r_T = 40 \text{ m}$       |
| air density       | $\rho = 1.293 \frac{\text{kg}}{\text{m}^3}$ |
| gear ratio        | $g_r = 1$                   |
| power coefficient | $c_p(\lambda, \beta) = c_{p,2}(\lambda, \beta)$ as in [2] |
| **Controller data** |                         |
| wind speed tresholds for regimes I, ..., IV | $v_{\text{cut-in}} = 4 \frac{\text{m}}{\text{s}}$, $v_{\text{nom}} = 11 \frac{\text{m}}{\text{s}}$, $v_{\text{cut-out}} = 25 \frac{\text{m}}{\text{s}}$ |
| power coefficient (computed numerically based on the WTS model in [2]) | $c_{p,\gamma=1.0} = 0.441$, $c_{p,\gamma=0.95} = 0.441$, $c_{p,\gamma=0.90} = 0.439$, $c_{p,\gamma=0.85} = 0.437$ |
| **Financial data** |                             |
| feed-in tariff    | $0.08 \frac{\text{€}}{\text{kWh}}$ |

The total (annual) energy production (in \[\text{Wh}\])

\[
E_T := \sum_{n=1}^{52560} E_T^I[n] + E_T^{II}[n] + E_T^{III}[n] + E_T^{IV}[n]
\]

is given by the sum of the energies of all regimes.

4.2. Discussion of the simulation results
The simulation results for ideal torque control (i.e. $\gamma = 1$) and non-ideal torque control ($\gamma \neq 1$) are shown in Fig. 5. All simulations are fed by the measured wind speed profile from FINO1. For non-ideal torque control, three different scenarios are investigated with three different deviation factors $\gamma \in \{0.95, 0.90, 0.85\}$.

The first subplot in Fig. 5a shows the measured wind speed over one year. The thresholds $v_{\text{cut-in}}, v_{\text{nom}}$ and $v_{\text{cut-out}}$ for the different operation regimes are marked by \ldots, \ldots, and \ldots, respectively. The resulting turbine power $p_T$ is shown in the second subplot. The third subplot depicts the evolution of the total energy $E_T$ over time. For decreasing values of the deviation factor $\gamma$, the impact of non-ideal torque control is more significant: turbine power and energy reduce more severely.

Figures 5b and 5c show the total energy\(^4\) and the corresponding revenue for a feed-in tariff of $0.08 \frac{\text{€}}{\text{kWh}}$, respectively. For $\gamma = 0.95$, the energy production is reduced by 0.293 GW h (or 3.2 %). For $\gamma = 0.85$, it is reduced by 0.909 GW h (or 10.0 %). The energy reductions correspond to annual earning losses of (i) 23 440 € for $\gamma = 0.95$, (ii) 48 080 € for $\gamma = 0.90$ and (iii) 72 720 € for $\gamma = 0.85$ (see also Tab. 2).

\(^3\) The wind data was measured at the research platform FINO1 (geographical coordinates: 54° 00’ 53.5” N, 06° 35’ 15.5” E) between 24th Nov. 2012 and 24th Nov. 2013. Mean values were saved with a 10 min resolution.

\(^4\) In view of Assumpt. (A.3), the turbine energy $E_T$ equals the produced electrical energy $E_{\text{elec}}$ [Wh] ($E_T = E_{\text{elec}}$).

Table 2: Comparison of earnings and losses.

| Earnings | Energy | Earnings | % |
|----------|--------|----------|---|
| losses $(\gamma = 1.00)$ | 9.122 GW h | 729 760 € | 100 % |
| losses $(\gamma = 0.95)$ | 0.293 GW h | 23 440 € | 3.2 % |
| losses $(\gamma = 0.90)$ | 0.601 GW h | 48 080 € | 6.6 % |
| losses $(\gamma = 0.85)$ | 0.909 GW h | 72 720 € | 10.0 % |
Figure 5: Comparative simulation results for ideal ($\gamma = 1.00$) and non-ideal ($\gamma \in \{0.95, 0.90, 0.85\}$) torque control.

Figure 6 illustrates the individual impacts of non-ideal torque control in regime II and III on the energy losses for the deviation factor $\gamma = 0.85$. The major share (i.e. 97% of the overall annual losses) of the total losses are due to the impacts of non-ideal torque control in regime III. Since the graph of the power coefficient is quite flat near the MPP (see Fig. 3), the impacts of non-ideal torque control in regime II are less significant. The losses in region II only account for 3% of the total losses.

Remark 4.1. For the simulations only values smaller than one, i.e. $\gamma < \gamma_{\text{max}} \leq 1$ were considered. Clearly, in regime III, a deviation factor of $\gamma > 1$ would result in a permanently higher power production than the rated power production. However, for this, the generator must apply a higher torque than the rated torque to the turbine which will cause damage to the wind turbine system (in particular, to the generator and/or the converter) and therefore will not remain undetected (e.g. temperature monitoring to guarantee the safety of the system). Whereas it is very unlikely that reduced power production will trigger protection systems.

5. Conclusion
It has been shown that non-ideal torque control is a problem and may (drastically) reduce energy production of wind turbine systems (if no counter measures are taken). For state-of-the-art wind turbine control systems, the impact of non-ideal torque control on the power production during
partial load (regime II) and full load (regime III) has been discussed. Exemplary simulations were performed for a variable-speed pitch-controlled 2 MW wind turbine system fed by a real wind speed profile (measured wind data over one year). The simulation results illustrate the possible earning losses depending on the deviations between actual and reference machine torque. Although, a few papers propose more sophisticated control methods that would not be affected by this problem, there is still not a completely satisfying solution at hand. Necessary steps to avoid non-ideal torque control are (i) condition monitoring, (ii) fault detection and identification, (iii) online parameter estimation and error/fault compensation and (iv) advanced control techniques (e.g. non-linear and/or adaptive methods).

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Prior work
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References
[1] Kost C, Mayer J N, Thomsen J, Hartmann N, Senkpiel C, Philippus S, Nold S, Lude S and Schlegl T 2013 Stromgestehungskosten Erneuerbarer Energien Tech. rep. Fraunhofer-Institut für Solare Energiesysteme
[2] Dirskerl C, Hackl C and Schechner K 2015 Elektrische Antriebe – Regelung von Antriebssystemen (Springer-Verlag) chap Modellierung und Regelung von modernen Windkraftanlagen: Eine Einführung, pp 1540–1614 4th ed
[3] Camblong H 2008 Control Engineering Practice 16 946–958
[4] Bianchi F D, De Battista H and Mantz R J 2006 Wind turbine control systems: principles, modelling and gain scheduling design (Springer)
[5] Odgaard P, Stoustrup J and Kinnaert M 2013 IEEE Transactions on Control Systems Technology 21 1168–1182
[6] Janssen K, Faulstich S, Hahn B, Hirsch J, Neuschäfer M, Pfaffel S, Rohrig K, Sack A, Schuldt L, Stark E and Zieble M 2015 Windenergiebericht Deutschland 2014 Tech. rep. Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES)
[7] De Doncker R, Pulle D W and Veltman A 2011 Advanced Electrical Drives Power Systems (Berlin: Springer)
[8] Schröder D 2015 Elektrische Antriebe - Regelung von Antriebssystemen 4th ed (Berlin Heidelberg: Springer)
[9] Dirskerl C and Hackl C M 2016 Dynamic power flow in wind turbine systems with doubly-fed induction generator Proceedings of the 2016 IEEE International Energy Conference
[10] Burton T, Sharpe D, Jenkins N and Bossanyi E 2011 Wind energy handbook 2nd ed (John Wiley & Sons)
[11] Nandi S, Toliyat H A and Li X 2005 IEEE Transactions on Energy Conversion 20 719–729 ISSN 0885-8969
[12] Schubert M 2006 Verfahren zur Regelung einer Windenergieanlage und Windenergieanlage mit einem Rotor
[13] Pao L Y and Johnson K E 2011 IEEE Control Systems Magazine 31 44–62
[14] Betz A 1926 [Ausg 1925] Wind-Energie und ihre Ausnutzung durch Windmühlen (Vandenhoeck & Ruprecht)
[15] Hackl C M 2015 Speed funnel control with disturbance observer for wind turbine systems with elastic shaft Proceedings of the 54th IEEE Conference on Decision and Control pp 2005–2012
[16] Corradini M, Ippoliti G and Orlando G 2013 IEEE Transactions on Control Systems Technology 21 1199–1206 ISSN 1063-6536
[17] Perišić N, Kirkegaard P H and Pedersen B J 2015 Wind Energy 18 1–19 ISSN 1099-1824
[18] Bossanyi E A 2000 Wind Energy 3 149–163 ISSN 1099-1824
[19] Magar K T, Balas M J and Frost S A 2015 Wind Energy ISSN 1099-1824
[20] Hackl C M 2014 Funnel control for wind turbine systems Proceedings of the 2014 IEEE International Conference on Control Applications pp 1377–1382
[21] Bossanyi E, Kumar A and Hugues-Salas O 2014 Wind turbine control applications of turbine-mounted lidar Journal of Physics: Conference Series vol 555 (IOP Publishing) p 012011
[22] Boukhezzar B, Lupu L, Sguerdidjane H and Hand M 2007 Renewable Energy 32 1273 – 1287 ISSN 0960-1481