2

Wind Turbine Control

2.1 Wind Turbine Baseline Controller

This section presents a conventional wind turbine controller for the entire operating range. The controlled elements considered are the *Generator Torque* T_g applied to the high speed shaft of the turbine and the *Pitch Angle* β, that alters the aerodynamic torque from the wind acting on the low speed shaft of the drive train. The presented controller is based on the descriptions given in [2].

A general overview of the generator torque as a function of the generator speed is depicted in Fig. 2.1. It should be noted that in contrast to the explanations in [2], the control design is presented here in normalized form, thus independent of the rated generator torque $T_{g,rated}$ and the rated generator speed $\omega_{g,rated}$. For that reason, Tab. 2.1 gives the rated values for the wind turbine defined in [2] that are used for the normalization.

Table 2.1: Rated Values of the 5MW Wind Turbine

Symbol	Value	Unit
$\omega_{r,rated}$	$12.1 \cdot \pi/30 = 1.2671$	$\frac{rad}{s}$
$\omega_{g,rated}$	$12.1 \cdot n_g \cdot \pi/30 = 122.9096$	$\frac{rad}{s}$
$T_{g,rated}$	$4.30935 \cdot 10^4$	Nm
P_{rated}	$5.296610 \cdot 10^6$	W

The controlled operation of the wind turbine can usually be divided into different regions. If the turbine operates in Regions 1, 1.5, 2 and 2.5 (cf. Fig. 2.1), the wind turbine is said to be operated in *Partial Load Region*, implying that the generated power is below the rated power of the wind turbine. If the power provided by the wind exceeds the rated wind speed v_{rated} and thus the rated power of the turbine, the power production needs to be limited. This region will be called *Full Load Region* or Region 3, cf. Fig. 2.1.

Depending on the region of the wind turbine, the control objectives vary. Whereas in partial load region the optimisation of the energy extraction from the wind is the main objective, in the full load region the energy extraction is limited to the rated power of the turbine. For the achievement of these purposes different actuators are employed. The energy optimisation in the partial load region is conducted by a variation of the applied generator torque as a

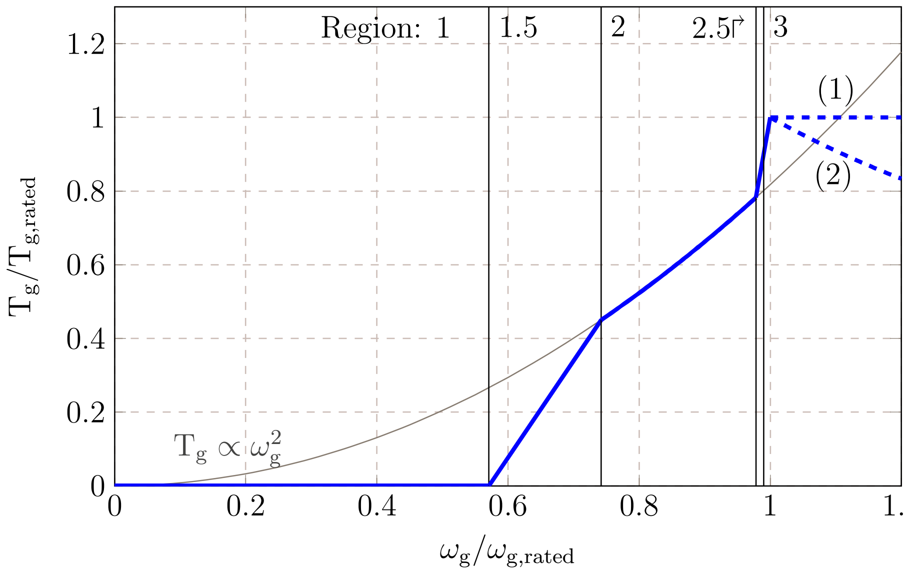


Figure 2.1: Generator Torque T_g as a Function of the Generator Speed ω_g

function of the current generator speed, i.e. $\mathrm{T_g} = f(\omega_\mathrm{g})$, whereas for the power limitation in Region 3 the pitch actuator of the wind turbine is used. The different control strategies for the regions are illustrated in the subsequent sections in more detail.

Since the generator torque is kept at $\mathrm{T_g} = 0\,\mathrm{Nm}$ while the turbine is operated in region 1 until the the generator speed reaches $\omega_\mathrm{g} = \omega_\mathrm{g,SP,1.5}$ and the desired ptich angle $\beta_\mathrm{d} = 0\,\mathrm{deg}$ remains *constant* in the entire partial load region, no section is devoted to region 1. Moreover, for each of the considered regions in the following, in the beginning of the section a table is given with the lower and upper bound of the generator speed and the corresponding generator torque in this operating point of the wind turbine.

2.1.1 Region 1.5

	Lower Bound	Upper Bound
ω_g	$\omega_\mathrm{g,SP,1.5}$ $= 0.5708$	$\omega_\mathrm{g,SP,2}$ $= 0.7421$
$\mathrm{T_g}(\omega_\mathrm{g})$	0	0.4503

Region 1.5 is considered a start-up region, such that the torque is linearly increased to the generator torque resulting from the optimal quadratic generator torque characteristic curve denoted as $\mathrm{T_g} \propto \omega_\mathrm{g}^2$ in Fig. 2.1, which will be considered in Sec. 2.1.2. Respecting the linear relation of the generator torque to the generator speed leads to a slope of

$$\mathrm{m}_{\mathrm{T_g},1.5} = \frac{\mathrm{T_g}(\omega_\mathrm{g,SP,2})}{\omega_\mathrm{g,SP,2} - \omega_\mathrm{g,SP,1.5}} \tag{2.1}$$

and consequently the generator torque while operation in this region is computed as

$$\mathrm{T_g}(\omega_\mathrm{g}) = \mathrm{m}_{\mathrm{T_g},1.5} \cdot \left(\omega_\mathrm{g} - \omega_\mathrm{g,SP,1.5}\right) . \tag{2.2}$$

2.1.2 Region 2

	Lower Bound	Upper Bound
ω_g	$\omega_{g,SP,2} = 0.7421$	$\omega_{g,SP,2.5} = 0.9782$
$T_g(\omega_g)$	0.4503	0.7823

Region 2 is devoted to the optimisation of the power extraction of the wind turbine. The quadratic law for the generator torque dependency on the generator speed is based on the aerodynamic characteristics of the wind turbine. For that reason the dependency of the power coefficient c_p with respect to the tip-speed ratio λ for a fixed pitch angle of $\beta = 0\,\text{deg}$ is depicted in Fig. 2.2a, since the objective in this region is power optimisation. As can be seen from the curve, there exists a tip-speed ratio λ_{opt} where the power coefficient reaches its maximum value. The tip-speed ratio is defined as

$$\lambda = \frac{\omega_r \cdot R}{v} \tag{2.3}$$

and thus for every wind speed v there exists a rotational speed $\omega_{r,opt}$, which results in an optimal tip-speed ratio λ_{opt}.

In fact, from the power extraction laws of the wind turbine rotor P_r, the aerodynamic torque T_a of the wind turbine can be described by [1]

$$\frac{P_r}{\omega_r} = T_a = \frac{1}{2}\rho\pi R^2 c_p(\lambda)\frac{v^3}{\omega_r} \ ,$$

which can be extended by R^3/R^3 and ω_r^2/ω_r^2, such that

$$T_a = \frac{1}{2}\rho\pi R^5 \frac{c_p(\lambda)}{\lambda^3}\omega_r^2 \tag{2.4}$$

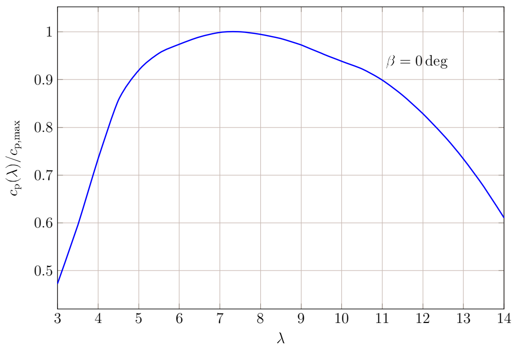
is formed. Note that in (2.4) the dependence of the aerodynamic torque to the wind speed is captured inside the tip-speed ratio. Since in steady state the aerodynamic torque equals the torque resulting from the generator $T_a = n_g T_g$ and the rotational speed can be described employing the generator speed $\omega_r = \frac{\omega_g}{n_g}$ by assuming a stiff drive train, the demanded generator torque is expressed by

$$T_g(\omega_g) = \underbrace{\frac{1}{2}\rho\pi R^5 \frac{c_p(\lambda_{opt})}{n_g \lambda_{opt}^3}}_{K_{opt}} \cdot \omega_g^2 \ , \tag{2.5}$$

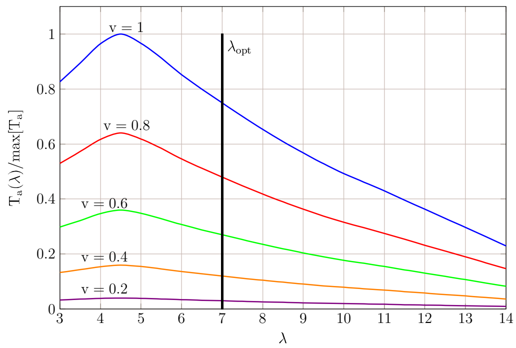
where K_{opt} is a constant defined by the optimal tip-speed ratio, the aerodynamics represented by c_p and the rotor radius. The quadratic control law given by (2.5) is denoted as $T_g \propto \omega_g^2$ in Fig. 2.1. For the 5 MW wind turbine defined in [2], a $K_{opt} = 0.025\,576\,4\,\text{Nm/rpm}^2$ is derived by the presented scheme resulting in (2.5). In a normalized form the corresponding gain for the $T_g \propto \omega_g^2$ control law is calculated by

$$k_{opt} = K_{opt}\frac{(\omega_{g,rated} \cdot 30/\pi)^2}{T_{g,rated}} \ . \tag{2.6}$$

Fortunately, the characteristics of the wind turbine cause that the obtained operating points



(a) Normalized Power Coefficient c_p as Function of the Tip-Speed Ratio λ at a fixed pitch angle $\beta = 0\,\mathrm{deg}$



(b) Normalized Aerodynamic Torque T_a as Function of the Tip-Speed Ratio λ; v also normalized

Figure 2.2: Aerodynamic Properties of the Wind Turbine with Respect to the Derivation of the quadratic optimal Control Law

given by (2.5) are stable equilibria of the system. This can be illustrated by employing Fig. 2.2b, where the aerodynamic torque is depicted as a function of the tip-speed ratio for different wind speeds and the operating points are denoted by λ_{opt}. Assuming that the turbine is in an optimal steady state operation, i.e. at $\lambda = \lambda_{opt}$, a sudden increase of the wind speed will result in an increase of the aerodynamic torque, since the tip-speed ratio for higher wind speeds decreases for constant generator speeds, cf. (2.3). An increased aerodynamic torque would result in an acceleration of the drive train and therefore an increase of the generator torque according to (2.5) until λ_{opt} is attained again. The same argumentation holds for a sudden decrease in wind speed, resulting in an overall stable operation of the wind turbine in region 2.

2.1.3 Region 2.5

	Lower Bound	Upper Bound
ω_g	$\omega_{g,SP,2.5} = 0.9782$	$\omega_{g,SP,3} = 0.99$
$T_g(\omega_g)$	0.7823	0.9

Region 2.5 is a transitional regime, that connects the full load region 3 to the quadratic optimal control law in region 2. As can be seen from Fig. 2.1, the $T_g \propto \omega_g$ control law reaches the rated generator torque $T_{g,rated}$ at ≈ 1.1 of the generator speed, and thus to obtain the rated turbine power at the rated generator speed, the generator torque needs to be transferred to its rated value faster than given by the $T_{g,rated} \propto \omega_g$ control law. For that reason the generator torque is controlled, such that the characteristics resemble a generator, which is operated at the synchronous speed of $0.9 \cdot \omega_{g,rated}$ and reaches its rated torque at a generator-slip percentage of 10 % [2]. As a consequence, the rated generator torque $T_{g,rated}$ is attained at the rated generator speed $\omega_{g,rated}$. This characteristic of the generator torque with respect to the synchronous speed $0.9 \cdot \omega_{g,rated}$ is depicted as the red dashed line in Fig. 2.3. Consequently, the corresponding

normalized slope of the of the torque controller is derived by

$$m_{T_{g,2.5}} = \frac{T_{g,0}}{\omega_{g,0} - 0.9 \cdot \omega_{g,0}} = \frac{1}{0.1} \; . \tag{2.7}$$

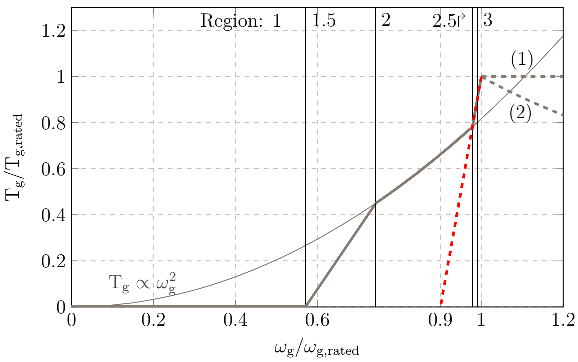


Figure 2.3: Generator Slope in Region 2.5

As a result, the torque in region 2.5 follows a linear relation based on

$$T_g(\omega_g) = m_{T_{g,2.5}}\omega_g + T_{g,aux} \; , \tag{2.8}$$

where $T_{g,aux}$ is an auxiliary constant to define the linear equation and can be calculated from any operating point on the slope of the generator torque in region 2.5.

To derive a lower bound $\omega_{g,SP,2.5}$ of this region and avoiding sudden changes of the generator torque, the intersection of the $T_g \propto \omega_g$ control law in region 2 and the linear torque relation in region 2.5 is calculated. Since this yields a quadratic equation, the obtained solution inside of the operating range of the wind turbine is given by

$$\omega_{g,SP,2.5} = \frac{m_{T_{g,2.5}}}{2 \cdot k_{opt}} - \sqrt{(\frac{m_{T_{g,2.5}}}{2 \cdot k_{opt}})^2 + \frac{1}{k_{opt}} \cdot T_{g,aux}} \tag{2.9}$$

as the set-point for region 2.5.

2.1.4 Region 3

	Lower Bound	Upper Bound
ω_g	$\omega_{g,SP,3}$ $= 0.99$	
$T_g(\omega_g \leq 1)$	0.9	Eq. (2.8)
$T_g(\omega_g > 1)$		(1) $T_{g,rated}$ (2) Pr/ω_g

The transfer from region 2→3 based on the generator speed ω_g is conducted slightly before the rated generator speed is reached. This strategy aims at an increased smoothness in the transition area with regards to the loads acting on the structural dynamics. For that reason the torque needs to be adjusted to reach its rated value based on (2.8). In case of a further increase of the generator speed above its rated value $\omega_g > \omega_{g,rated}$, different strategies can be employed. In Fig. 2.1 a constant torque at its rated value, i.e. $T_g = T_{g,rated}$, is illustrated as (1). However, there exist approaches that vary the generator torque as a result of an increased generator speed, such that the power is kept constant and $P = \omega_g \cdot T_g$ is fulfilled. This strategy is denoted as (2) in Fig. 2.1.

Region 3 differs from the aforementioned regimes. Whereas in the regions before the objective of the control scheme is striving for power optimization, in the full load region 3 the wind turbine is desired to be operated at rated power Pr. This results from wind speeds exceeding the rated wind speed v_r and thus a power generation above the rated wind turbine power. As overloading of the structural and electrical components of the wind turbine needs be circumvented, in this region a reduced excitation of the turbine by the wind is enforced. For that reason in variable-pitch wind turbines the pitch angle is adjusted to alter the aerodynamic torque acting on the rotor of the wind turbine. However, the aerodynamics, e.g. represented by the power coefficient c_p in Fig. 2.2, are highly nonlinear with respect to the pitch angle β, rotor speed ω_r and wind v.

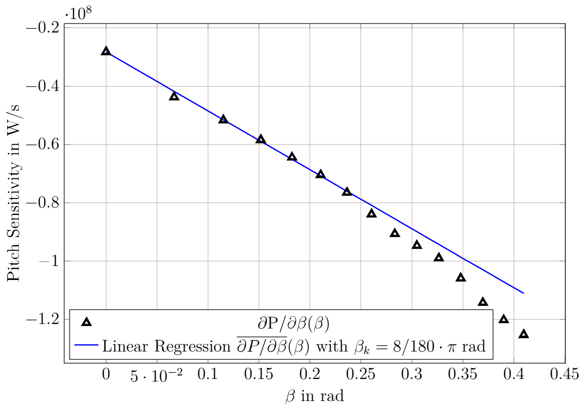


Figure 2.4: Pitch Sensitivity as Function of the Pitch Angle, based on [2]

In Fig. 2.4 the power sensitivity as a function of a change in the pitch angle β around its steady state operating point, i.e. $\Delta\beta = \beta - \beta_{OP}$, is illustrated. As can be seen, the power sensitivity varies significantly over the operating range. For that reason in [2] a gain scheduling technique is proposed, which takes the varying sensitivity into account. It is based on a wind turbine description in a feedback loop, where the generator speed is controlled to remain at the rated value by a PI controller. After linearisation of a nonlinear model for the rotational dynamics of the wind turbine and assuming that a variation of the rotational speed around its rated value can be neglected, the proposed closed-loop system description results in a second order system. By the definition of the desired dynamic characteristics of the second order closed-loop system given by the natural frequency ω_n and damping ratio ζ, the control gains for the PI controller can be calculated to

$$K_p(\partial P/\partial\beta(\beta)) = 2k\frac{\zeta \cdot \omega_n}{-\partial P/\partial\beta(\beta)} \tag{2.10}$$

$$K_I(\partial P/\partial\beta(\beta)) = k\frac{\omega_n^2}{-\partial P/\partial\beta(\beta)} , \tag{2.11}$$

where k is a constant depending on the wind turbine mechanics. To account for this varying sensitivity, a linear regression is proposed as

$$\overline{\partial P/\partial\beta}(\beta) = \frac{\partial P/\partial\beta(\beta = 0)}{\beta_k}\beta + \partial P/\partial\beta(\beta = 0) , \tag{2.12}$$

which is also depicted in Fig. 2.4. The angle β_k is chosen such that the sensitivity doubles compared to the initial pitch sensitivity, i.e. $\partial P/\partial\beta(\beta_k) = 2\partial P/\partial\beta(\beta = 0)$. Inserting (2.12) in (2.10) and (2.11) for the power sensitivity coefficients yields the scheduling law for the pitch dependent PI controller gains

$$\mathrm{K_p}(\beta) = 2\mathrm{k}\frac{\zeta \cdot \omega_\mathrm{n}}{-\partial P/\partial\beta(\beta = 0)} \cdot \frac{1}{1 + \beta/\beta_\mathrm{k}} \tag{2.13}$$

$$\mathrm{K_I}(\beta) = \mathrm{k}\frac{\omega_\mathrm{n}^2}{-\partial P/\partial\beta(\beta = 0)} \cdot \frac{1}{1 + \beta/\beta_\mathrm{k}} \ . \tag{2.14}$$

As a result, the desired pitch angle variation is derived as

$$\Delta\beta = \mathrm{K_p}(\beta)(\omega_\mathrm{g} - \omega_\mathrm{g,rated}) + \mathrm{K_I}(\beta)\int(\omega_\mathrm{g} - \omega_\mathrm{g,rated}) \ . \tag{2.15}$$

Bibliography

[1] Robert Gasch and Jochen Twele. *Wind Power Plants: Fundamentals, Design, Contruction and Operation*. Springer-Verlag Berlin Heidelberg, 2012.

[2] J. Jonkman, S. Butterfield, W. Musial, and G. Scott. Definition of a 5-MW Reference Wind Turbine for Offshore System Development. Technical Report NREL/TP-500-38060, National Renewable Energy Laboratory, 2009.