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2 Controller design objectives

2.1 Advanced Controller

Wind turbine use closed-loop control (maximum energy capture over normal operation and less structural load) systems to continuously adjust their operations based on feedback. Figure 1, illustrates the advanced closed-loop control diagram of a wind turbine.

The torque controller optimizes power production below rated speed and maintain rated power above rated wind speed by adjusting generator torque (M_G) based on generator speed (Ω_G). Advance torque control uses a PI controller with anti-windup to regulate the generator torque based on the difference between the actual and reference generator speeds. Above rated wind speed, Pitch controller maintains the rated generator speed $(\Omega_{G,rated})$ by adjusting blade pitch angle (θ), which ensures the rated power is maintained. With increasing wind speed, the pitch angle increases to reduce power coefficient (c_p). Once the wind speed reaches the rated value, the generator torque is maintained at its rated value. The control is categorized into different regions, as detailed in Section 2.2.

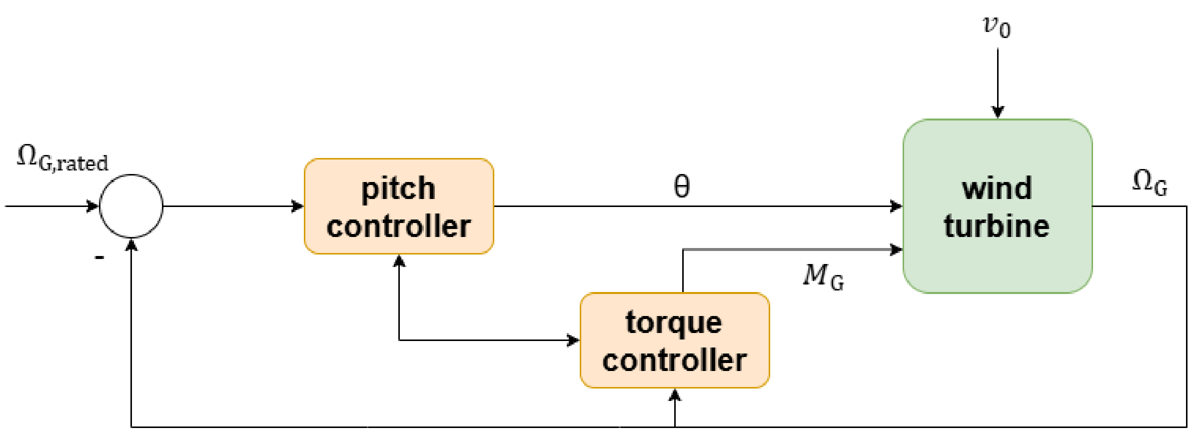

Figure 2.1 Advance Wind Turbine Controller

2.2 Control Regions

Wind turbine operations are segmented into three primary regions based on varying wind speed. These regions are defined by the turbine power output relative to wind speed. These regions are detailed below and illustrated in Figure 2.

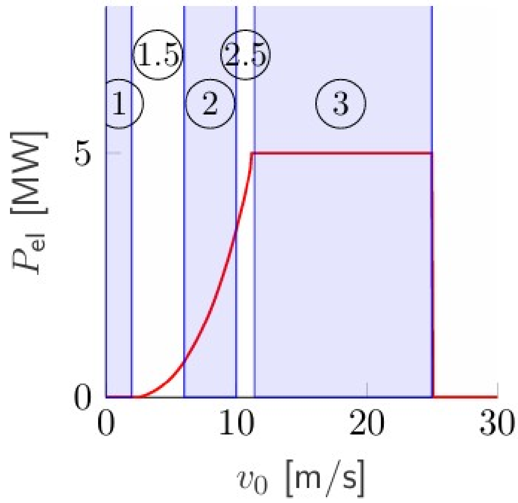

Figure 2.2 Wind turbine control regions

Region 1: When the wind speed is below the cut-in speed (v_{in}), the turbine does not generate any power and remains stationary.

Region 1.5: This phase indicates the shift to Region2, where wind speeds are sufficient to accelerate rotor. The generator torque is Carefully controlled to accelerate the transition to Region 2. While energy production has started, the power output remains relatively low. The goal is to quickly reach Region 2, where the turbine can operate more efficiently.

Region 2: Wind speeds are above the cut-in speed (v_{in}) but below the rated wind speed (v_{rated}). The primary objective is to maximize energy yield. To achieve this, the turbine operator at the optimal power coefficient $(c_{P,opt})$, which is determined by reaching the optimal tip seed ratio (λ_{opt}) and pitch angle (θ_{opt}). The control system ensures that the turbine maintains these optimal conditions by regulating the rotational speed through the torque controller. In this region, the generator torque is adjusted based on rotor speed, as shown in Equation 2.1.

$$M_G = \frac{1}{2}\rho R^5 \frac{P, opt}{\lambda_{opt}^3 r_{GB}^3} \Omega_G^2 \tag{2.1}$$

$$M_G = k\Omega_G^2 \tag{2.2}$$

Region 2.5: This phase represents a transition between Region 2 and Region 3. In this region, the wind speed is increasing, and the turbine is approaching its rated wind speed. The control system continues to optimize the generator torque to ensure a smooth transition. Energy production is higher compared to Region 2, but the turbine has not yet reached its maximum power output. The pitch controller begins to act to keep the thrust on the rotor as low as possible while aiming to reach the rated speed as quickly as possible.

Region 3: In this region, wind speeds have reached the rated wind speed, and the primary goal is to generate maximum power. The control goal is maintain rated power and generator speed as well as reduce structure loads. The torque controller maintains the generator torque at its rated value. The pitch controller actively adjusts the blade pitch angle to regulate the power and keep it within the turbine rated capacity.

2.3 Advanced Generator Torque controller

Generator torque is one of the two main control inputs for a wind turbine. The performance of an advanced generator torque controller offers significant improvements and greater flexibility compared to a baseline torque controller. The primary goals of the advanced torque controller are to reach the optimal power curve earlier and to maintain it for a longer duration compared to the baseline controller. Additionally, the dynamics in Regions 1.5 and 2.5 are tunable, allowing for more precise control.

Goals of the advanced torque controller:

- Achieve the optimal power curve earlier.
- Maintain the optimal power curve for a longer period.
- Enable tunable dynamics in Regions 1.5 and 2.5.

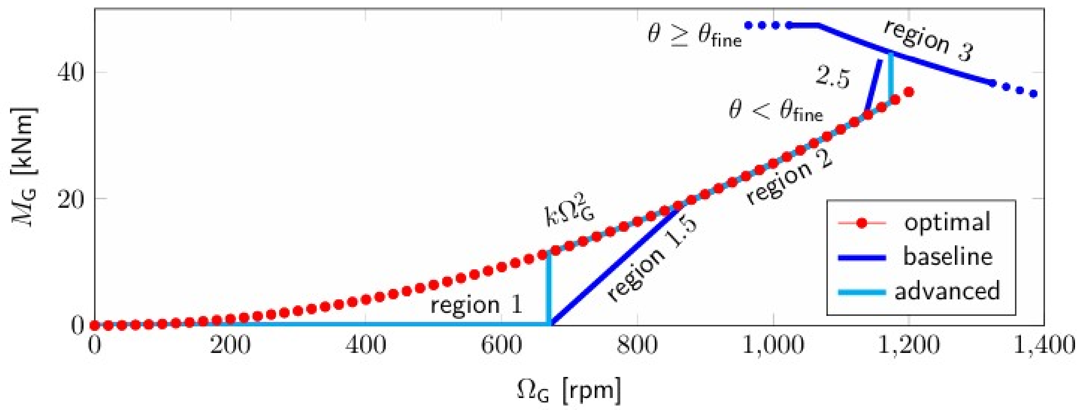

Figure 2.3 Wind turbine control regions

Strategy for the Advanced Torque Controller:

Region 1.5: Lowest generator speed $\Omega_{G,1.5}$ to avoid the 3P frequency interacting with the tower's eigenfrequency. Torque PI controller used for fine-tuning.

Region 2.5: Generator speed $\Omega_{G,2.5}$ = $\Omega_{G,rated}$. Switch from $\Omega_{G,1.5}$ to $\Omega_{G,2.5}$ if the measured generator speed Ω_G exceeds

$$\Omega_{G,R2switch} = \frac{1}{2}(\Omega_{G,1.5} + \Omega_{G,2.5}) \tag{2.3}$$

Torque Limits:

The generator torque limits are determined by the measured generator speed Ω_G and incorporate Anti-Windup mechanisms.

- if Ω_G < $\Omega_{G,R2switch}$:

$$M_{G,lb} = 0 \tag{2.4}$$

$$M_{G,ub} = k\Omega_G^2 \tag{2.5}$$

- if Ω_G > $\Omega_{G,R2switch}$:

$$M_{G,lb} = k\Omega_G^2 \tag{2.6}$$

$$M_{G,\text{ub}} = \min\left(M_{G,\text{rated}}\frac{\Omega_{G,\text{rated}}}{\Omega_G}, M_{G,\text{max}}\right) \tag{2.7}$$

Region 2: The controller aims to maximize energy yield while ensuring the turbine operates efficiently.

Region 3: The torque controller maintains the generator torque at the rated value to protect the turbine from excessive mechanical stress due to high wind speeds.

2.4 Collective Pitch Controller (CPC) (Julius)

Collective pitch control (CPC) adjusts the pitch for all 3 blades similarly. The pitch control behavior has a high impact on the structural loads therefor on the life time of the wind turbine and thus on costs. CPC can be implemented with a standard PI-Controller. Main task of the CPC is to make the rotor area more permeable for the wind in order to reduce the power coefficient. This is done by pitching the rotor blades in a less advantageous aerodynamic position. With increasing wind speed the power output increases as well as the loads. In order to keep the loads within an acceptable limit the power output of the wind turbine must be limited.

The pitch controller is only active in region 3, when the wind speed is above the rated wind speed as described in figure 2.2. In region 3 the pitch controller maintains rated speed and the generator torque controller rated torque. In the OPTIMUS Shakti wind turbine a gain scheduled PI controller is used to control the rotor speed.

The concept of gain scheduling is widely used and a common feature in blade pitch controllers. With the use of gain scheduling the parameter of the controller are changed based on the operating point of the system.

2.5 Tower Damper Felix

3 Further Things

3.1 Wind Field Generation Felix

3.2 Simple Storage System Dummy (Julius)

In order to assist the storage development team in the beginning of the project phase a simple energy storage system dummy was developed and integrated into the used IEA Wind Task 37 $3.4\,\mathrm{MW}$ reference wind turbine Simulink model (figure 3.1). The further development of the storage model was executed by the storage team.

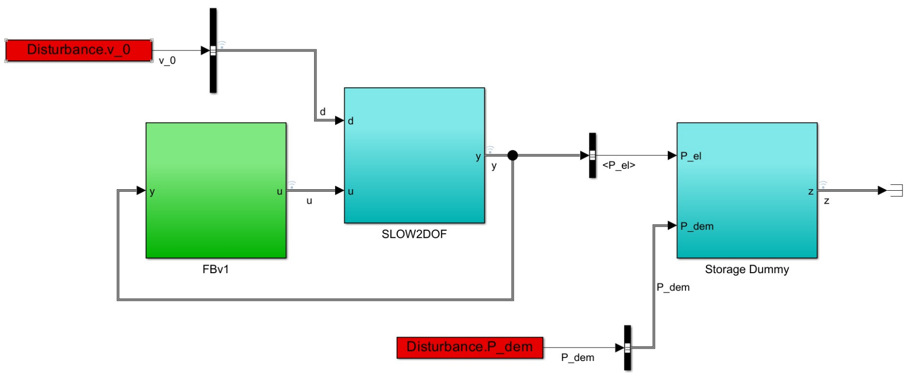

Figure 3.1 Storage dummy in Simulink model

3.2.1 Description

The storage system dummy was realized by a simple battery management system (BMS) in combination with a integrator block. The BMS is capable to simulate the storage in 3 states *standby*, *charge* and *discharge*.

3.2.2 Scenarios

In order to explore different possibilities in which the storage system could be applied multiple scenarios where implemented into the simulation model. A curtailment event as described in scenario 5 is shown in figure 3.2.

1. **No grid power demand:** The storage system is in working condition. The storage system is not at full capacity. There is no power in feed into the grid. The storage is getting charged.

2. **Rated power demand from grid:** The storage system is in working condition. There is rated power feed into the grid. The storage is not getting charged.
3. **50 % of rated power demand from grid:** The storage system is in working condition. The storage system is not at full capacity. There is a power demand from the grid of $50\,\%$ of rated power. The storage is getting charged with a reduced rate of charge.
4. **Turbine operated below rated power, grid demand is exceeding production:** The storage system is in working condition. The storage is charged to $50\,\%$ of its maximum capacity. The WT is operating below rated power and the grid demand is higher than the power production of the WT. The storage system is getting discharged.
5. **Curtailment scenario of 4h in 25h period:** The storage system is in working condition. The storage system is not at full capacity. The WT is operating at rated power. The power must be reduced for a certain amount of time because of a curtailment order from the grid operator. The storage system is getting charged.

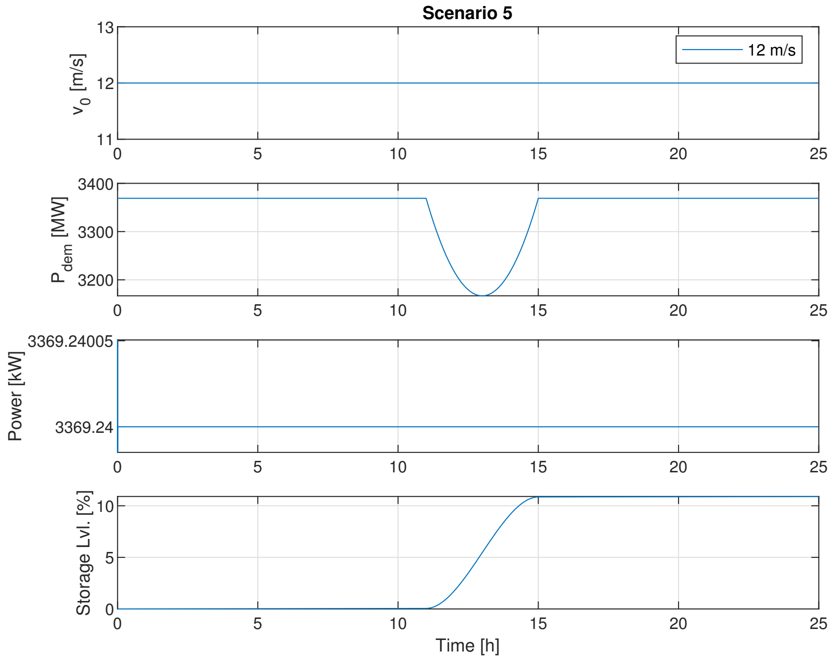

Figure 3.2 Curtailment scenario for 4h duration, a storage capacity of $5\,\mathrm{MWh}$ and a curtailment rate of $6\,\%$.

3.3 Tower Bending Stiffness (Julius)

For the implementation of the tower damper in the SLOW model the tower equivalent bending stiffness k_{Te} and the initial tower top deflection X_{T0} is needed. With OpenFAST the steady states calculations (section 4.1) with a wind speed range from $3\,\mathrm{m/s}$ to $9\,\mathrm{m/s}$ are done. The bending stiffness of the tower can be calculated with:

$$k_{\mathrm{Te}} = \frac{F_{\mathrm{a}}}{X_{\mathrm{T}} - X_{\mathrm{T0}}} \tag{3.1}$$

Where F_a is the aerodynamic thrust force onto the rotor plane and X_T the deflection of the tower top. The initial tower top deflection X_{T0} is determined from the calculated steady states via a polyfit of the curve to get the deflection of the tower at $F_\mathsf{a} = 0\,\mathrm{N}$. With 3.1 the bending stiffness in every steady state is determined and averaged over the number of points. This leads to an tower equivalent bending stiffness of $k_{\mathsf{Te}} = 2.185\,\mathrm{MN/m}$ and a initial tower top deflection of $X_{\mathsf{T0}} = -0.021\,\mathrm{m}$.

3.4 Peak shaving idea

Put it maybe also in since we did show a plot with it?

4 Controller tuning

4.1 Steady States

4.2 DEL calculation thetaK Felix

4.3 Minimum Pitch Angle Optimization (Julius)

The optimization of the minimum pitch angle is a simple adjustment which leads to a small increase in the AEP. The optimization was done with a brute force approach and the steady states calculations (Section 4.1). In control region 2 the WT should work at optimum Cp and λ. The use of minimum pitch angle can lead to an more efficient state of the turbine at the start of region 2 and therefor increase the AEP. For different pitch angles the steady states where calculated. As optimum, min. pitch angle the angle which leads to the highest Cp was chosen. As a result the min. pitch angle of $0.5°$ was determined and is shown in figure 4.1. During the calculation the pitch angle was optimized in a range of $0°$ to $5°$ with a step size of $0.1°$.

The determined min. pitch angle of $0.5°$ leads to an increase in AEP of $0.29\,\%$ compared to min. pitch angle of $0°$. (Calculated with Weibull parameters of TC III and $k = 2$.)

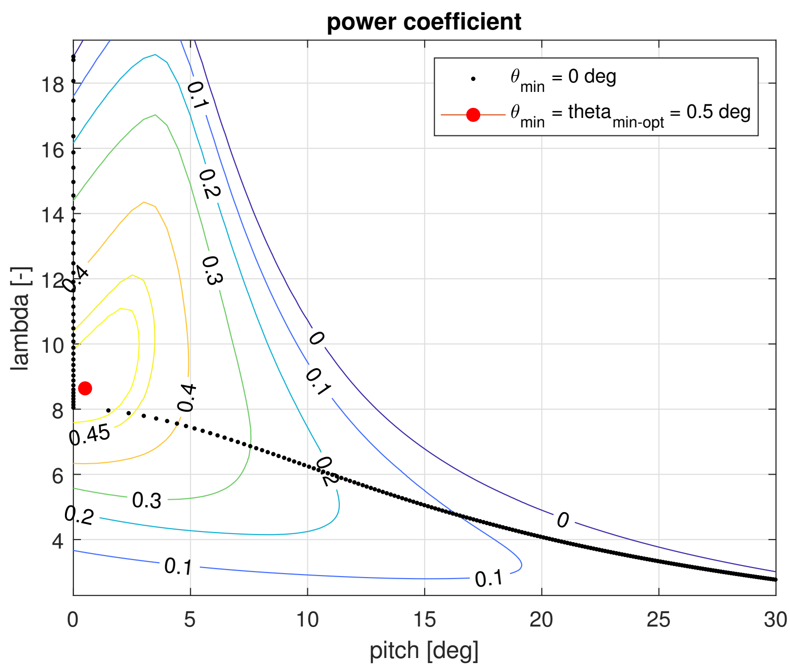

Figure 4.1 brute force optimization for minimum pitch angle θ

4.4 Minimum Pitch Angle Optimization for Region 1.5 (Julius)

Since the control region 1.5 has a large wind speed range of $3.28\,\mathrm{m/s}$ the optimization of the pitch angle could lead to an increase in AEP. As optimization process a brute force approach was used in order to find the optimum pitch angle for every operating wind speed in region 1.5. During the calculation the pitch angle was optimized in a range of $0°$ to $5°$ with a step size of $0.1°$. The results of the optimization can be seen in figure 4.2. The result shows, that keeping a static pitch angle through region 1.5 is not leading to the optimal power production. A calculation of the AEP with a dynamic pitch adjustment for region 1.5 leads to an increase of $0.19\,\%$ compared to a static minimum pitch angle of $0.5°$ as shown in section 4.3. (Calculated with Weibull parameters of TC III and $k = 2$.) Since the calculation is done without transition regions for the adjustment of the pitch the increase in AEP after implementation of the control behavior is to be expected less than the named $0.19\,\%$. The approach of changing the pitch angle dynamically in region 1.5 was not implemented in the OPTIMUS Shakti project but could be interesting for further optimization of the developed WT.

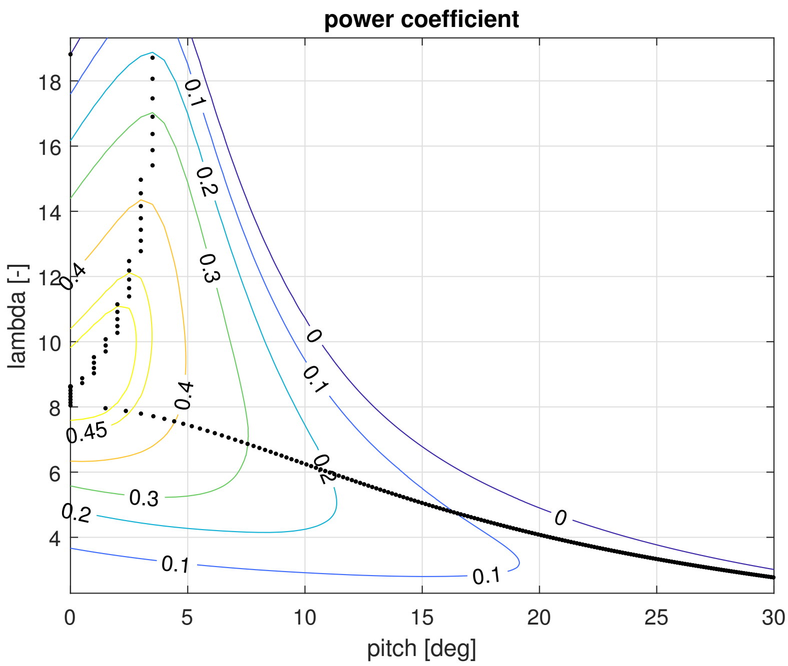

Figure 4.2 brute force optimization for minimum pitch angle θ in region 1.5

5 Challenges and Teamwork

5.1 Generator speed and Region 2.5

5.2 Rated wind speed

5.3 Aerodynamics in FAST

6 Summary

6.1 Conclusion

7 Appendix