Response to Reviewers

Evaluation of different power tracking operating strategies considering turbine loading and power dynamics

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First of all, thank you for taking the time to review our manuscript and provide valuable feedback. Your constructive remarks certainly helped us to improve our manuscript.

In general, three major changes have been made. First, the simulation studies covering the consequences for the turbine loading in different operating strategies was widely extended to cover several power demand setpoints and operation at nominal power trajectories. Secondly, the literature suggested by the reviewers was introduced into the manuscript, where the differences to the proposed approach are discussed and the resulting loading was compared to the existing literature. Finally, a more detailed description of the applied control approach is given to enhance comprehensibility for the reader. Please find the detailed response to your remarks in the following.

Note that the line numbers in this response correspond to the marked-up manuscript indicating the changes made. For your convenience, we highlighted adjustments either with red if removed or blue if altered/added in the document.

I. RESPONSE TO REVIEWER 1

1) The paper presents two derating/active power control strategies and their performance in terms of loads and power tracking. Moreover, the authors modelled the turbine power response by using transfer functions which can be easily used for wind farm control design. The topic is very interesting and highly relevant for the readers who are interested in wind turbine and farm control. However, I found the structure of the paper is not well-organised and the contribution of the paper is not clearly highlighted. As mentioned by the authors, similar derating strategies were also proposed by (Aho et al. 2016) with studies of the loads. Can the authors highlight the key novelty of this paper?

Thank you for this encouraging comment and the detailed review. Different derating strategies have been proposed and discussed in the literature, where most of the approaches use an augmented version the usually applied gain-scheduled PI controller. As the turbine is a nonlinear system, the dynamics vary depending on the current operating point. The power derating of the turbine results in different operating points compared to the nominal operating trajectories, and, as a result, a straighforward application of the gain-scheduled control scheme without an adaption to the variation of dynamics results in a suboptimal operation. Compared to other works, in this study the derating is integrated in the control design from the beginning (i.e., choice of linearization points to model the turbine dynamics), and thus the two operating strategies can be compared while having very similar dynamical disturbance rejection properties. As a result, the implications from the different operating strategies considering the loading and power tracking dynamics can be compared while at the same time the influence of the control on the differences is mitigated by a dedicated control design.

To clarify this aspect, we have introduced the following paragraph in the revised manuscript on page 3 lines 64-68:

> *In this article, the loading of the turbine structure depending on the chosen strategy is compared, where identical performance constraints determine the individual feedback gains used to obtain a similar closed-loop disturbance rejection dynamics in both operating strategies despite being operated at different trajectories. This aims for a mitigation of the effects introduced by the control algorithms, such that a plain comparison of the different operating strategies can be conducted.*

Further, we think the discussion on the attainable power tracking dynamics and the reduced order modeling inherits novel aspects from a wind farm or electrical power system perspective, which is expressed in the following paragraph on page 3 line 69-75:

> *Additionally to the loading perspective, this paper aims to feed the discussion on the integration of dynamical turbine models for control design and simulation studies of large-scale power systems and wind farms. The employed model-based control framework allows to enforce similar turbine dynamics with respect to the wind in both investigated schemes, such that fundamental properties only influenced by the operating strategy and subject to varying power demands may be revealed and discussed. This is exploited to study the power tracking behavior of the two distinct strategies and derive simplified analytical models of the turbine power output dynamics. These models are useful for portraying the turbine dynamics when participating in large-scale power system simulations and control design.*

2) In addition, the authors only presented two equations to describe their control design. It is unclear to me if these two strategies will work during the transition between normal controller and derating. In addition, from my understanding, the chosen simulation cases were assumed that the wind speed was always sufficient to generate the demanded power. In reality, the wind speed sometimes might not be high enough for producing the required power, then how would the controller behave? Does it need to switch back to the normal controller and how would it affect the loads?

Both operating strategies comprise and actually share the normal operation trajectories due to the choice of the linearization points shown in Fig. 1 and Equation (2). Therefore, a demand higher than possibly produced by the turbine due to the inflow automatically results in normal operation trying to enforce the maximum power extracted. This is implicitly integrated for $p_d = 1$. To underline this aspect, we have added normal operation as reference for the load evaluation in Section 4.

To further clarify this, on page 4 line 96 the following sentence is introduced:

> *For a power tracking command of $p_d = 1$ for both strategies equally, the turbine is operated on the commonly considered operating trajectory trying to maximize the power extraction in partial load region and limiting the power to its rated value in full load region.*

2) Title. Do not use unnecessary acronyms in the title. Not everyone knows what APC means.

We agree. Therefore, the tile is changed to *Evaluation of different power tracking operating strategies considering turbine loading and power dynamics*, and the abstract is adjusted such that APC is not explicitely mentioned but simply referred to as power tracking.

3) Introduction. I found there is a lot of relevant studies missing, including some of the earliest works on this topic. For example, [1], [2], [3], [4], [5] and [6].

We have introduced all the mentioned literature in our work. A short description of the conducted works is given in the Introduction and a distinction is made in the following paragraph on page 2 lines 46-68. The loading observed within the mentioned studies are compared to our simulation results in Section 4.

4) Introduction. '... the paper aims to feed the discussion on the integration of dynamical turbine models for control design and simulation study of large-scale power systems. I don't think this is the only contribution by the paper. Please clarify the novelty and contribution of this paper.

Please see the answer to your first remark.

5) Section 2. Equation (2). Do the authors assume derating always happens in the above-rated wind region? The paper claimed that the generator torque is a function of the wind speed, which is not typical for a normal controller. Did the authors use some sort of a wind speed-based look-up table to implement these derating strategies?

No additional look-up tables were used, but all the information is covered in the derived Takagi-Sugeno model. First, the linearization points and the corresponding steady state values at a given wind speed are identified in the linearization analysis and are represented by x_{0i} and u_{0i} for the state and input, respectively (see equation (3) in the revised manuscript). In operation of the control scheme, the input is calculated from both, a feedback and a feedforward term (see equation (5) in the revised manuscript), where in partial load region the generator torque and in full-load region the pitch is used to apply feedback action. The feedfoward term is scheduled by the estimated wind speed and contains the input steady-state values u_{0i} captured in the linearization analysis (and may be considered as a look-up table). The commonly applied quadratic dependency of the genrator torque in the partial-load region is implicitly encoded in the choice of linearization points. In both, partial-load and full-load region, the control scheme is being scheduled by the estimated wind speed from the disturbance observer $\hat{v}$. For more detailed explanation on the control design, a performance comparison to the Delft Research Controller (Mulders and van Wingerden, 2018) and an experimental validation of the applied scheme, please see (Pöschke et al., 2020) and (Pöschke et al., 2022).

6) Page 3, Line 75. Typo. (Fig. 1 and (2)) —> (Fig. 1 and 2)

This is referring to Fig. 1 and Equation (2). To clarify, we have explicitly stated this in the manuscript on page 4 line 110:

> *The operating strategies share a common operational concept for a power demand of $p_d = 1$ (Fig. 1 and Equation (2)), which represents the nominal operating strategy used in wind turbine control for energy maximization.*

7) Section 3. The authors claimed that the linear model dynamics were obtained somehow. I didn't understand how the linear model was obtained. Is it via the linearization tool in FAST?

Most importantly, I found Section 3 is redundant. Why would the readers need to know this 'control design' section? The derating strategies have already been presented in Section 2.

We have gained the linear models directly from the linearization functionality in FAST, although, the necessary models may also be derived analytically if desired. Please see the answer to Remark 4) of Reviewer 2.

In general, a lot of different approaches may be used to enforce the desired operating strategies described in Section 2. Therefore, Section 3 is devoted to explaining the general idea of the control design using Takagi-Sugeno modeling and linear matrix inequalities. To give a more detailed description of the applied controller, Section 3 was extended to enhance comprehensibility. Specifically, we added an analytic description of the model in equation (3), the observer dynamics in equation (4) and the input calculation given by equation (5).

To clarify the aspect of using the linearization functionality of FAST, the statement made at the beginning of the control design section is altered on page 4 line 104-107 as:

> *The steady-state inputs of the wind turbine are derived for the corresponding operating points, and subsequently, a linearization analysis using the built-in functionality of FAST (Jonkman and Jonkman, 2016) is conducted to capture the rotational dynamics at each point.*

8)Section 3. "... the observer estimates the current effective wind speed by a measurement of the rotational speed". Typically, the wind speed estimator also requires the knowledge of pitch angle and generator torque. Is there something missing or the authors are referring to some better designs?

We agree, for calculation of the observer in equation (4) the rotational speed as state, pitch angle and generator torque as input are needed. As a result, we changed the corresponding sentence on page 5 line 122-124 to:

> *The control scheme is built on a disturbance observer. The observer estimates the current effective wind speed by a measurement of the rotational speed, generator torque and pitch angle.*

8) Section 4. The authors presented a blending of OS1 and OS2. I am wondering if there are any low-pass filters used for the torque signal and rotor speed set-point signal?

There are no filters implemented in the scheme, such that the FAST outputs are directly used within the controller. The switching between the different operating strategies depends on the evolution of the operating strategy signal n_{OS} (as part of the premise variable $z = [\Delta p, n_{\mathrm{OS}}, v]^{\mathrm{T}}$ in Section 3 of the revised manuscript) that is externally commanded. The signal was defined such that $n_{\mathrm{OS}} = 1$ means operation at OS1 and $n_{\mathrm{OS}} = 2$ results in operation at OS2. A linear transition from $n_{\mathrm{OS}} = 1 \rightarrow 2$ is externally commanded within 15 s and results in the turbine trajectories shown in Fig. 2.

9) Section 4.1 and Section 4 are similar. For example, both sections refer to the same figure. Perhaps it would be easier to read if both sections are combined. Also, the titles of Section 4.1 and 4.1.1 are similar.

To avoid confusion and also following the suggestion of Reviewer 2, we have removed the section numbers for 4.1.1 and 4.2.1, such that the discussions are directly integrated in Sections 4.1 and 4.2.

10) Figure 2. Caption. What are (a), (b) and (c)? They are not shown in the figure. In addition, the authors tend to put all plots into one figure, and in the text, different sections refer to the same figure. It is hard to read. For example, Figure 2 (a), (b), (c) are referred in Section 4.1 but Figure 2 (d) is mentioned in Section 4.1.1. I suggest the authors separate out Figure 2 (d) from Figure 2 as they are in a different time scale. Moreover, Figure 2(d) is more relevant to Fig 3 (a).

We agree. As a result, all figures were revised, and separated accordingly. Now, Fig. 2 shows the operating trajectories of OS1, OS2 and the blending among them at a short timescale. Fig. 3 contains a longer term time series that compares the operating trajectories of OS1 to OS2. Additionally, the estimated wind speed from the observer is compared with a single wind vector in the wind field to illustrate the reconstruction performance.

11) Figure 3. Figure 3 (b) and (c) are not really linked Figure 3 (a). The authors should separate them.

We agree and have separated the figures.

12) Section 4.1.1. '...fewer blade-tower interactions due to the reduced rotational speed,...'. Why was that? Isn't it that the opposite is true, that the reduced rotor speed makes the 3p frequency closer to the tower mode, thus, it will increase the coupling between 3p mode and tower mode?

I think these are two different aspects. The number of times a blade passes the tower in a certain time period (or more precisely the varying flow conditions around the tower structure) depends on the current rotational speed, and thus the excitation due to the tower blade interaction is reduced when operating at a lower rotational speed. I think this effect is the reason for the reduced out-of-plane blade loading in OS2. On the other hand, it is true that a reduction of rotational speed causes the 3p excitation of the rotor to be closer to the eigenfrequency of the tower, which is the reason for introducing the lower rotational speed limit in OS2. We have adjusted the discussion on the consequences for tower loading, such that the relation to the eigenfrequency of the tower becomes apparent on page 9 line 210-211:

> *Additionally, in OS2 the turbine operates at smaller rotational speed, and consequently, the 3P excitation of tower due to the rotation is closer to the eigenfrequency of the tower movement.*

13) Section 4.2. Interesting power tracking studies. Did the authors consider the switching between the normal controller and OS1 or OS2? What do OS1 and OS2 behave when the wind speed is not sufficient to generate the required power?

Switching to normal mode is considered in the study in Section 4.2. The turbines are operated at 70% power production prior to the switching, such that a $\Delta p = 0.3$ results in operation at $p_d = 1$ and thus the nominal operating trajectory. Whenever $p_d = 1$, the controller operates the turbine at the usually considered trajectories for maximum power extraction, i.e., when the available power is not sufficient to supply the demand.

14) Section 5. '... it is discussed how different operational strategies can be designed for wind turbines using a model-based control design'. Did the authors use model-based design for developing the derating strategies in Section 2? Or did I miss something?

We agree that this sentence is misleading. As a result, the sentence was altered on page 14 line 322-323 to:

> *Within this contribution, it is discussed how different operational strategies for wind turbine can be integrated into a model-based control design by choice of the linearization points.*

II. Response to Reviewer 2

1) The investigated problem is indeed very irelevant for wind turbine control. The article includes interesting results but their presentation and discussion should be improved. Please find my brief comments below and note that they are built on top of Reviewer 1 inputs:

As we are hoping you are referring to relevant, we thank you for the encouraging comment and your valuable review.

2) Introduction: There are many studies in this area as Reviewer 1 indicated. One addition to the previous suggestions is Christos Galinos et al. 2018 J. Phys.: Conf. Ser. 1104 012019, where the effect of turbine derating strategies are also investigated, mainly focusing on wake. Novelty with respect to all the listed previous studies should be clarified.

The study (Galinos et al., 2019) is included in the manuscript as it specifically addresses the aspect of control on the individual turbine level closely related to the work carried out in our study. While we are aware that derating has also consequences for the entire wind farm and the flow within, our interest in the derated operation of wind turbines is mainly motivated by an electrical grid perspective. Therefore, we focus on discussing the implications from the different control strategies in this matter. As suggest in your Remark 10), to open the discussion on the topic the following sentence is added on page 15 line 342-344:

> Additionally, as shown in (Zhu et al., 2017; Lio et al., 2018), operating the turbine at lower rotational speeds decreases the thrust coefficient of the turbine, and thus mitigates the wake induced effects for downstream turbines.

3) Operating strategies: It is indeed not clear if down-regulation is activated below rated as well as "With ωopt (v) and Topt (v) being the optimal (or limited above rated power) rotational speed and generator torque depending on the current effective wind speed v..." reads as if the limits are introduced above rated only. Should be clarified.

To clarify, we have restated this sentence on page 3 line 86 as:

> *With $\omega_{\text{opt}}(v)$ and $T_{\text{opt}}(v)$ being the steady-state rotational speed and generator torque for partial and full load region depending on the current effective wind speed v, and p_d is normalized desired power output of the turbine ...*

4) Control design: The need for linearization (and how does it capture dynamics really?) and its process should be clarified. Why not use the entire Cp surface if in the end a 'nonlinear decsription' is generated? The discretization induces additional uncertainties for your results and could potentially be avoided.

In general, nonlinear analytical models may also be used for the derivation of the applied model structure. These models may either be derived by the so-called sector nonlinearity approach, but this has implications for the structural properties of the derived models as discussed in (Pöschke et al., 2017). Another approach when having a nonlinear analytical description is to linearize analytically and choose parameter values for the different components (e.g., inertia of the rotor). Both approaches assume either possessing an analytical description of the C_p surface, or using a look-up table at discretized operating points. The grounding analytical description also naturally provides uncertainties depending on the chosen model complexity and parameter values.

FAST captures a lot of relevant dynamical properties of the coupled components in the operation of an individual turbine. Thus, while the discretization certainly introduces uncertainties, the numerous relevant models captured in FAST influence the obtained models from the linearization process and thus directly affect the gained convex model description used for control design. FAST numerically computes the linearized dynamics by a central-difference perturbation technique (Jonkman and Jonkman, 2016).

Validation of the derived models has shown that the TS models provide an accurate description of the turbine dynamics useful for control design and simulation purposes. In Fig. 1, the comparison of a TS model gained from linearization with the state trajectories of FAST when operated by the same controller subsequently with identical inputs is shown (no coupling beween FAST and the TS model exists).

The main benefit from capturing the dynamics as convexly blended linear submodels is the possibility to apply Lyapunov functions that provide stability measures and subsequently derive linear matrix inequality constraints that can be numerically solved efficiently using various available solvers (VanAntwerp and Braatz, 2000).

5) Control design: How does "... the observer estimates the current effective wind speed by a measurement of the rotational speed"? Especially for OS1, where the rotational speed is kept at optimum, majority of the wind speed dynamics is reflected on the pitch acitivity. Another set of equantions is needed to explain the approach utilised for the wind speed observer.

We have introduced the dynamical description of the disturbance observer in Equation (4). It is true that we need information about the current generator torque and pitch angle. As a result, the following sentence on page 5 line 323-324 is adjusted to:

> *The observer estimates the current effective wind speed by a measurement of the rotational speed, generator torque and pitch angle.*

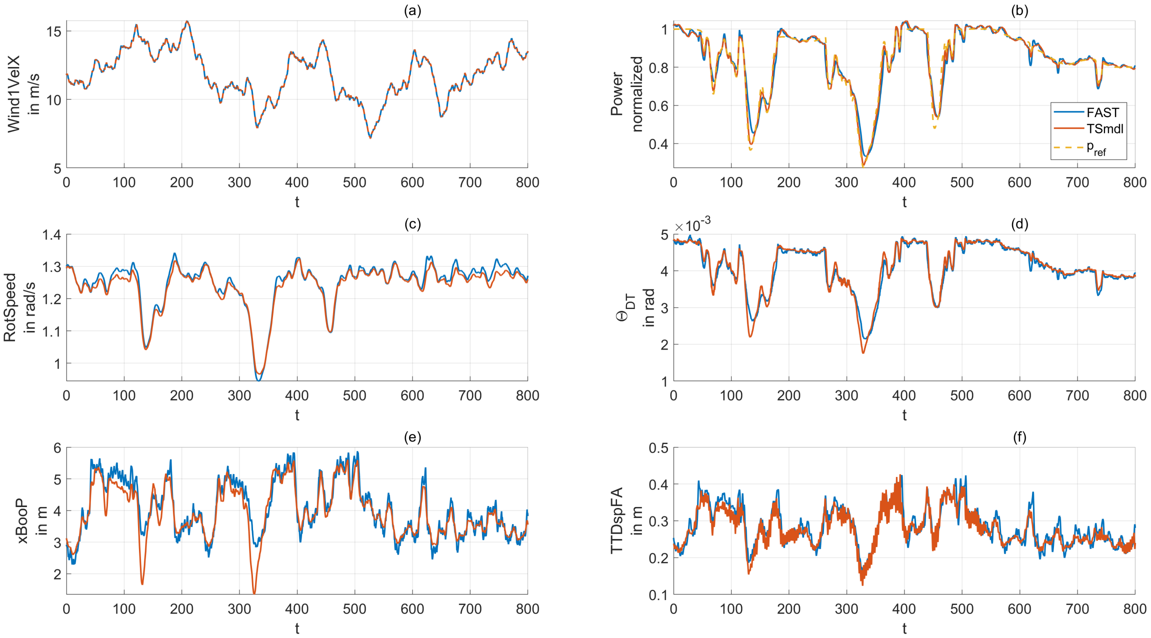

Figure 1: *Comparison of different state trajectories of a Takagi-Sugeno (TS) wind turbine model gained by linearization and FAST when operated in identical wind and power commands. (a) exitation wind speed (b) power (c) rotational speed (d) drivetrain torsion (e) blade out-of-plane bending (f) tower top displacement fore-aft*

6) Results: Subsection 4.1.1 should be combined with 4.1 for a better flow in the article.

We agree and have integrated 4.1.1 into 4.1 and 4.2.1 into 4.2.

7) Results (Section 4.1) Figure 3(a): What is Δpd here? It seems like an isolated case within Figure 4, should be stated in the caption and the text for clarity.

Thank you for noticing that we didn't introduce Δp_d properly. To clarify this, the following paragraph was added to the manuscript on page 10 line 238-242:

> *To assess the dynamics involved, the turbine is faced with instantaneous demand changes while operating in different constant wind conditions at a constant power output of $p_d = 0.7$ prior to the event. The stepwise changes in the power demand $p_d = 0.7 + \Delta p_d$ are bidirectional, i.e., increase and reduction of the power output demand at steps of Δp is simulated. The applied steps are defined as*
>
> $$\Delta p_d = \begin{cases} 0 & \text{if } t \leq 60\,\text{s} \\ \{-0.3,\ -0.2,\ -0.1,\ 0.1,\ 0.2,\ 0.3\} & \text{otherwise} \end{cases}$$
>
> .

8) Results (Section 4.1) Figure 4: It is the most interesting result of the study in terms of load analysis and not discussed in the text at all. The behaviour should be analysed in detail and comparatively with respect to delta set-points.

To provide a more detailed analysis of the ultimate loading due to stepwise changes in the power demand, we extended the paragraph describing the loading on page 11 lines 257-266 and the following discussion on page 14 lines 312-320.

9) Conclusions: Suggested rewording "... where a de- or acceleration..." –> ""... where a deceleration or acceleration..."

We agree and altered the sentence on page 14 line 325-327.

10) Conclusions: Potential implications of OS1 vs. OS2 to the wake of the turbine can be briefly discussed to open up the discussion for flow control studies.

We agree. To provide a general perspective on the matter, we added the following sentence into the Conclusion on page 15 lines 342-344:

> Additionally, as shown in (Zhu et al., 2017; Lio et al., 2018), operating the turbine at lower rotational speeds decreases the thrust coefficient of the turbine, and thus mitigates the wake induced effects for downstream turbines.

10) Thanks for your efforts, looking forward to read the revised version!

Thank you!

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