

First Author: Nikhar J. Abbas

Manuscript Title: A Reference Open-Source Controller for Fixed and Floating Offshore Wind Turbines

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### Author's Response to Reviewers

We would like to thank the reviewers for taking the time to thoroughly review this manuscript. We have carefully considered all of their suggestions, and have attempted to acknowledge all suggested modifications, clarifications, and overall updates to the paper. The tables below directly address each of the reviewer comments and how we have updated the manuscript accordingly. All equation references correspond to the revised manuscript.

Please note that, outside of the changes directly addressed in this document, updates have been made to the results section of the manuscript in order to reflect the reviewers' suggested theoretical changes and more recent version of the ROSCO controller.

Additionally, a color-coded revised version is provided at the end of this document, which shows all of the changes that were made to the manuscript. All text in blue has been added to the manuscript, and the text in red has been removed. Figures that have received major revisions and updates are underlined in blue.

Comments from Referee #1	Authors' Response
Page 6, p. about Region 2.5: You mention that "due to the PI and controllers and the setpoint smoother, there is no specific range for Region 2.5". Since the PI controller and the setpoint smoother as implemented should not change the steady states, it should be always possible to calculate, at which wind speed the steady state of the rotor speed reaches rated rotor speed (depending on $k$ of your $k \cdot \Omega^2$ ) and at which wind speed the static pitch is larger than the fine pitch. This should also allow to calculate the limits of region 2.5 even with the peak shaving. Please consider this.	<u>Response</u> Thank you for pointing this out. We have tried to clarify the description of Region 2.5 in the manuscript.
	<u>Changes</u> We have added and also edited the text in the region 2.5 description in section 2.1.
Figure 2 left: TSR seems to continue to be constant at the end of region 2, but rated rotor speed is already reached (which is not possible). For the 5MW, rated rotor speed is also reached before rated power. It would be	<u>Response</u> Thank you for noting this. The figures have been updated accordingly.
	<u>Changes</u>

<p>further helpful to add region 2.5 in the plot (see comment above).</p>	<p>Figure 2 has been updated to properly to show the tip speed ratio and to have a shaded area to denote region 2.5.</p>
<p>Section 2.5: The authors write that the integral gains are in general negative for standard horizontal-axis wind turbines. However, this depends on the definition of your speed error (reference – measurement or measurement-reference). From my perspective, the positive gains are more common (see e.g. Jonkman 2009). Please revise this part.</p>	<p><u>Response</u>          Though it is true that Jonkman (and others) have denoted HAWT controller gains as positive, in ROSCO, the gains are negative because an increase of rotor speed results in a negative speed error, so an increase of collective blade pitch or generator torque is desired. This is consistent with others in the community, such as the Delft Research Controller. The manuscript has been updated to reflect <i>why</i> the gains are negative given our formulation. Section 2.5 now gives a more thorough formulation of the system used to tune the ROSCO controller.</p> <p><u>Changes</u>          Changes have been made to section 2.5 to clarify our convention. Equations (12) and (13) have been added to clarify the form of the input and output perturbations.</p>
<p>Equation (15): Equation (15) is usually obtained setting the rotor motion from Equation (2) to zero and integrating the aerodynamic torque from Equation (3), see e.g. Bossanyi 2000. However, the efficiencies of the generator and gearbox are not part of Equation (2) and (3) of your paper. From my perspective, the efficiency of the gearbox should be part of Equation (2) and thus also (15), but the generator efficiency is only important to calculate the electrical power from the generator torque and thus should not be a part of Equation (2) and thus also not of Equation (15). Please make this part more consistent.</p>	<p><u>Response</u>          Thank you for the detailed analysis of the equations – they have been updated accordingly.</p> <p><u>Changes</u>          We have updated equations (2) and (15) (which is now equation (17) in the revised manuscript).</p>
<p>Equation (21): If “constant power” is used, one can also include the partial derivative of the generator torque with respect to the generator speed in Equation (5). Neglecting this usually causes a large deviation from my experience, also for the 5 MW reference</p>	<p><u>Response</u>          Thank you for noting this missing piece of information. We have included a more detailed investigation into this term and updated the theory and results in the manuscript accordingly.</p>

<p>wind turbine. For the ROSCO controller and for the paper it would be nice, if you could include this part or provide some investigation that in your case this is neglectable</p>	<p><u>Changes</u> Equations (23) and (24) and their surrounding text have been added to Section 4 to clarify, theoretically, how constant power actuation can affect the second order linearized model (equation (5)) in above-rated operation. The results for the NREL 5MW wind turbine, which uses constant power operation, have been updated with the requisite theory included in the controller tuning process.</p>
<p>Section 5.5: Usually (in the Bladed interface), the tower top fore-aft acceleration is a translational degree-of-freedom and thus the integrated signal is the tower top fore-aft speed. This has been used in your reference (van der Veen 2012). However, you use the “tower top pitch angle” (i.e. rotational DOF), which is also possible (but much harder to measure/estimate in reality) and would provide similar results I assume. But since ROSCO is using the Bladed interface and aims to reflect the industrial state-of-the-art, please consider changing to the translational DOF.</p>	<p><u>Response</u> Thank you for noting this. The equations and results in the manuscript have been updated to reflect this suggestion.</p>
	<p><u>Changes</u> The formulation of the floating feedback gain in Section 5.5 has been updated to reflect the use of a tower top fore-aft translational acceleration signal. Additionally, the results for the IEA-15MW wind turbine have been updated with the updated controller.</p>
<p>Equation (5) etc.: Please use consider using <math>\Delta</math> instead of <math>d</math> for <math>\beta</math>, <math>v</math> etc. and introducing that <math>\Delta</math> is the deviation from the steady state. Using simply <math>d</math> might cause confusion with the operator “d”.</p>	<p><u>Response</u> Thank you for pointing out the potential confusion here. The equations have been updated as suggested.</p>
	<p><u>Changes</u> <math>\Delta</math> has been used throughout the manuscript as suggested in order to be clearer.</p>
<p>Equation (9) etc: Please consider that “d” is an operator and thus using <math>\mathrm{d}</math> instead of simply <math>d</math> would be more appropriate.</p>	<p><u>Response</u> Thank you for noting this, the equation has been updated.</p>
	<p><u>Changes</u> Many of the times that <math>d</math> was used have now been converted to <math>\Delta</math>. <math>\mathrm{d}</math> has been used in the necessary equations that remain (e.g. equation (9)).</p>

<p>Equation (6) etc: the tip speed ration might be good to introduce. And here, using <math>\partial</math> as in Equation (4) would be more appropriate, since the tip speed ratio depends on both wind speed and generator speed.</p>	<p><u>Response</u> The tip speed ratio is introduced in equation (1). Thank you for noting the necessity for using <math>\partial</math> - the equations have been updated accordingly.</p>
<p>Equation (12): The transfer function <math>H(s)</math> connects the Laplace transform of the input to the one of the output. The Laplace transforms themselves do not depend on <math>s</math>. Thus, the fraction with <math>d\Omega_g(s)</math> is a bit sloppy. Best might be to simply remove this and explain that the transfer function is obtained by using the Laplace transform and Equation (5) and (9).</p>	<p><u>Changes</u> We have added a reference to the definition of the tip-speed ratio in (1) right after equations (6)-(8). <math>\partial</math> is now used in all necessary equations.</p>
<p>Figure 2 and Figure 5 caption, Appendix A etc.: Units are in non-italic in the rest of the paper (which makes sense, since they are not variables), but here you have <math>kNm</math>, <math>MNm</math>, etc.. Please consider changing them.</p>	<p><u>Response</u> Thank you for noting this. The manuscript has been updated to be more theoretically rigorous.</p>
<p>Figure 3: setpoint smoother has more inputs than only the generator speed.</p>	<p><u>Changes</u> We have followed your suggestion and explicitly explained how the closed loop transfer function is obtained by taking the Laplace transforms of Equations (5) and (9) and combining them in a standard negative-feedback loop.</p>
<p>l 297: “but the power is much more consistent” is not clear to me. Maybe just remove or add something to better explain it. Maybe you mean “more consistent compared to the constant torque case”?</p>	<p><u>Response</u> Thank you for your attention to detail. The manuscript has been updated accordingly.</p>
<p>Figure 3: setpoint smoother has more inputs than only the generator speed.</p>	<p><u>Changes</u> All units have been changed to be non-italicized</p>
<p>Figure 3: setpoint smoother has more inputs than only the generator speed.</p>	<p><u>Response</u> Thank you for pointing this out, the figure has been updated.</p>
<p>l 297: “but the power is much more consistent” is not clear to me. Maybe just remove or add something to better explain it. Maybe you mean “more consistent compared to the constant torque case”?</p>	<p><u>Changes</u> Figure 3 has been updated to more accurately show the setpoint smoother inputs.</p>
<p>l 297: “but the power is much more consistent” is not clear to me. Maybe just remove or add something to better explain it. Maybe you mean “more consistent compared to the constant torque case”?</p>	<p><u>Response</u> Thank you for pointing out this source of confusion – the manuscript has been updated for clarity. The subscript has also been fixed.</p>

<p>in Equation (20) you use “rat” as subscript, but in the rest of the paper “rated”. Please consider to have this consistent.</p>	<p><u>Changes</u> The paper has been modified to specifically state that the power is more consistent in the constant power case than in the constant torque case, and the subscript has been fixed.</p>
<p>Section 3.1, last sentence: From my perspective, the proportional and integral gains for the torque PI controller are often chosen to be constant for simplicity, since applying Equation (13) usually does not provide significantly differences over the considered operation points. Please check if this could be also helpful here. The reason provided in the paper (“less erratic control actuation...”) seems to be a bit vague for a Journal paper.</p>	<p><u>Response</u> Thank you for your comments on this.</p>
	<p><u>Changes</u> The phrasing here has been updated to note that fixing the controller gains simplifies the problem without negative effects.</p>
<p>I 377: Equation (17) should be included here since Equation (16) is TSR tracking only.</p>	<p><u>Response</u> Thanks for pointing this out, equation (17) (which is now equation (18) in the revised manuscript) has been included.</p>
	<p><u>Changes</u> The equation reference has been updated.</p>

Comments from Referee #2	Authors' Response
<p>My main comment after going through the very extensive manuscript is: while undoubtedly the ROSCO controller and toolbox are a significant contribution to the community and represent a very large effort, the authors should also consider highlighting the scientific contributions of the paper, avoiding reading the article as a "ROSCO user manual". It seems that most of the effort has been towards implementing well known methods and approaches, and automatizing some of the processes, which is of course a great effort that merits appreciation, however it does not automatically and necessarily entail publication in a scientific journal.</p>	<p><u>Response</u>  Thank you for commenting on this – we certainly see how there may be some confusion as to whether or not this should have been published as a user manual. We believe this manuscript is much more than a user manual, and we have updated the manuscript and tried to improve clarity as to what the scientific contributions of this work are, and why this work merits publication in a scientific journal.</p> <p>Additionally, we would like to note that this manuscript provides very little information as to how to actually use and implement the ROSCO tools. The paper itself focuses on the mathematical methods used for tuning and implementation of the controller, and how they are applied within the context of wind turbines. Though some of the methods and approaches have been discussed elsewhere in the literature (as cited), to the author's knowledge, there is no other publication that provides the theoretical and mathematical detail on automated controller tuning and implementation methods as completely as this one does.</p> <p><u>Changes</u>  Changes have been made to the introduction to further highlight what we believe to be the scientific contributions of this work.</p>

# A Reference Open-Source Controller for Fixed and Floating Offshore Wind Turbines

Nikhar J. Abbas<sup>1,2</sup>, Daniel S. Zalkind<sup>2</sup>, Lucy Pao<sup>1</sup>, and Alan Wright<sup>2</sup>

<sup>1</sup>University of Colorado Boulder, Boulder, CO, 80309, USA

<sup>2</sup>National Renewable Energy Laboratory, Boulder, CO 80303, USA

**Correspondence:** Nikhar J. Abbas (nikhar.abbas@colorado.edu)

**Abstract.** This paper describes the development of a new reference controller framework for fixed and floating offshore wind turbines that greatly facilitates controller tuning and represents standard industry practices. The reference wind turbine controllers that are most commonly cited in the literature have been developed to work with specific reference wind turbines. Although these controllers have provided standard control functionalities, they are often not easy to modify for use on other turbines, so it has been challenging for researchers to run representative, fully dynamic simulations of other wind turbine designs. The Reference Open-Source Controller (ROSCO) has been developed to provide a modular reference wind turbine controller that represents industry standards and performs comparably to or better than existing reference controllers. The formulation of the ROSCO controller logic and tuning processes is presented in this paper. Control capabilities such as tip-speed ratio tracking generator torque control, minimum pitch saturation, wind speed estimation, and a smoothing algorithm at near-rated operation are included to provide a controller that is comparable to industry standards. A floating offshore wind turbine feedback module is also included to facilitate growing research in the floating offshore arena. All of the standard controller implementations and control modules are automatically tuned such that a non-controls engineer or automated optimization routine can easily improve the controller performance. This article provides the framework and theoretical basis for the ROSCO controller modules and generic tuning processes. Simulations of the National Renewable Energy Laboratory (NREL) 5-MW reference wind turbine and International Energy Agency 15-MW reference turbine on the University of Maine semisubmersible platform are analyzed to demonstrate the controller's performance in both fixed and floating configurations, respectively. The simulation results demonstrate ROSCO's peak shaving routine to reduce maximum rotor thrusts by ~~nearly 14~~over 10% compared to the NREL 5-MW reference wind turbine controller on the land-based turbine and to reduce maximum platform pitch angles by ~~slightly more than 35~~approximately 20% when using the platform feedback routine instead of a more traditional low-bandwidth controller.

*Copyright statement.*

## 1 Introduction

As wind turbine research has evolved during the past few decades, the need for reference wind turbine controllers has also changed. Traditionally, reference wind turbine controllers have been used for two primary purposes. First, the control systems  
25 research community has extensively used reference controllers as a baseline to compare and evaluate more modern and advanced control algorithms (Lackner and van Kuik, 2010; Schlipf et al., 2013). Second, researchers interested in aero-structural dynamics have used reference controllers to enable dynamic simulations in studies concerning other aspects of the wind turbine (Wayman et al., 2006; Sathe et al., 2013). In both applications, a reference controller provides a standardized method by which  
30 wind energy researchers can compare and contrast their various turbine designs, aerodynamic models, structural analysis tools, and more.

There has been a lack of reference controllers that can be easily adapted to a wide variety of different wind turbines. The National Renewable Energy Laboratory (NREL) and the Technical University of Denmark (DTU) have published perhaps the most ubiquitous of these reference turbines and respective controllers with the NREL 5-MW (Jonkman et al., 2009) and DTU  
35 10-MW (Bak et al., 2013; Hansen and Henriksen, 2013) turbine models. Generally, for new turbine models, the tuning processes for these turbines' respective controllers necessitate a control systems engineer to generate linear models of the turbine at multiple operating points using aeroelastic simulation solvers to schedule controller gains. At the very least, someone familiar with the NREL 5-MW reference controller tuning process must be able to adequately modify the controller accordingly, as shown in Griffith and Ashwill (2011), where the reference controller is scaled for a rotor with a novel blade design.

Additionally, trends in the wind energy industry are heavily favoring larger and more flexible rotor designs (Veers et al.,  
40 2019). As wind turbines have grown and modeling tools have improved and increased in fidelity, design constraints—such as blade tip deflection—have become increasingly important. Without a controller that performs consistently across turbine designs and is representative of the controllers in the field, dynamic simulations cannot be entirely trusted to provide reliable results that can be used for turbine design. The need to run representative dynamic simulations of large flexible turbines necessitates a controller and controller tuning process that can be implemented consistently by the non-controls engineer in a  
45 streamlined fashion.

Finally, completely automated optimization tools for medium- to high-fidelity wind turbine designs are becoming well established in research and industry. These tools—such as the Wind-Plant Integrated System Design & Engineering Model (WISDEM®) (Dykes et al., 2014), HawtOpt (Zahle et al., 2015), and Cp-max (Bottasso et al., 2012)—generally include some  
50 element of dynamic wind turbine simulation within the optimization loop. Naturally, changes in the wind turbine design often necessitate an update to the controller. An automated controller tuning process and generalized implementation method provide the opportunity for automated control codesign, where the system and controller are designed concurrently (Garcia-Sanz, 2019; Zalkind et al., 2020).

In addition to the need for a generic controller for land-based and fixed-bottom wind turbines, to the authors' knowledge, the availability of a modern, open-source controller with specific logic for floating offshore wind turbines (FOWTs) is not  
55 available. Simply reducing the controller bandwidth, as presented by Larsen and Hanson (2007), has been shown to have



disadvantages (Fleming et al., 2014). For the same reasons that a generic controller with automated tuning processes is useful for land-based turbines and rotor design, a specific control implementation for FOWTs has its own utility.

~~The motivation~~ There are numerous motivations for the development of the Reference Open-Source Controller (ROSCO) tool chain ~~is threefold. First, continued~~ and the publication of this manuscript. Continued development, refinement, and expansion of the Delft Research Controller (Mulders and van Wingerden, 2018) provides a wind turbine controller that is consistent with industry-standard control functionalities for use in the research community. ~~Second~~ Additionally, the implementation of generalized tuning procedures through open-source software provides a means for non-controls engineers to conveniently implement and modify a standard wind turbine controller for use in their research applications. This manuscript provides a more theoretically comprehensive collection of how to tune and implement a baseline wind turbine controller for fixed and floating applications than currently exists in the literature. Specifically, the presented methods contribute, in detail, to the growing body of scientific literature in the wind energy field, and show how analytical turbine models and power coefficient surfaces can be used to rapidly tune a wind turbine controller in a completely automated fashion. This manuscript also provides methods for analytical tuning of a feedback term and pitch saturation routines to specifically address challenges presented by floating offshore wind turbines. Finally, these generalized tuning procedures and controller implementations provide a framework by which systems design optimization tools such as WISDEM can include a controller for time-domain simulations in the optimization loop.

The structure of this manuscript is as follows. In Section 2, we give a high-level overview of the ROSCO tool chain and implementation methods. Here, we also discuss the structure of the ROSCO controller and some requisite theoretical background for the proceeding sections. In Section 3 and Section 4, we discuss the primary generator torque and collective blade pitch controllers, respectively. In Section 5, we provide details on the primary individual “modules” of the controller. For each module detailed in this paper, we provide a review of its purpose, how the generic tuning processes are applied, and in some cases a brief time-domain simulation result to showcase its functionality. Then, in Section 6, we provide power and loads analysis results for the ROSCO controller on turbines in both land-based and floating configurations. Finally, Section 7 discusses some conclusions and future directions of ROSCO.

## 80 **2 Foundations of the Reference Open-Source Controller**

ROSCO was developed to provide a modular control systems architecture with a Fortran-based software structure similar to that of OpenFAST (NREL, 2019), a complete aero-servo-hydro-elastic wind turbine simulation tool developed at NREL. The initial work and foundation for the ROSCO controller was done by researchers at the Delft University of Technology and presented in (Mulders and van Wingerden, 2018). The standard controller functionalities are designed to perform comparably with existing reference controllers in the literature, such as the NREL 5-MW and DTU 10-MW controllers. In addition to the standard control functionalities, a number of controller features are included that are considered to be similar to those on many industry turbines. The primary functions of the controller are still to maximize power in below-rated operation and to regulate rotor speed in above-rated operation. The controller ~~is available for download and implementation on GitHub (NREL, 2021a):~~

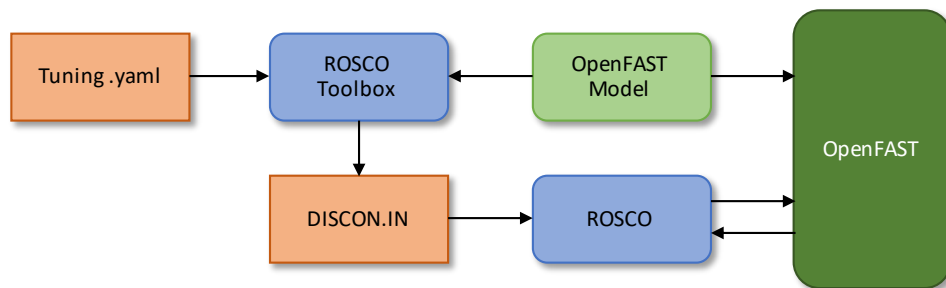
~~The controller~~ was developed to communicate with wind turbine simulation software (e.g., OpenFAST) using the Bladed-style control interface (DNV-GL, 2018). The controller source code is compiled once and reads a controller input file. The controller input file can be renamed and changed for any horizontal-axis wind turbine, and it is generally referred to as the “DISCON.IN” file.

To facilitate usage of ROSCO, a related “ROSCO toolbox” was developed. The ROSCO toolbox is a Python-based tool set developed for tuning, implementing, and post-processing OpenFAST simulations using ROSCO. ~~The ROSCO toolbox is~~ Both ROSCO and the ROSCO toolbox are available for download and implementation on GitHub ~~as well~~ (NREL, 2021b) (NREL, 2021a):

<https://github.com/NREL/ROSCO>.

The primary purpose of the ROSCO toolbox is to automatically execute the generalized tuning procedures for a given OpenFAST turbine model and to generate the necessary input file for the controller. A separate .yaml (Ben-Kiki et al., 2009) formatted parameter file is used for these generic tuning procedures. This file includes relevant turbine and controller tuning parameters that are generally available ~~a-priori~~ a-priori. Only four parameters are *necessary* for tuning a complete controller, though additional tuning inputs are available for the user to introduce further modifications and fine-tune the controller performance. In addition to the controller tuning scripts, post-processing scripts, plotting scripts, and a MATLAB/Simulink version (MATLAB, 2019) of ROSCO are available through the ROSCO toolbox.

The general workflow for using the ROSCO tool chain is shown in Figure 1. The tuning file provides necessary controller tuning inputs to the ROSCO toolbox. The ROSCO toolbox then reads an OpenFAST model and writes the DISCON.IN file. The DISCON.IN file is used as the input file to the ROSCO controller and can be directly modified to change the controller performance, to turn on and off individual control modules, or to change the desired control logic. OpenFAST communicates with ROSCO using the bladed-style control interface.



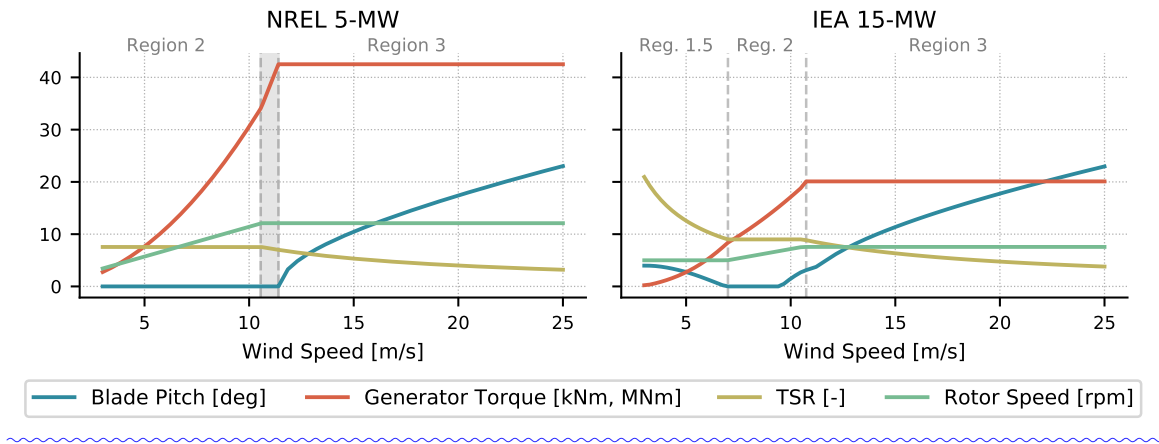
**Figure 1.** The general workflow of the ROSCO tool chain. The orange squares denote ROSCO-related input files, the blue squares denote the ROSCO software tools themselves, and the green squares denote the OpenFAST wind turbine model and OpenFAST itself.

The work by Mulders and van Wingerden (2018) modularized the controller architecture and established an input file framework for the compiled Fortran code. Since then, numerous modules and controller features have been introduced and the functionalities of the controller have been expanded significantly into what is now ROSCO. In this article, we provide an

overview of the primary controller modules that are generically tuned by the ROSCO toolbox or were added specifically for ROSCO.

## 115 2.1 Control Regions

There are generally two methods of actuation in the standard reference wind turbine controllers, including ROSCO. A variable-speed generator torque controller is used to control the generator power, and a collective blade pitch controller is used to regulate rotor speed. These methods of actuation are commonly separated into four regions of operation, with transition logic between them. The steady-state operating points, as shown in Figure 2 for the NREL 5-MW and International Energy Agency (IEA) 15-MW wind turbines, are a convenient way to visualize the regions of operation.



**Figure 2.** The steady-state operating points for the NREL 5-MW and IEA 15-MW wind turbines with the ROSCO controller are shown to illustrate how the turbine operation changes in different regions for different types of controller implementation. The plotted operation points are based on the turbine parameters needed by the ROSCO toolbox tuning procedures and from the  $C_p$  surfaces generated by cc-blade (see Section 2.3). The different control regions are separated by the vertical grey dashed lines. Regions 1 and 4 are not shown. Region 2.5 is specified by the shaded area between Region 2 and Region 3 for the NREL-5MW turbine, and does not specifically exist for the IEA-15MW turbine (Gaertner et al., 2020). Constant torque operation is shown in Region 3 for both turbines. The pitch-saturation routine (see Section 5.3) used by the IEA 15-MW wind turbine results in the nonzero blade pitch trajectory in Region 1.5 and across-in the upper portion of Region 2 and beginning of Region 3. Also note that the generator torque is in kNm-kNm for the NREL 5-MW turbine and MNm-MNm for the IEA 15-MW turbine and that the y-axis is shared for both plots.

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In Figure 2, regions 1 and 4 are considered to be below cut-in wind speed and above cut-out wind speed, respectively, so they are not of particular interest. Here, we provide a brief overview of each region and compare how they are implemented in the NREL 5-MW reference wind turbine controller versus ROSCO. In the following sections, we provide more in-depth descriptions of the logic and tuning processes.

125 **Region 1** is when the wind speed is below the turbine’s cut-in wind speed. This region is generally uninteresting for standard control purposes, and it is not shown in Figure 2 for either turbine.

**Region 1.5** is when the wind speed is above the turbine’s cut-in wind speed but the turbine cannot operate at its optimal tip-speed ratio (TSR). In the traditional NREL 5-MW reference controller, a linear transition from no generator torque to the minimum optimal generator torque is used. In ROSCO, a proportional-integral (PI) controller modifies the generator torque to maintain a defined minimum rotor speed, and the blades are pitched to their minimum allowable blade pitch angle. In turbines designed to operate at a higher TSR in low wind speeds because of a minimum rotor speed constraint, minimum blade pitch angles can be scheduled by a wind speed estimate to improve power output (see Section 5.3.2). ROSCO’s different Region 1.5 behaviors are shown in Figure 2, where Region 1.5 does not span a specific range of wind speeds for the NREL 5-MW wind turbine because of the use of a PI controller and increased blade pitch angles are seen in low wind speeds for the IEA 15-MW turbine.

**Region 2** is when the wind speed is large enough that the turbine can operate at its optimal TSR but is still below rated. Here, the torque controller aims to maximize power as much as possible, and the blade pitch angle is fixed. In ROSCO, the generator torque controller either follows a traditional squared law (Bossanyi (2000)) or employs a TSR tracking PI controller (see Section 3.1.2) to track a rotor speed reference that is based on a wind speed estimate (see Section 5.1) and optimal TSR. The blades are pitched to fine pitch, where they are generally designed to be the most aerodynamically efficient.

**Region 2.5** is when the wind speed is ~~near rated~~ larger than the wind speed that corresponds with rated rotor speed, but less than the wind speed that corresponds with rated power. Here, the turbine is operating in transition between regions 2 and 3. In the NREL 5-MW reference controller, a linear transition and switching logic are used across ~~a specific~~ this transitional range of wind speeds. In ROSCO, a PI controller is used in both the pitch and torque controllers to regulate the rotor speed to their respective set points. A set point smoother (see Section 5.2) is used to ensure that only the pitch or torque controller is active at any point in time and that there is a smooth transition between them. ~~Because of the use of PI controllers and the set point smoother, there is no specific range of wind speeds for Region 2.5 in ROSCO.~~

**Region 3** is when the wind speed is above rated. The blade pitch controller regulates the rotor speed, and the generator torque is either constant or maintains constant power output. In ROSCO, a gain-scheduled PI collective pitch controller is used to regulate the rotor speed. For floating systems, the NREL 5-MW reference controller reduces the pitch controller bandwidth to prevent platform instability. In ROSCO, an additional feedback term is added to this controller for FOWTs (see Section 5.5) to help stabilize the platform using collective pitch, without the need to detune the rotor speed controller. The generator torque is either kept constant at its rated torque value, or the controller adjusts the torque to maintain constant power output.

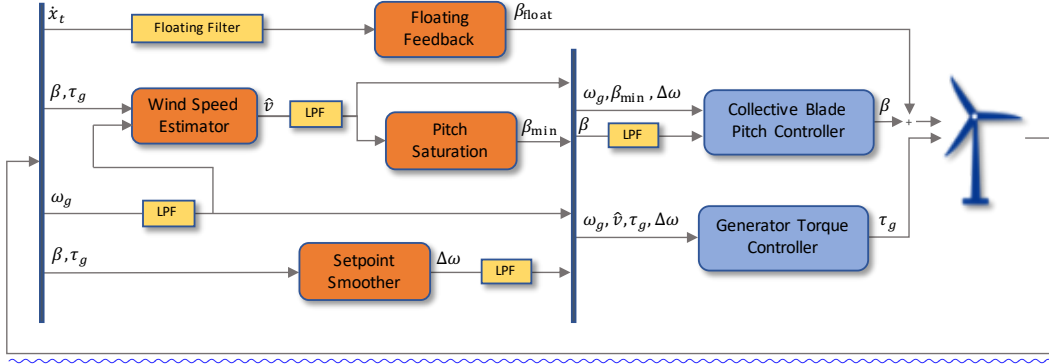
**Region 4** is when the wind speed is greater than the turbine’s cut-out wind speed. Here, the blades are pitched to reduce rotor thrust to zero. Other than triggering a shutdown maneuver, this region is also generally uninteresting for standard control purposes and is not shown in Figure 2.

In the case of the generator torque and blade pitch controllers, a generator speed signal is low-pass filtered and fed back to the respective controllers. The low-pass filter can be chosen as a first- or second-order filter, and the ROSCO toolbox tuning processes generically tunes the cutoff frequency for the filter to be one-quarter of the blade’s first edgewise natural frequency,

160 as suggested in Jonkman et al. (2009). This helps prevent the controller from actuating at a frequency that excites the first edgewise mode of the blade.

## 2.2 Implementation Structure

The high-level block diagram of ROSCO shown in Figure 3 provides an overview of the control modules that are implemented in ROSCO. The combination of these modules ensures smooth actuation across the range of operation regions, as described in Section 2.1. Table 1 provides a brief description of each controller module.



**Figure 3.** A block diagram showing the general controller logic in ROSCO. The shown signals in the figure are the primary time-varying signals passed between various parts of the controller, no constant set-points or parameters are shown. The generator torque and collective blade pitch controllers described in sections 3 and 4, respectively, are shown in blue. The orange squares denote the various controller modules that are described in Section 5. The yellow squares are filters. The details of the floating filter are described in Section 5.5, and the standard low-pass filter implementations are provided in Appendix A. For the feedback signals,  $\dot{\phi} \cdot \dot{x}_t$  is the tower-top **pitch-angle fore-aft velocity**,  $\beta$  is the collective blade pitch angle,  $\omega_g$  is the generator speed, and  $\tau_g$  is the generator torque. For outputs from the controller modules,  $\beta_{float}$  is the floating controller's contribution to the blade pitch angle (see Section 5.5),  $\beta_{min}$  is the minimum blade pitch angle (see Section 5.3),  $\hat{v}$  is the estimated wind speed (see Section 5.1), and  $\Delta\omega$  is a controller reference set point shifting term from the setpoint smoother (see Section 5.2).

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## 2.3 The Power Coefficient Surface

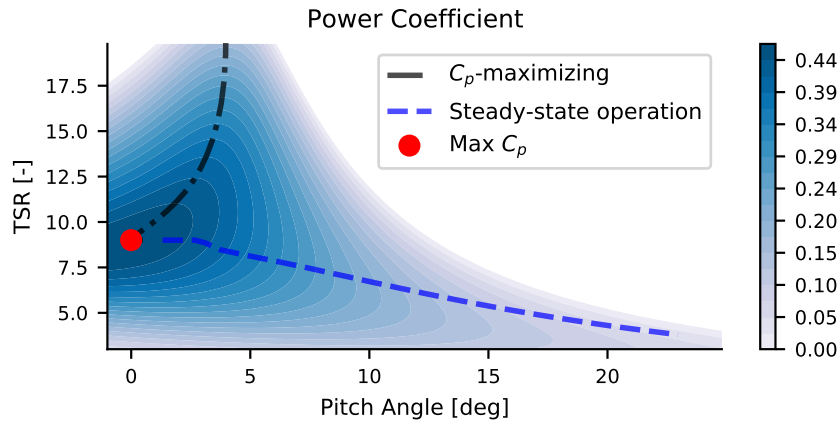
Many tuning procedures and module implementations in this work are based on the so-called  $C_p$  surface. The power coefficient,  $C_p$ , is the ratio of the power extracted from the wind to the power available in the wind (Burton et al., 2011). For any given wind speed, the  $C_p$  surface can be calculated to represent the aerodynamic efficiency of the turbine as a function of collective blade pitch angle and TSR. The TSR is the ratio of the speed of the tip of the wind turbine blade to the rotor-averaged wind speed:

$$\lambda = \frac{\omega_r R}{v}, \quad (1)$$

**Table 1.** The primary ROSCO modules and each of their available functionalities. The flag column shows the flag that must be set in the controller input file to activate each functionality. The functionalities column gives the possible flag values and a high-level description of available functions for each module. Section 5 gives more details of these functionalities. Modules with a section number reference in this table are primary modules that are discussed in more detail in this article. Functionalities with an asterisk denote functionalities that are used in the traditional NREL 5-MW wind turbine controller.

Module	Flag	Functionalities
Blade pitch controller (Section 4)	PC_ControlMode	(0) Fixed pitch (for debug) (1)* Gain-scheduled blade pitch control to regulate rotor speed
Generator torque controller (Section 3)	VS_ControlMode	(0) Square law below rated, constant torque above rated (1)* Square law below rated, constant power above rated (2) Tip-speed ratio tracking below rated, constant torque above rated (3) Tip-speed ratio tracking below rated, constant power above rated
Set point smoother (Section 5.2)	SS_Mode	(0) No set point smoothing (1) Set point smoothing
Yaw control	Y_ControlMode	(0) No yaw control (1) Yaw rate control (2) Yaw by individual pitch control
Wind speed estimator (Section 5.1)	WE_Mode	(0) Filtered hub-height wind speed estimate (1) Immersion and invariance estimator (2) Extended Kalman filter
Individual pitch control	IPC_ControlMode	(0) No individual pitch control (1) 1P reductions (2) 1P and 2P reductions
Pitch saturation (Section 5.3)	PS_Mode	(0) No pitch saturation (1) Pitch saturation
Shutdown (Section 5.4)	SD_Mode	(0) No shutdown control (1) Shutdown at maximum pitch
Floating-specific feedback (Section 5.5)	Fl_Mode	(0) No floating-specific feedback (1) Include floating feedback term
Distributed aerodynamic control	Flp_Mode	(0) No flap control (1) Constant flap angle (2) PI flap control

where  $\omega_r$  is the rotor speed,  $R$  is the rotor radius, and  $v$  is the wind speed. Similar parameter surfaces can be generated for the thrust and torque coefficients of the turbine,  $C_t$  and  $C_q$ , respectively. An example  $C_p$  surface is shown in Figure 4 for the IEA



**Figure 4.**  $C_p$  surface for the IEA 15-MW wind turbine. The dash-dotted black line shows the below-rated steady-state operating points that result from a  $C_p$ -maximizing minimum pitch schedule at low wind speeds when the turbine has a minimum rotor speed constraint. The dashed blue line shows the expected steady-state operation points that are used to calculate the controller gain schedules.

The overlaid lines on the  $C_p$  surface shown in Figure 4 represent the expected steady-state operation point of the wind turbine. The dash-dotted black line shows the steady-state operating points at low wind speeds, where the TSR is high because of a constraint on the wind turbine’s minimum rotor speed. By imposing a blade pitch angle that is greater than fine pitch at low wind speeds, the turbine can operate at a higher point on the  $C_p$  surface. In below-rated operation, the turbine is expected to operate with a fixed blade pitch angle and a constant TSR (see Figure 2); this operation point is denoted by the red dot in Figure 4. In above-rated wind speeds, the blades pitch to regulate the rotor speed, and there is a reduction in TSR (see Figure 2), as denoted by the dashed blue line in Figure 4.

In the standard ROSCO toolbox tuning procedure, the steady-state blade element momentum solver cc-blade (Ning, 2013) is used to find the  $C_p$ ,  $C_t$ , and  $C_q$  surfaces quickly and efficiently. Similarly, parameter surfaces can be generated and written to a text file using any other blade element momentum or coupled aeroelastic solver. Using more complex solvers will, naturally, provide a more realistic  $C_p$  surface, though at a significant increase in computation time. Anecdotally, the authors have found the  $C_p$  ~~surfaces~~ surfaces generated using cc-blade to be sufficiently accurate for controller synthesis on numerous wind turbines thus far. Future work includes a more substantive analysis of the controller performance sensitivity to  $C_p$  ~~surfaces~~ surfaces generated using different aerodynamic solvers.

Within the ROSCO toolbox tuning processes, the  $C_p$  surface is primarily used to facilitate the calculation of the plant parameters, as discussed in Section 2.4. These parameters are used for tuning the blade pitch and generator torque controller gains and for accurate implementation of the wind speed estimator. The  $C_p$  surface is also used to determine the minimum blade pitch schedule in low wind speeds, if needed, and to determine the optimal below-rated TSR to maximize power output. Finally, the  $C_p$  surface is used within ROSCO itself so that the wind speed estimator can accurately estimate the operational

195 state of the wind turbine. The  $C_t$  surface is used to determine the minimum blade pitch schedule for the so-called “peak shaving” routine, as described in Section 5.3.1.

## 2.4 Plant Model

A number of generic tuning processes have been developed for the the ROSCO controller. The first publication on this work (Abbas et al., 2020) provided an initial formulation of the primary tuning processes in ROSCO. By using simplified analytical  
200 models of the wind turbine, the need for numerical linearization routines using servo-aeroelastic codes such as OpenFAST is avoided. To define the simplified wind turbine for control systems development, a first-order model of the wind turbine is used (Pao and Johnson, 2011):

$$\dot{\omega}_g = \frac{N_g}{J} (\tau_a - N_g \tau_g \eta_{gb}) \quad (2)$$

where the aerodynamic torque is:

$$205 \quad \tau_a = \frac{1}{2} \rho A_r \frac{C_p(\lambda, \beta)}{\omega_r} v^3. \quad (3)$$

In (2),  $\omega_g$  is the generator speed,  $J$  is the rotor inertia,  $N_g$  is the gearbox ratio, ~~and~~  $\tau_g$  is the generator torque, and  $\eta_{gb}$  is the gearbox efficiency. In (3),  $\rho$  is the air density, and  $A_r$  is the rotor area. The power coefficient  $C_p(\lambda, \beta)$  is found via lookup table. The first-order linearization of (3) at some nominal steady-state operational point is:

$$\underline{d}\Delta\tau_a = \Gamma_{\omega_g}|_{\text{op}} \underline{d}\Delta\omega_g + \Gamma_{\beta}|_{\text{op}} \underline{d}\Delta\beta + \Gamma_v|_{\text{op}} \underline{d}v\Delta v, \quad (4)$$

210 where  $\Gamma_{\omega_g} = \frac{\partial \tau_a}{\partial \omega_g}$ ,  $\Gamma_{\beta} = \frac{\partial \tau_a}{\partial \beta}$ , and  $\Gamma_v = \frac{\partial \tau_a}{\partial v}$ ; and “op” denotes the expected, steady-state operational  $\omega_g$ ,  $\beta$ , and  $v$  for any linearization point. Equation (2) can then be rewritten in a linearized form as:

$$\underline{d}\Delta\dot{\omega}_g = A(v_{\text{op}}) \underline{d}\Delta\omega_g + B_{\tau_g} \underline{d}\Delta\tau_g + B_{\beta}(v_{\text{op}}) \underline{d}\Delta\beta + B_v(v_{\text{op}}) \underline{d}v\Delta v, \quad (5)$$

where  $\Delta$  denotes a perturbation from the steady state value. Equation (5) is the plant model used to define the generator torque and blade pitch controller gains, where:

$$215 \quad A(v_{\text{op}}) = \frac{1}{J} \frac{d\tau_a}{d\lambda} \frac{d\lambda}{d\omega_g} \frac{\partial \tau_a}{\partial \lambda} \frac{\partial \lambda}{\partial \omega_g} \quad (6)$$

$$\frac{d\tau_a}{d\lambda} \frac{\partial \tau_a}{\partial \lambda} = \frac{N_g}{2} \rho A_r R v^2 \frac{1}{\lambda_{\text{op}}^2} \left( \frac{dC_p}{d\lambda} \frac{\partial C_p}{\partial \lambda} \lambda_{\text{op}} - C_{p,\text{op}} \right) \quad (7)$$

$$\frac{d\lambda}{d\omega_g} \frac{\partial \lambda}{\partial \omega_g} = \frac{1}{N_g} \frac{R}{v_{\text{op}}}, \quad (8)$$

and  $\lambda$  is the tip-speed ratio as defined in (1). The coefficients  $B_{\tau_g}$  and  $B_{\beta}(v_{\text{op}})$  are described in sections 3.1.2 and 4, where the blade pitch and generator torque controllers are described, respectively. To calculate the  $C_p$  surface gradients, a second-order  
220 central differencing approach is used.



Notably, this ~~This~~ linearized plant model is used to separately tune above- and below-rated controllers. ~~In above-rated operation, the generator torque is assumed to be constant, so  $d\tau_g = 0$ . Similarly, in below-rated operation, the blade pitch angle is assumed to be constant, so  $d\beta = 0$ . Finally, Note that~~  $B_v$ , the disturbance ( ~~$d\Delta v$~~ ) input matrix to the system, is set to 0 for the controller tuning.

## 225 2.5 Proportional-Integral Reference Tracking Control

A reference tracking PI controller is used in above-rated and below-rated operation. The PI controller is generically defined as:

$$y = k_p u + k_i \int_0^T u dt, \quad (9)$$

where  $u$  is an input to the controller;  $y$  is the output from the controller passed to the wind turbine; and  $k_p$  and  $k_i$  are the proportional and integral gains, respectively. For example, the standard PI blade pitch controller has inputs and outputs such that:

$$u = \underline{d\Delta\omega_g}, \quad y = \underline{d\Delta\beta}, \quad (10)$$

and the TSR tracking PI generator torque controller has inputs such that:

$$u = \underline{d\Delta\omega_g}, \quad y = \underline{d\Delta\tau_g}. \quad (11)$$

In (10) and (11), the generator speed error input,  $-\Delta\omega_g$ , is defined as a perturbation from the reference speed such that:

$$235 \quad \underline{\omega_g(t) = \omega_{g,\text{ref}} + \Delta\omega_g} \quad \longrightarrow \quad \underline{-\Delta\omega_g = \omega_{g,\text{ref}} - \omega_g(t)}, \quad (12)$$

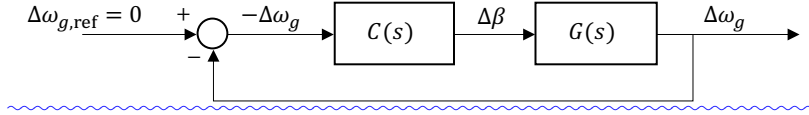
while  $\Delta\beta$  and  $\Delta\tau_g$  are perturbations from their respective nominal steady state values such that:

$$\underline{\beta(t) = \beta_{\text{op}} + \Delta\beta}, \quad \underline{\tau_g(t) = \tau_{g,\text{op}} + \Delta\tau_g}. \quad (13)$$

~~Combining~~ By combining the PI controller formulation in (9) with ~~the linear model in~~ (10) or (11) ~~and (5) in a standard negative-feedback loop results in the~~, a differential equation relating the reference generator speed perturbation  $\Delta\omega_{g,\text{ref}}$  and ~~the actual generator speed perturbation  $\Delta\omega_g$  is obtained. If we take the Laplace transform of this differential equation, the closed-loop transfer function~~ ~~from  $\Delta\omega_{g,\text{ref}} = 0$  to  $\Delta\omega_g$  results in:~~

$$H(s) = \frac{\underline{d\Omega_g(s)} \quad \underline{\Delta\omega_g(s)}}{\underline{d\Omega_{g,\text{ref}}(s)} \quad \underline{\Delta\omega_{g,\text{ref}}(s)}} = \frac{B(k_p(v_{\text{op}})s + k_i(v_{\text{op}}))}{s^2 + (Bk_p(v_{\text{op}}) - A(v_{\text{op}}))s + Bk_i(v_{\text{op}})}, \quad (14)$$

where ~~the subscript “g,ref” denotes the generator speed reference speed; and~~  $B$  is either  $B_{\tau_g}$  or  $B_{\beta}(v_{\text{op}})$ , depending on whether the turbine is in below- or above-rated operation, respectively. ~~For a standard horizontal-axis wind turbine,  $B$  is negative in below- and~~ A block diagram to visualize this closed-loop system in above-rated operation, ~~so  $k_i$  and  $k_p$  are generally negative.~~



**Figure 5.** A block diagram showing the closed-loop system used to tune the ROSCO controller in above-rated operation. The blocks  $C(s)$  and  $G(s)$  represent the controller and plant transfer functions, respectively.

is shown in Figure 5. Note that  $\Delta\omega_{g,\text{ref}} = 0$  because we would not like the rotor speed to differ from the reference value,  $\omega_{g,\text{ref}}$ .

This closed-loop system is a simple second-order system, so we define the PI gains as:

$$k_p(v_{\text{op}}) = \frac{1}{B}(2\zeta_{\text{des}}\omega_{\text{des}} + A(v_{\text{op}})), \quad (15)$$

$$250 \quad k_i(v_{\text{op}}) = \frac{\omega_{\text{des}}^2}{B}, \quad (16)$$

where the closed-loop response is characterized by a desired natural frequency,  $\omega_{\text{des}}$ , and damping ratio,  $\zeta_{\text{des}}$ . For a standard horizontal-axis wind turbine,  $B$  is negative in below- and above-rated operation, so  $k_i$  and  $k_p$  are negative. Therefore, based on this formulation, an increase in rotor speed results in  $-\Delta\omega_g < 0$  and an increase of generator torque or blade pitch angle. By defining the desired natural frequency and damping ratio of the rotor speed response, the user can modify the dynamic response of the rotor to changes in the wind speed. Increased desired natural frequencies will decrease the response time of the rotor, whereas increased damping ratios will reduce the amount of oscillation in the response. To learn more about second-order system responses, the authors recommend Franklin et al. (2019) to the curious reader.

If PI controllers are employed for below- and above-rated operation, we are left with the need to define four controller tuning inputs. The choice of  $\omega_{\text{des}}$  and  $\zeta_{\text{des}}$  for the below- and above-rated operating regions are the only parameter decisions that need to be made by the control designer or optimization routine, though additional tuning of the individual modules discussed in Section 5 might further improve controller performance.

## 2.6 Filters

Four filters are commonly used in the ROSCO controller (see Figure 3): first- and second-order low-pass filters, a first-order high-pass filter, and a notch filter. Appendix A shows the continuous-time formulations of these filters. The filters are converted to discrete time for implementation using the bilinear transform.

## 3 The Generator Torque Controller

Four total variable-speed generator torque control methods are available in ROSCO (see Table 1). Two methods of optimal power generation are available for below-rated operation, and two methods of maintaining power output near the turbine's rated value are available in above-rated operation.

### 270 3.1 Below-Rated Torque Control

In below-rated operation, the generator torque controller's goal is to maximize power production. If the blades are pitched to fine pitch, maximum aerodynamic efficiency can be achieved and power can be maximized if the torque controller maintains the TSR corresponding to the peak of the  $C_p$  surface. In ROSCO, this is done in one of two ways.

#### 3.1.1 $K\omega^2$ Law

275 A study of equation (2) in steady state, such that  $\dot{\omega}_g = 0$ , provides the foundation for the so-called " $K\omega_g^2$  law" for optimal torque control (Bossanyi, 2000; Johnson et al., 2006). By restructuring equation (2), and assuming that the wind turbine is operating at its optimal TSR,  $\lambda_{\text{opt}}$ , and corresponding power coefficient,  $C_{p,\text{max}}$ , one can realize a quadratic relationship between the generator speed and demanded generator torque. This relationship is commonly defined as:

$$\tau_g(t) = K\omega_g^2(t), \quad \text{where} \quad K = \frac{\pi \rho R^5 C_{p,\text{max}}}{2\lambda_{\text{opt}}^3 N_g^3 \eta_{\text{gen}} \eta_{\text{gb}}} \frac{\pi \rho R^5 C_{p,\text{max}}}{2\lambda_{\text{opt}}^3 N_g^3 \eta_{\text{gb}}}. \quad (17)$$

280 ~~In equation,  $\eta$  denotes efficiencies of the generator (gen) and gearbox (gb).~~

#### 3.1.2 Tip-Speed Ratio Tracking Torque Control

Two primary motivations are behind the development of the TSR tracking controller in ROSCO. First, although the  $K\omega_g^2$  law has historically worked reliably in idealized simulation environments, the calculation of  $K$  can be subject to modeling and assumption errors. For example, the assumption that  $R$  is a constant value across wind speeds does not hold as strongly  
285 in modern, highly flexible rotors as it has in the past. Fortunately, modern rotors are still commonly designed to maximize aerodynamic efficiency at a specific TSR. Second, industry collaborators have indicated that a TSR tracking controller is more representative of the controllers often used in the field.

If the blades are pitched to their most aerodynamically efficient angle and the wind turbine rotor is operating at its optimal TSR, the turbine power is theoretically maximized. This suggests that if the wind speed can be measured or estimated accurately, a generator torque controller can be designed to maintain the rotor's  $\lambda_{\text{opt}}$  and maximize power capture. In ROSCO, a  
290 standard PI controller is used to track a generator speed reference. For the generator torque controller:

$$\omega_{\text{ref},\tau} = N_g \frac{\lambda_{\text{opt}} \hat{v}}{R}, \quad (18)$$

where  $\hat{v}$  is the estimated rotor-effective wind speed provided by the wind speed estimator described in Section 5.1. This reference signal is also constrained by:

$$295 \omega_{g,\text{min}} \leq \omega_{\text{ref},\tau} \leq \omega_{g,\text{rated}}, \quad (19)$$

where  $\omega_{g,\text{min}}$  is the minimum allowable generator speed ~~and the subscript "rated" denotes the value as calculated at rated operation~~

A straightforward and automated tuning process has been developed for the PI gains for the TSR tracking torque controller. With the assumption that the blade pitch is held constant at fine pitch in below-rated operation,  $\dot{\beta} = 0$   $\Delta\beta = 0$  in (5). This  
 300 means that  $B = B_{\tau_g}$  in equations (15) and (16) and is defined as:

$$B = B_{\tau_g} = \frac{-N_g^2}{J} \quad (20)$$

for the generator torque controller. With this,  $\omega_{des}$  and  $\zeta_{des}$  can be chosen to describe the below-rated closed-loop rotor speed response, and (15) and (16) can be calculated for the generator torque controller. Equation (15) suggests that  $k_p(v)$  and  $A(v)$  are both dependent on  $v$ ; however, it was found that defining-fixing  $k_{p,vs} = k_p(v = v_{rated})$ , where the subscript “vs” denotes  
 305 variable-speed torque control, ~~provides less erratic control actuation~~ simplifies the controller implementation without negatively affecting ~~the power capture~~ power production or generator loads.

### 3.2 Above-Rated Torque Control

There are two standard methods of actuating the generator torque in above-rated operation. Defining  $P$  as the generator power output, in above-rated operation the generator torque is defined to be:

$$310 \quad \tau_{g,ar}(t) = \frac{P_{rated}}{\omega_{g,rated}}, \quad \text{or} \quad \tau_{g,ar}(t) = \frac{P_{rated}}{\omega_g(t)}, \quad (21)$$

for constant torque or constant power output, respectively, ~~where the subscript “rated” denotes the value as calculated at rated operation.~~

If the  $K\omega_g^2$  law is used for below-rated torque control, the torque controller switches to above-rated operation when the blades are pitched beyond an offset, denoted by `PC_Switch` in the `DISCON.IN` file. When the turbine is in above-rated operation,  
 315 the generator torque is then defined directly by the relationships in (21). If the TSR tracking control is used for below-rated operation, the above-rated generator torque output is simply constrained such that  $\tau_g(t) \leq \tau_{g,ar}(t)$ . In above-rated operation, the set point smoother (see Section 5.2) shifts the reference generator speed such that the generator torque is saturated at its maximum allowable value, resulting in either constant torque or constant power output.

If constant torque control is used, power output changes are directly correlated to the changes in the generator speed in  
 320 above-rated operation. If constant power control is used, there are still some changes in power output because  $\omega_g(t)$  in (21) is low-pass filtered, but the power is ~~much more consistent~~ more consistent than in the constant torque case. As discussed by Jonkman (2010), using a constant generator torque controller in above-rated operating conditions can help improve FOWT platform stability.

## 4 The Blade Pitch Controller

325 In below-rated operation, the generator speed is less than the rated generator speed, so the blade pitch angle,  $\beta$ , saturates at  $\beta = \beta_{min}$ . This is generally the fine-pitch angle, unless a pitch saturation schedule is implemented, as described in Section 5.3.

In above-rated operation, a PI controller is used to determine the collective blade pitch angle to keep the turbine at a rotor speed reference. The above-rated rotor speed reference  $\omega_{g,\text{ref}}$  for the blade pitch controller is generally defined as

$$\omega_{\text{ref},\beta} = \omega_{\text{rated}}. \quad (22)$$

330 It is well established, and common in reference controllers, to employ a gain schedule to improve blade pitch controller performance (Jonkman et al., 2009; Hansen and Henriksen, 2013; Mulders and van Wingerden, 2018). In the ROSCO toolbox we use the  $C_p$  surface to prescribe this gain schedule, rather than using aero-servo-elastic linearization tools.

When tuning the pitch controller's gain schedule, ~~it is assumed that the turbine's generator torque is kept constant, so  $d\tau_g = 0$~~  we cannot directly assume that the generator torque is kept constant because it may change if constant power operation is used. In constant power operation, the first-order Taylor series expansion of the generator torque in (21) is:

$$\tau_{g,\text{ar}}(t) = \frac{P_{\text{rated}}}{\omega_{g,\text{rated}}} - \frac{P_{\text{rated}}}{\omega_{g,\text{rated}}^2} \Delta\omega_g \quad (23)$$

Considering that the generator torque as defined by (13) can be rewritten as  $\tau_{g,\text{ar}}(t) = \tau_{g,\text{rated}} + \Delta\tau_g$  in ~~Consequently,  $B = B_\beta(v_{\text{op}})$~~  above-rated wind speeds, we define:

$$\Delta\tau_g = -\frac{P_{\text{rated}}}{\omega_{g,\text{rated}}^2} \Delta\omega_g \quad (24)$$

340 If constant power operation is used, then  $A(v_{\text{op}})$  in (6) is re-defined to:

$$A(v_{\text{op}}) = \frac{1}{J} \frac{\partial \tau_a}{\partial \lambda} \frac{\partial \lambda}{\partial \omega_g} - B_{\tau_g} \frac{P_{\text{rated}}}{\omega_{g,\text{rated}}^2}. \quad (25)$$

For constant torque operation, it can be assumed that  $\Delta\tau_g = 0$ , so no modifications are made to  $A(v_{\text{op}})$ . In both cases,  $B$  in equations (15) and (16) is:

$$B = B_\beta(v_{\text{op}}) = \frac{N_g}{J} \frac{\partial \tau_a}{\partial \beta} = \frac{N_g}{2J} \rho A_r R v_{\text{op}}^2 \frac{1}{\lambda_{\text{op}}^2} \left( \frac{\partial C_p}{\partial \beta} \Big|_{\lambda_{\text{op}}, \beta_{\text{op}}} \lambda_{\text{op}} \right). \quad (26)$$

345 For any wind speed  $v_{\text{op}}$ , the expected steady-state  $C_{p,\text{op}}$  can be calculated by (Bottasso and Croce, 2009):

$$C_{p,\text{op}} = C_{p,\text{rated}} \left( \frac{\lambda_{\text{op}}}{\lambda_{\text{rated}}} \right)^3. \quad (27)$$

Through the relationship in (27) and the  $C_p$  surface, we can find the expected blade pitch angles,  $\beta_{\text{op}}(\lambda_{\text{op}})$ , for any TSR. In steady-state above-rated operation, the generator speed is considered to be constant, so the TSR is only a function of the wind speed, and we can define  $\beta_{\text{op}}(v)$ . This enables us to change  $A(v_{\text{op}})$  and  $B_\beta(v_{\text{op}})$  to be  $A(\beta_{\text{op}})$  and  $B_\beta(\beta_{\text{op}})$  for controller tuning purposes. Equations (15) and (16) are then defined for the blade pitch controller to be  $k_{p,\text{pc}}(\beta_{\text{op}})$  and  $k_{i,\text{pc}}(\beta_{\text{op}})$ , and the blade pitch controller gain schedule can be implemented as a function of blade pitch angle rather than an estimated wind speed. In

the ROSCO implementation of the blade pitch controller, a low-pass-filtered blade pitch angle,  $\beta_{\text{lpf}}$ , is used to interpolate the necessary pitch controller gains,  $k_{p,\text{pc}}(\beta_{\text{lpf}}(t))$  and  $k_{i,\text{pc}}(\beta_{\text{lpf}}(t))$ , for the PI controller at each time step.

365 Notably, the  $C_p$  surface gradients used to calculate both  $A(v_{\text{op}})$  and  $B(v_{\text{op}})$  approach zero near the “peak” of the  $C_p$  surface. Because  $B_\beta(v_{\text{op}})$  is in the denominator of (15) and (16), the gains would theoretically approach infinity near rated operation. To avoid unrealistically high gains,  $A(v_{\text{op}})$  and  $B(v_{\text{op}})$  are each approximated by a linear fit for the blade pitch controller gain calculation in the ROSCO toolbox. With this foundation, the blade pitch controller’s gain schedule can be generated using the ROSCO toolbox for any user-defined  $\omega_{\text{des}}$  and  $\zeta_{\text{des}}$ .

## 5 Additional Control Modules

360 ROSCO is modularized such that various control methods can be switched on and off without the need to recompile any code. Here, we present the theoretical foundations for the module implementations and their respective generic tuning processes.

### 5.1 Wind Speed Estimator

In this section, we discuss the wind speed estimator used in ROSCO. The wind speed estimate is used in the TSR tracking generator torque controller (see Section 3.1.2) and pitch saturation (see Section 5.3) routines. The employed wind speed estimator is inspired by Knudsen et al. (2011) and is based on a continuous-discrete extended Kalman filter. The theoretical background of the continuous and discrete-time extended Kalman filters used in this work is further detailed in Grewal (2011). 365 The Kalman filter uses informed definitions of the covariance matrices based on the expected wind fields to provide a wind speed estimate,  $\hat{v}$ . The derivatives are evaluated in continuous time, whereas the measurement updates are evaluated in discrete time. A forward Euler integration method is used to propagate the state and covariance estimates forward in time.

370 The nonlinear continuous-time state-space model used for the continuous-discrete Kalman filter implemented in the controller is defined as

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}) + \boldsymbol{\xi}_s \quad (28)$$

$$y = h(\mathbf{x}, \mathbf{u}) + \xi_m, \quad (29)$$

where the system noise is  $\boldsymbol{\xi}_s = [n_1 \ n_2 \ n_3]^T$ , and  $n_i$  is considered to be zero-mean white noise. The measurement noise,  $\xi_m$ , 375 is assumed to be white noise with a constant covariance. The system state, inputs, and outputs are defined as:

$$\mathbf{x} = [\omega_r \ v_t \ v_m]^T \quad (30)$$

$$\mathbf{u} = [\beta \ \tau_g]^T \quad (31)$$

where  $v_t$  is the turbulent component of the wind speed, and  $v_m$  is the mean wind speed. The nonlinear state equations are defined as:

$$380 \quad \dot{\omega}_r = \frac{1}{J}(\tau_a - N_g \tau_g) \quad (32)$$

$$\dot{v}_t = -a(v_m)v_t + n_1 \quad (33)$$

$$\dot{v}_m = n_2 \quad (34)$$

and the output is:

$$y = \omega_r + \xi_m, \quad (35)$$

385 To complete the state equation definitions, we establish:

$$a(v_m) = \frac{\pi v_m}{2L} \quad (36)$$

$$\hat{v} = v_t + v_m. \quad (37)$$

In (36),  $L$  is a turbulence length-scale parameter generically defined as  $L = 3D$ , where  $D$  is the rotor diameter.

390 In the Kalman filter, the covariance matrices are based on the wind model as defined by Knudsen et al. (2011). In the ROSCO implementation of this wind speed estimator, the process noise ( $\mathbf{Q}$ ) and measurement noise ( $\mathbf{R}_m$ ) covariances are:

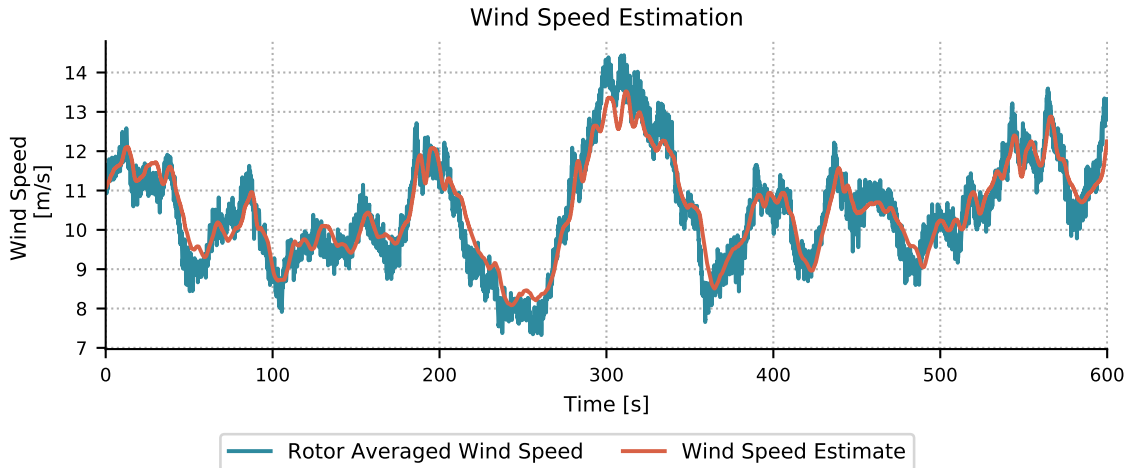
$$\mathbf{Q} = \begin{bmatrix} 1e^{-5} & 0 & 0 \\ 0 & \frac{\pi v_m^3 t_i^2}{L} & 0 \\ 0 & 0 & \frac{2^2}{600} \end{bmatrix}, \quad \mathbf{R}_m = 0.02, \quad (38)$$

where the turbulence intensity is defined as  $t_i = 0.18$ , the upper limit of the turbulence intensity for standard inflow wind conditions as defined by DNV-GL (2018). A continuous-discrete Kalman filter is then implemented through the following formulation:

395 – Prediction update:

$$\dot{\hat{\mathbf{x}}}(t) = f(\hat{\mathbf{x}}_{k-1|k-1}, \mathbf{u}_k), \quad (\text{Predicted state estimate}) \quad (39)$$

$$\dot{\hat{\mathbf{P}}}(t) = \mathbf{F}(t)\mathbf{P}_{k|k} + \mathbf{P}_{k|k}\mathbf{F}^T(t) + \mathbf{Q}_k - \mathbf{K}_{k-1}\mathbf{R}_m\mathbf{K}_{k-1}^T, \quad (\text{Predicted covariance estimate}) \quad (40)$$



**Figure 6.** Wind speed estimator results for the NREL 5-MW wind turbine with 10 minutes of simulation time and an average wind speed of 11  $m/s$ .

– Measurement update:

$$\tilde{y}_k = y_k - h_k(\hat{\mathbf{x}}_{k|k-1}), \quad (\text{Innovation residual}) \quad (41)$$

$$400 \quad \mathbf{S}_k = \mathbf{H}_k \mathbf{P}_{k|k-1} \mathbf{H}_k^T + \mathbf{R}_m, \quad (\text{Innovation covariance}) \quad (42)$$

$$\mathbf{K}_k = \mathbf{P}_{k|k-1} \mathbf{H}_k^T \mathbf{S}_k^{-1}, \quad (\text{Near-optimal Kalman gain}) \quad (43)$$

$$\hat{\mathbf{x}}_{k|k} = \hat{\mathbf{x}}_{k|k-1} + \mathbf{K}_k \tilde{y}_k, \quad (\text{Updated state estimate}) \quad (44)$$

$$\hat{v}_k = [0 \quad 1 \quad 1] \hat{\mathbf{x}}_{k|k}, \quad (\text{Wind speed estimate}) \quad (45)$$

$$\mathbf{P}_{k|k} = (\mathbf{I} - \mathbf{K}_k \mathbf{H}_k) \mathbf{P}_{k|k-1}, \quad (\text{Updated covariance estimate}) \quad (46)$$

405 where the state transition and output Jacobians are defined as:

$$\mathbf{F}(t) = \left. \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \right|_{\hat{\mathbf{x}}_{k-1|k-1}, \mathbf{u}_k}, \quad \mathbf{H}_k = \left. \frac{\partial \mathbf{h}}{\partial \mathbf{x}} \right|_{\hat{\mathbf{x}}_{k|k-1}}. \quad (47)$$

Wind speed estimator results from a 10-minute simulation of the NREL 5-MW turbine are shown in Figure 6. In the presented simulation, the root-mean-square error between the rotor-averaged wind speed and the wind speed estimate is 0.48  $m/s$ .

## 5.2 Set Point Smoothing

410 The generator torque and blade pitch controllers will conflict with each other in near-rated operation if the generator torque and blade pitch reference speeds are defined only by (19) and (22). To avoid this, we employ a set point smoother regime that is akin to a Region 2.5 controller (Schlipf; Zalkind and Pao, 2019). Practically, the so-called “set point smoother” shifts the



generator speed reference signal of the saturated controller while the unsaturated controller is active, so the controllers do not have conflicting behaviors. This encourages one controller to stay active while the other is not.

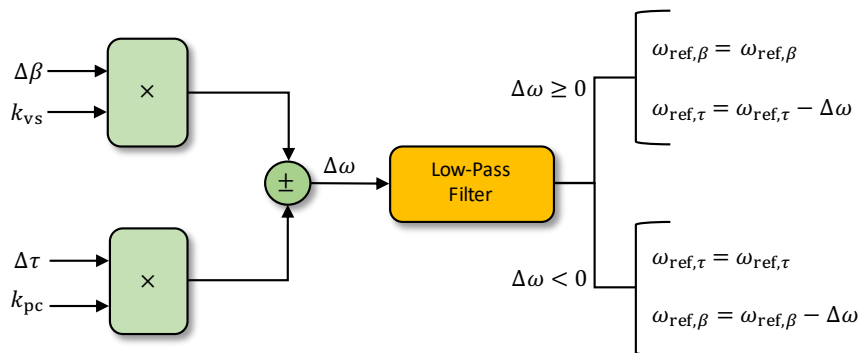
415 We first define an offset to the rotor speed set point,  $\Delta\omega$ , as:

$$\Delta\omega = \left[ \underbrace{\left( \frac{\beta - \beta_{\min}}{\beta_{\max}} \right)}_{\Delta\beta} k_{vs} - \underbrace{\left( \frac{\tau_{g,\max} - \tau_g}{\tau_{g,\max}} \right)}_{\Delta\tau} k_{pc} \right] \omega_{g,\text{rated}}, \quad (48)$$

where  $k_{vs}$  and  $k_{pc}$  are unitless gain factors that are greater than 0, and  $\beta_{\max}$  is the blade pitch angle at cut-out wind speed. Equation (48) is defined such that  $\Delta\beta = 0$  in below-rated operation, and  $\Delta\tau = 0$  in above-rated operation. A piecewise logic is then implemented to shift the blade pitch or generator torque reference generator speeds:

$$420 \quad \omega_{\text{ref},\tau} = \begin{cases} \omega_{\text{ref},\tau} - \Delta\omega & \Delta\omega \geq 0 \\ \omega_{\text{ref},\tau} & \Delta\omega < 0 \end{cases} \quad \text{and} \quad \omega_{\text{ref},\beta} = \begin{cases} \omega_{\text{ref},\beta} & \Delta\omega \geq 0 \\ \omega_{\text{ref},\beta} - \Delta\omega & \Delta\omega < 0 \end{cases}. \quad (49)$$

Figure 7 shows a block diagram displaying the set point smoother logic.

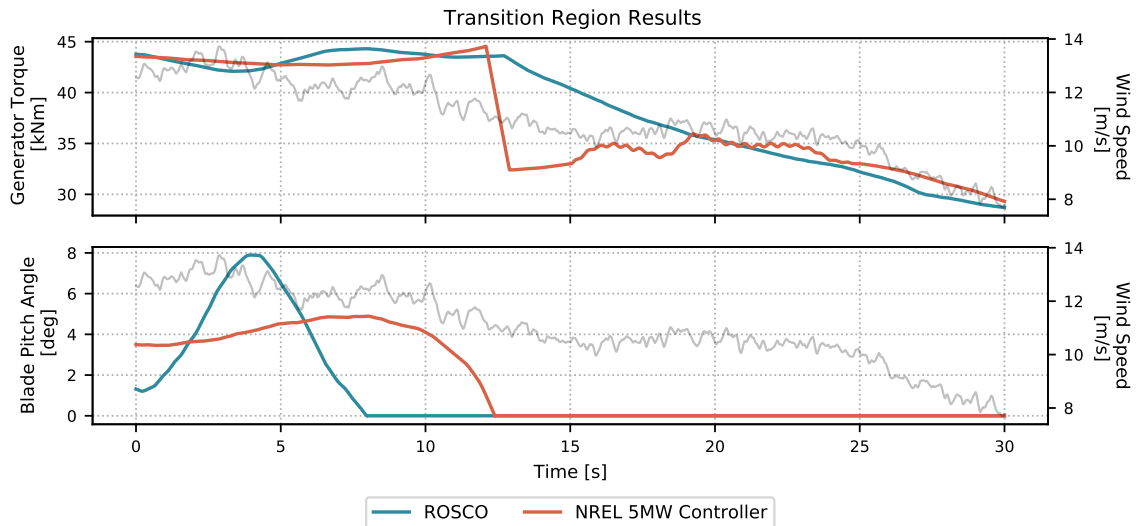


**Figure 7.** A block diagram of the set point smoother logic defined in (48)–(49) is shown here. The term  $\Delta\omega$  shifts the blade pitch or generator torque controller to help avoid unwanted controller interactions.

The shifting term in the set point smoother defined in (48) includes normalization terms, so no specific tuning is necessary. The ROSCO toolbox tuning processes define  $k_{vs} = 1$  and  $k_{pc} = 1e-3$ . These values were chosen because of their utility across turbine models, although specific tuning of these can improve the controller performance near rated operation.

425 Figure 8 shows results from a 10-minute time-domain simulations of the NREL 5-MW wind turbine near rated operation. The set point smoother employed in ROSCO provides significantly smoother transitions from above- to below-rated operation. When the blade pitch is greater than zero (the first 12 seconds in Figure 8), the torque controller set point decreases, which biases the generator torque toward its maximum value. When the generator torque is less than its rated value (the last 12 seconds in Figure 8), the set point for the pitch controller increases, and it biases the pitch to its minimum value. The smoother  
430 shifts the saturated controller's set point linearly depending on how "far" it is from rated operation. By separating the control

regions this way, resonances such as those seen in the time history of the NREL 5-MW torque controller’s signal between 15 and 25 seconds can be reduced.



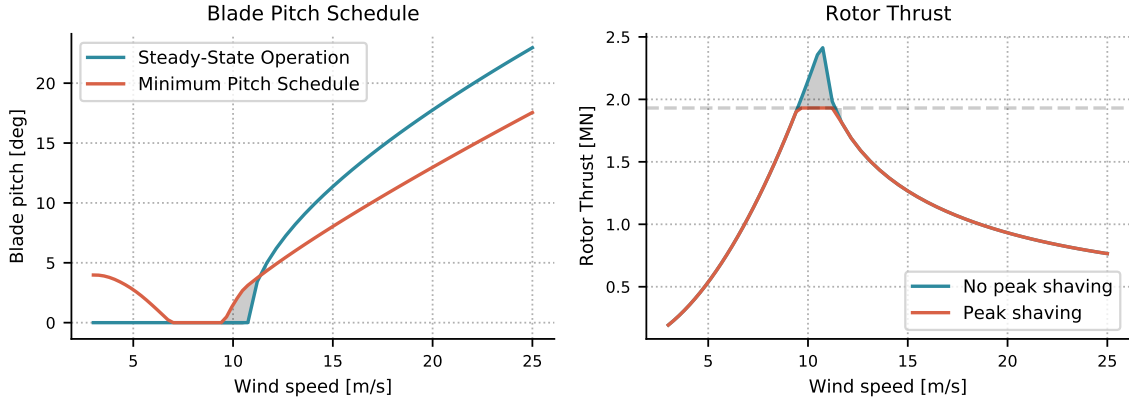
**Figure 8.** Time-domain simulation results from the NREL 5-MW wind turbine near rated wind speeds. The rotor-averaged wind speed is plotted in the background as grey curves in each plot.

### 5.3 Minimum Pitch Saturation

A method for saturating the minimum blade pitch angle for a given wind speed estimate is also included in ROSCO. This has  
 435 primarily been used for two purposes: to limit the rotor thrust through a peak shaving algorithm and to implement a minimum  
 pitch angle at low wind speeds for power maximization in the presence of a minimum rotor speed constraint. The ROSCO  
 controller simply defines a minimum blade pitch angle for a given wind speed as [defined-specified](#) by a lookup table in the  
 DISCON.IN file. Figure 9 provides an example minimum pitch schedule for the IEA 15-MW wind turbine with a minimum  
 rotor speed constraint and peak shaving, along with the corresponding rotor thrust that is expected with and without peak  
 440 shaving. The following two subsections describe the two primary aspects of the minimum pitch schedule in more detail.

#### 5.3.1 Peak Shaving

Thrust limiting, or peak shaving, is often used to reduce peak tower base loads. Generally, the largest rotor thrusts are seen  
 near rated operation and have a strong affect on tower base loads. It is has also been shown that rotor thrust is correlated to the  
 blade pitch actuation (Bossanyi, 2003; Fischer and Shan, 2013; Petrović and Bottasso, 2017). We impose a minimum blade  
 445 pitch angle,  $\beta_{\min}(v)$ , to “shave” the peak of the rotor thrust curve and subsequently reduce tower base loads near rated. The



**Figure 9.** Expected steady-state pitch saturation for the IEA 15-MW wind turbine, based on the  $C_t$  surface calculated with cc-blade. The blade pitch schedule (left) shows the expected steady-state value of the pitch angle along with the imposed minimum pitch angles with pitch saturation for both peak shaving and power maximization in low wind speeds. The righthand plot shows the expected rotor thrust with and without peak shaving. The grey region in the blade pitch schedule corresponds to the pitch angles that result in a rotor thrust above the maximum allowable thrust, shown as the grey region in the righthand plot.

rotor thrust can be defined by:

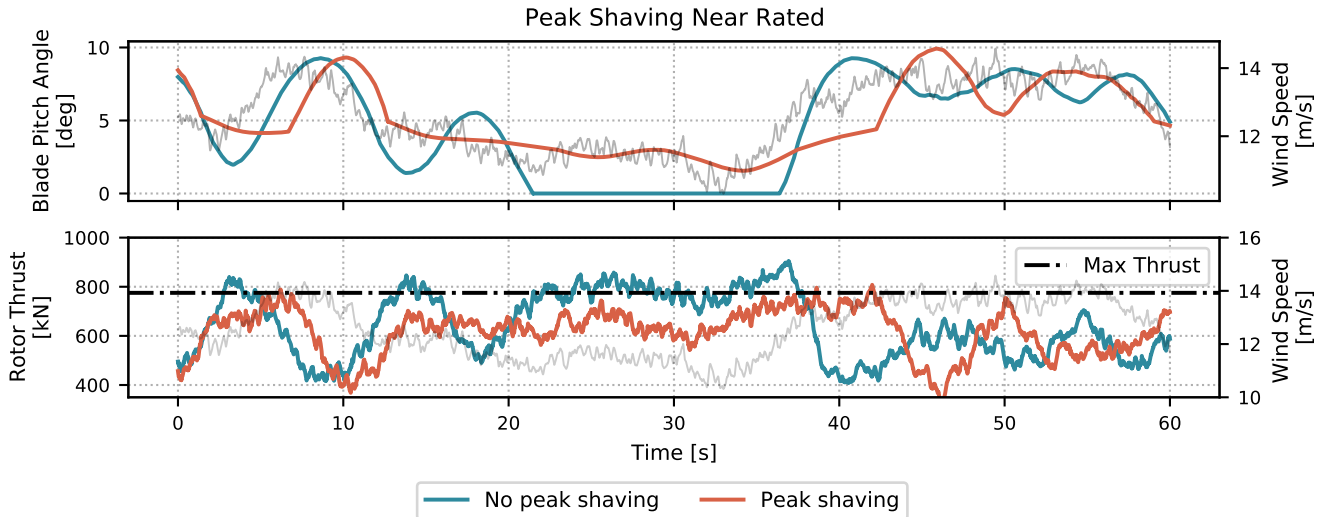
$$T_r(v) = \frac{1}{2} \rho A_r v^2 C_t(\lambda, \beta), \quad (50)$$

where  $C_t$  is the rotor thrust coefficient. Given a maximum allowable rotor thrust,  $T_{r,\max} = a \max(T_r(v))$ , where  $a \leq 1$ , the maximum allowable thrust coefficient is defined as:

$$450 \quad C_{t,\max}(v) = \frac{2T_{r,\max}}{\rho A_r v^2}. \quad (51)$$

For all operational TSRs, we can find a blade pitch angle,  $\beta_{\min}(C_{t,\max}, \lambda)$ , through a  $C_t$  surface similar to the  $C_p$  surface shown in Figure 4. Notably,  $C_{t,\max}(v)$  and  $\lambda$  are both parameterized by  $v$ , so we can define a minimum blade pitch schedule,  $\beta_{\min}(v)$ , that is dependent on a wind speed estimate. Figure 10 shows an example 60-second time series for the NREL 5-MW wind turbine in near-rated operation. Based on the wind speed estimate, the blades are pitched to reduce the rotor thrust to stay at or  
455 below the maximum allowable thrust limit.

Peak shaving algorithms implemented with minimum pitch saturation can result in power losses because the turbine will no longer be operating at its highest efficiency near rated. Though the default peak shaving algorithm in the ROSCO toolbox reduces the maximum rotor thrust by 25%, ultimately the trade-off between power production and load reductions must be made by the control system designer.



**Figure 10.** A sample 1-minute time series from a 10-minute turbulent simulation of the NREL 5-MW wind turbine to showcase the peak shaving routine in ROSCO. The peak shaving percentage was tuned to 20% for this simulation. The wind speed is shown in the background of each plot, and the maximum allowable thrust is denoted by the dash-dotted black line in the lower plot.

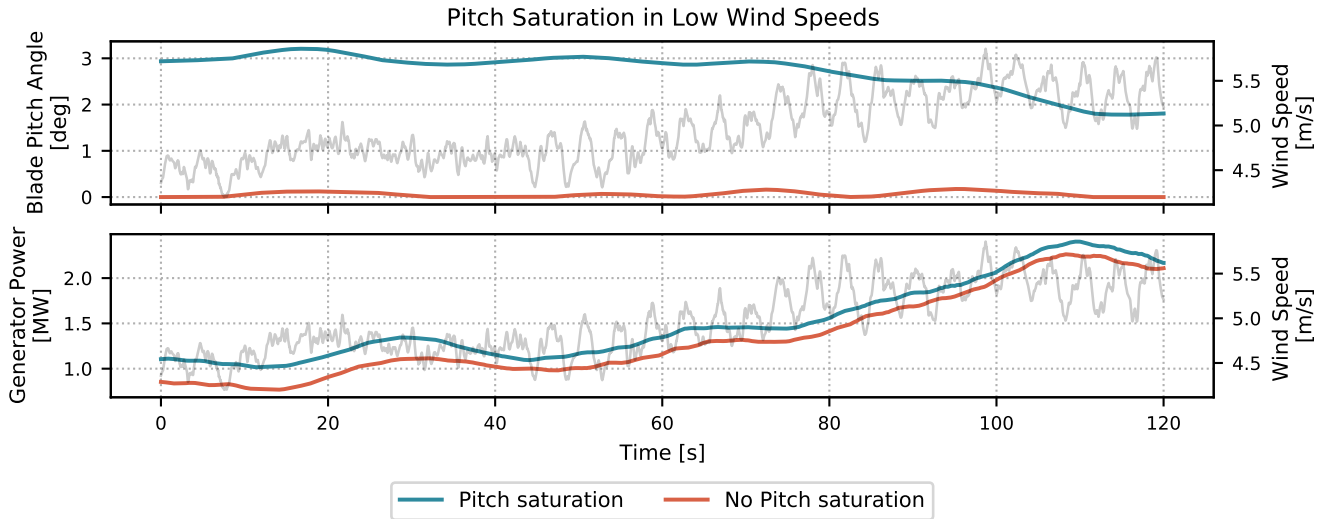
### 460 5.3.2 Power Maximization in Low Wind

In certain wind turbine configurations, such as the IEA 15-MW wind turbine (Gaertner et al., 2020), minimum or maximum blade tip-speed limits might be imposed for reasons such as tower resonance avoidance or noise avoidance. If a minimum tip-speed constraint exists, the wind turbine cannot operate at  $\lambda_{\text{opt}}$  in low wind speeds. A minimum pitch schedule can be implemented such that the power can be maximized in low wind speeds while the generator torque controller works to satisfy the minimum rotor speed constraints. The black dash-dotted line in Figure 4 provides insight into how the power output can be improved through a minimum pitch angle at low wind speeds by moving the turbine’s expected operating point to the “top” of the  $C_p$  surface for high TSRs.

Figure 11 shows an example of how the power can be increased. A 10-minute simulation was run in OpenFAST for an inflow wind with normal turbulence and a  $5\text{-m/s}$  average wind speed. With the pitch saturation module turned on, the blade pitch angle is changed based on the wind speed estimate and the pitch saturation lookup table, resulting in a slightly increased power output.

### 5.4 Shutdown

A simple shutdown routine is included in ROSCO for shutdown during high wind speed events. A first-order low-pass-filtered blade pitch angle signal triggers turbine shutdown if it exceeds a certain threshold. If the shutdown is initiated, the blades are pitched to feather at their maximum pitch rate to slow down the rotor. If the TSR tracking torque controller is being used,  $\omega_{\text{ref},\tau}$



**Figure 11.** A sample 2-minute time series from a 10-minute turbulent simulation of the IEA 15-MW wind turbine showing how increased blade pitch angles can increase power output at low wind speed. The rotor-averaged wind speeds are plotted in grey in the background.

is set to the minimum rotor speed. This encourages the torque controller to help slow down the rotor initially. Once the blades are pitched such that very little lift is generated and the rotor is nearly stopped, the torque controller will saturate at zero in an unsuccessful attempt to speed up the rotor to the minimum rotor speed.

It is shown in Bottasso et al. (2014) that there are shutdown methods that could reduce possible design-driving loads during shutdown. Future work includes the investigation and inclusion of these methods in the ROSCO controller. Additionally, a number of events can trigger wind turbine shutdowns, such as generator overspeeds and yaw misalignment. Future work also includes the addition of improved shutdown event-detection and control methods for such cases.

## 5.5 Floating Offshore Wind Turbine Feedback

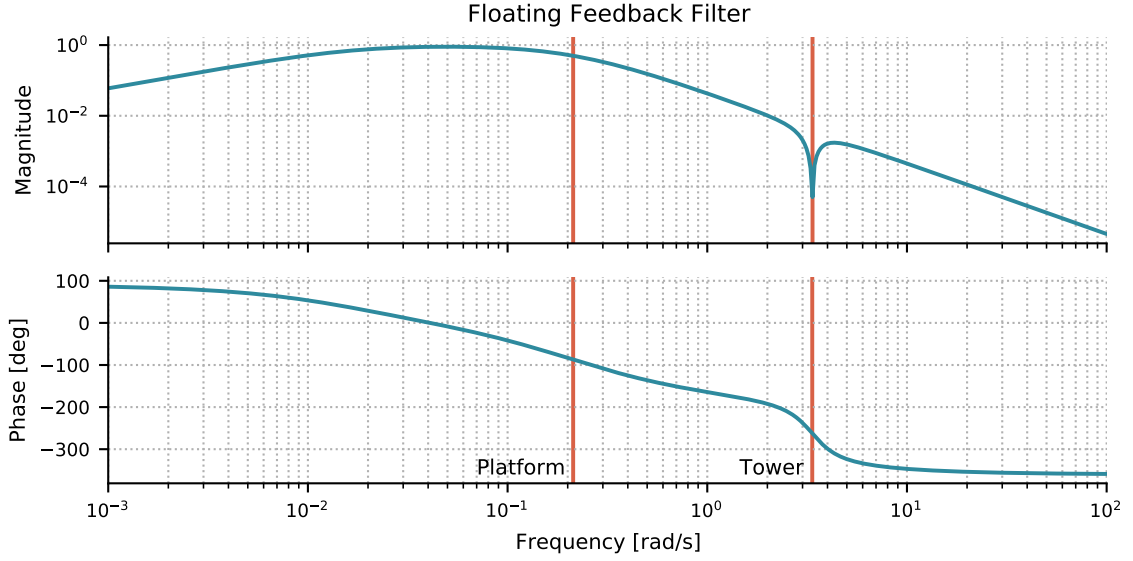
An additional control feedback term is included to account for FOWTs in a method referred to as “parallel compensation” (Van Der Veen et al., 2012). The tower-top acceleration is filtered, integrated, and multiplied times a proportional gain feedback,  $k_{\beta_{\text{float}}}$ . This modifies the blade pitch control signal to become:

$$d\Delta\beta = k_p d\Delta\omega_g + k_i \int_0^T d\Delta\omega_g dt + k_{\beta_{\text{float}}} d\dot{\phi} \Delta x_t, \quad (52)$$

where  $\phi x_t$  is the tower-top pitch angle position in the fore-aft direction. The block diagram in Figure 3 provides a visualization of how this signal is implemented.

Although some research suggests the use of a platform pitch feedback signal for FOWT control (Fleming et al., 2014, 2016), the tower nacelle fore-aft signal is used in ROSCO so that the overall controller implementation can maintain the structure

of the bladed-style communication interface (DNV-GL, 2018). A first-order high-pass filter combined with a second-order low-pass filter are used to filter the nacelle fore-aft **rotational**-acceleration signal. The ROSCO toolbox generically places high- and low-pass filter cutoff frequencies at  $0.01 \text{ rad/s}$   $0.01 \text{ rad/s}$  and the platform's first fore-aft natural frequency, respectively. 495 Additionally, a notch filter is used to remove the tower fore-aft frequency component of the feedback signal for the floating controller. A Bode diagram of the final form of this filter is shown in Figure 12 for the IEA 15-MW wind turbine on the University of Maine (UMaine) semisubmersible platform (Allen et al., 2020). After this nacelle fore-aft **rotational**-acceleration signal is filtered and integrated, it is similar to a platform pitching velocity signal that is often used for FOWT control.



**Figure 12.** A Bode plot showing the filter used for the tower-top motion feedback signal for the IEA 15-MW turbine on the UMaine semisubmersible platform. The first platform and tower fore-aft natural frequencies are shown in red and labeled accordingly. These natural frequencies are inputs to the ROSCO tuning process to shape this filter.

For consistency with the theme of the ROSCO tool set, a generic tuning process has been developed for this floating-feedback 500 term. We start by defining the simplified second-order equation of tower-top motion as:

$$J_t \underline{d\ddot{\phi}} \underline{\ddot{x}}_t + c_t \underline{d\dot{\phi}} \underline{\dot{x}}_t + k_t \underline{d\phi} = \underline{l} \underline{x}_t \underline{dT} \underline{=} \underline{T}_r, \quad (53)$$

where  $J_t$  is the total system inertia in the platform pitching direction,  $c_t$  is a damping constant,  $k_t$  is a restoring constant,  $l_t$  is 505 the tower height, and  $T_r$  is the rotor thrust as defined by (50). The rotor effective wind speed is modified by tower motion such that:

$$\underline{dv} \underline{\Delta} \underline{v} = \underline{dv} \underline{\Delta} \underline{v}_w - \underline{l} \underline{\Delta} \underline{\dot{x}}_t \underline{d\dot{\phi}}, \quad (54)$$

where  $d\underline{v}_w - \underline{\Delta}v_w$  is the change in freestream wind speed. Similar to the derivation of (4), we can linearize (50) to be:

$$\underline{dT} \underline{\Delta T}_r = \Pi_{\omega_g} \underline{d} \underline{\Delta} \omega_g + \Pi_{\beta} \underline{d} \underline{\Delta} \beta + \Pi_v \underline{d} v_w \underline{\Delta} v, \quad (55)$$

where  $\Pi_{\omega_g} = \frac{\partial T_r}{\partial \omega_g}$ ,  $\Pi_{\omega} = \frac{\partial T_r}{\partial \beta}$ , and  $\Pi_v = \frac{\partial T_r}{\partial v}$ .

For the controller, we have suggested that a proportional feedback term should be added to the standard blade pitch PI controller, such that the control input should be defined by (52). We also define the generator position as  $\theta$  such that:

$$\dot{\theta} = \omega_g, \quad \ddot{\theta} = \dot{\omega}_g. \quad (56)$$

After substituting (52) and (54)–(56) in equations (53) and (5), we arrive at the equations of motion for the closed-loop tower-top **pitching** (57) and rotor (58) dynamics:

$$d \ddot{\underline{\phi}} \underline{\dot{x}}_t = \frac{1}{J_t} \left[ -k_t \underline{d} \underline{\phi} \underline{d} x_t + (-c_t - \Pi_v \underline{l}_t^2 + \Pi_{\beta} \underline{l}_t k_{\beta_{\text{float}}}) d \underline{\phi} \underline{\dot{x}}_t + \Pi_{\beta} \underline{l}_t k_i d \theta + (\Pi_{\omega} \underline{l}_t + \Pi_{\beta} \underline{l}_t k_p) d \dot{\theta} + \Pi_v \underline{l}_t d v_w \right], \quad (57)$$

$$d \ddot{\theta} = \frac{N_g}{J} \left[ (\Gamma_{\beta} k_{\beta_{\text{float}}} - \Gamma_v \underline{l}_t) d \underline{\phi} \underline{\dot{x}}_t + \Gamma_{\beta} k_i d \theta + (\Gamma_{\omega_g} + \Gamma_{\beta} k_p) d \dot{\theta} + \Gamma_v d v_w - N_g d \tau_g \right]. \quad (58)$$

If we then convert equations (57) and (58) into the state-space form  $\dot{\underline{x}} = \underline{A} \underline{x} + \underline{B} \underline{u}$ , where  $\underline{u} = [d v_w \quad d \tau_g]^T$  and  $\underline{x} = [d \underline{\phi} \quad d \underline{\phi} \quad d \theta \quad d \dot{\theta}]^T$ ,  $\underline{\dot{x}} = \underline{A} \underline{x} + \underline{B} \underline{u}$ , where:

$$\underline{u} = [\underline{\Delta} v_w \quad \underline{\Delta} \tau_g]^T, \quad (59)$$

$$\underline{x} = [\underline{\Delta} x_t \quad \underline{\Delta} \dot{x}_t \quad \underline{\Delta} \theta \quad \underline{\Delta} \dot{\theta}]^T, \quad (60)$$

520 we can define:

$$\underline{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -k_t & (-c_t - \Pi_v \underline{l}_t^2 + \Pi_{\beta} \underline{l}_t k_{\beta_{\text{float}}}) & \Pi_{\beta} \underline{l}_t k_i & (\Pi_{\omega} \underline{l}_t + \Pi_{\beta} \underline{l}_t k_p) \\ 0 & 0 & 0 & 1 \\ 0 & (\Gamma_{\beta} k_{\beta_{\text{float}}} - \Gamma_v \underline{l}_t) & \Gamma_{\beta} k_i & (\Gamma_{\omega_g} + \Gamma_{\beta} k_p) \end{bmatrix}, \quad \underline{B} = \begin{bmatrix} 0 & 0 \\ \Pi_v \underline{l}_t & 0 \\ 0 & 0 \\ \Gamma_v & -N_g \end{bmatrix}. \quad (61)$$

Note that  $A(4,2)$  is the state transition term from  $d \underline{\phi}$  to  $d \ddot{\theta}$   $\underline{\Delta} \dot{x}_t$  to  $\underline{\Delta} \ddot{\theta}$ . This suggests that if  $\Gamma_{\beta} k_{\beta_{\text{float}}} - \Gamma_v \underline{l}_t = 0$   $\Gamma_{\beta} k_{\beta_{\text{float}}} - \Gamma_v = 0$ , then the tower-top pitching velocity will have no direct affect on the rotor acceleration. To attempt to achieve this, we define:

$$k_{\beta_{\text{float}}} = \frac{\Gamma_v \underline{l}_t}{\Gamma_{\beta}} = \frac{\partial \tau_a}{\partial v} \left( \frac{\partial \tau_a}{\partial \beta} \right)^{-1} \underline{l}_t \quad (62)$$

525 Including the additional parallel-compensation term  $\beta_{\text{float}}$  reduces the need to detune the standard blade pitch PI controller because of the infamous negative-damping problem (Larsen and Hanson, 2007). If tuned appropriately, the parallel compensation term can help negate the affect of tower-top motion and subsequent changes to the relative wind speed at the rotor. Additionally, combining the use of this  $\beta_{\text{float}}$  feedback term with a peak shaving routine from Section 5.3.1 can reduce the tower-top pitching transients and further stabilize the system. Though the peak shaving does, theoretically, reduce power output near rated operation, the tower-top stabilization benefits generally outweigh the power losses because less fore-aft tower motion can lead to increased power output.

## 6 Example Results and Analysis

In this section, we use ROSCO v2.2.3.0 and present results from both land-based and floating wind turbine simulations. First, the ROSCO controller, as tuned by the ROSCO toolbox, is compared to the NREL 5-MW wind turbine controller using the  
 535 land-based NREL 5-MW wind turbine. Then, results from the IEA 15-MW atop the UMaine semisubmersible floating wind turbine configuration (Allen et al., 2020) are shown to illustrate the effect of the FOWT  $\beta_{\text{float}}$  control feedback loop. The subset of the International Electrotechnical Commission (IEC) design load cases (DLCs) (DNV-GL, 2016) shown in Table 2 were run for both turbines to offer a comparison of controller performance.

**Table 2.** Simulated DLCs to showcase the difference in controller performance. The wind speeds were separated by increments of  $2 \text{ m/s}$ , with normal and extreme turbulence models defined by the IEC et al. (2006) standards. The sea-state-related inputs are relevant only for the FOWT simulations. Simulations were run for codirectional waves (i.e., wind and waves are aligned) to isolate the negative-damping phenomena that is generally of interest to the control designer.

DLC	Wind Condition	Wind Speeds	Seeds	Waves
1.1	Normal turbulence	3 to 25 m/s	6	Normal sea state, co-directional
1.3	Extreme turbulence	3 to 25 m/s	6	Normal sea state, co-directional

### 6.1 NREL 5-MW Land-Based Wind Turbine Results

540 The land-based NREL 5-MW turbine with the ~~the~~ NREL 5-MW wind turbine controller is compared to ROSCO with the ROSCO toolbox generic tuning values and ROSCO with minimal manual tuning and peak shaving implemented. As previously stated, there are only four *necessary* tuning parameters when tuning ROSCO using the generic ROSCO toolbox tuning functionalities. For the NREL 5-MW configuration, the choices for  $\zeta_{\text{des}}$  and  $\omega_{\text{des}}$  are shown in Table 3. The controller tuning parameters used for ROSCO's pitch controller in the results presented in this section were chosen to be the same as those  
 545 used for scheduling the gains of the NREL 5-MW reference controller. ROSCO's TSR tracking torque controller was tuned manually so that below-rated simulations resulted in consistent TSR tracking.

**Table 3.** ROSCO controller tuning values for the collective blade pitch and TSR tracking torque controllers for the DLC simulations of the NREL 5-MW wind turbine.

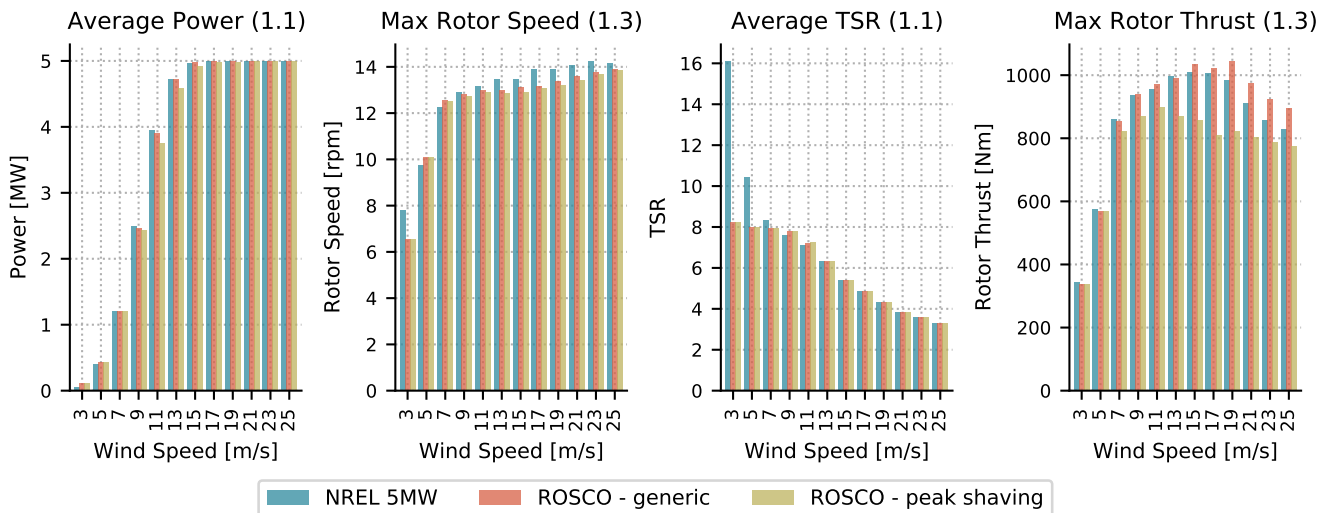
	$\zeta_{\text{des}} (-)$	$\omega_{\text{des}} (\text{rad/s})$
Collective blade pitch controller	0.7	0.6
Tip-speed ratio tracking torque controller	0.7	0.15

The collective blade pitch controller gain schedules from the ROSCO tuning process are similar to those from the NREL 5-MW reference controller's tuning process, but they are not the same. The NREL 5-MW reference controller's gain schedule



is based on the turbine’s sensitivity of aerodynamic power to the collective blade pitch angle, a value that has generally been found using more computationally expensive aeroelastic solvers, whereas the ROSCO tuning process depends directly on the  $C_p$  surface.

High-level comparison results of the ROSCO controller compared to the NREL 5-MW reference controller are shown in Figure 13. Results are shown from both the generic ROSCO controller and a “tuned” ROSCO controller with peak shaving. For the tuned controller, all controller tuning input parameters were kept the same as for the generic ROSCO controller with the exception of modifying the set point smoother gains to be  $k_{vs} = 5$  and  $k_{pc} = 0.01$  and implementing the standard peak shaving routine. The results from the generic ROSCO controller are consistent with the expected steady-state operating points shown in Figure 2. In the results from the generic ROSCO controller, there is a noticeable increase in rotor thrust compared to the NREL 5-MW reference controller. This is attributed to the difference in pitch controller gains, and it can be mitigated with slightly different controller tuning parameters. Also, note that the NREL 5-MW reference controller exhibits significantly higher TSRs because of the torque controller’s linear transition between regions 1 and 2 (Jonkman et al., 2009) rather than the PI controller-based transition that is used in ROSCO. The ROSCO controller tracks the optimal TSR of 7.5 well during below-rated operation.



**Figure 13.** Results from simulations of the NREL 5-MW land-based wind turbine. Average power, maximum rotor speeds, average TSRs, and maximum rotor thrusts are shown for DLCs 1.1 and 1.3. The dynamic results from the ROSCO controller are comparable to those from the NREL 5-MW reference controller. “ROSCO - generic” refers to ROSCO with the most generic tuning methods, and “ROSCO - tuned peak shaving” refers to ROSCO with tuned set point smoother gains and peak shaving implemented.

The power output and subsequent annual energy production from the ROSCO controller is 0.4% greater than that of the NREL 5-MW reference controller without peak shaving. This is consistent with observations by Holley et al. (1999) and Bossanyi (2000), who note that minor energy production gains are possible to be achieved through an optimal

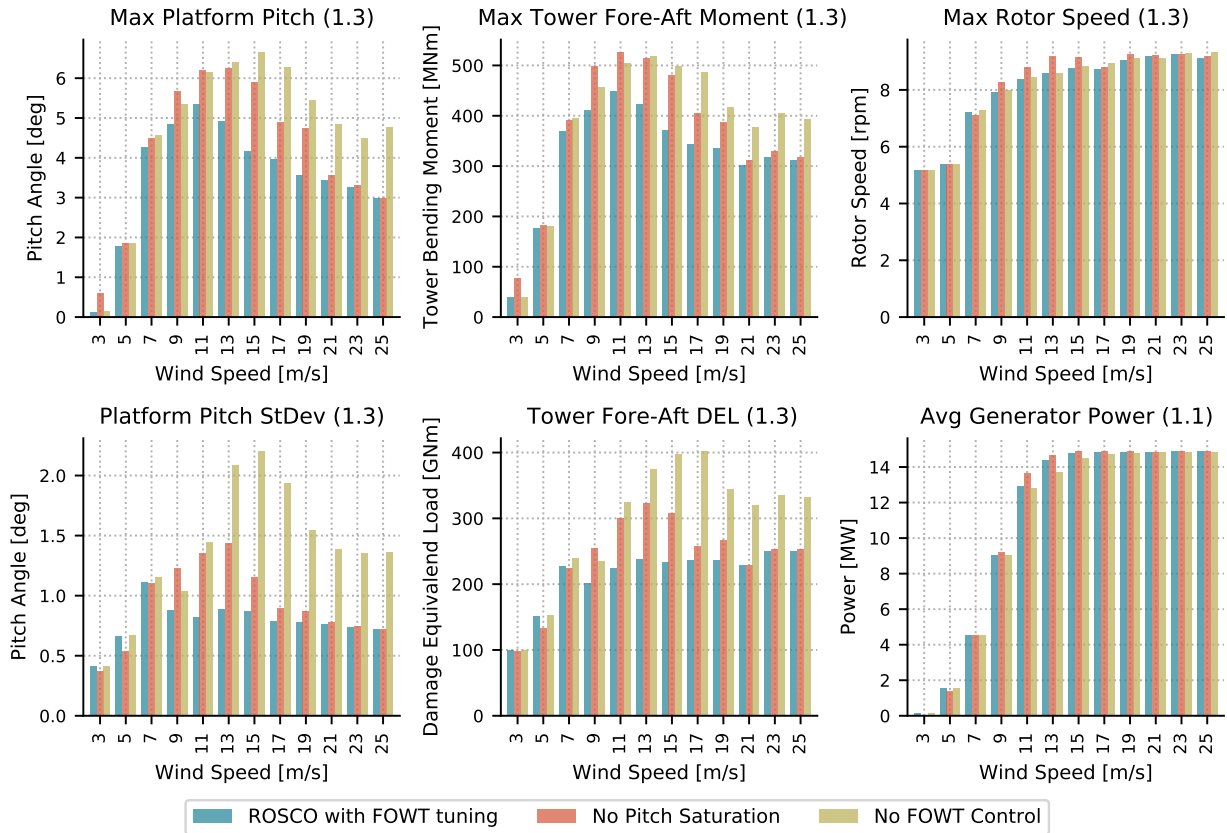
TSR-tracking controller ~~are possible~~, though at cost of more generator power fluctuations. ~~The maximum standard deviations~~ In fact, the maximum standard deviation of the power output during DLC 1.1 ~~are only 5% higher using ROSCO than when using decreased by 1.5% when using ROSCO instead off~~ the NREL 5-MW reference controller, so ~~very minor power production increases can be expected for the controller tuning used in this study~~ no significant power increases are expected. The annual energy production from the ROSCO controller is 1.7% less than that of the NREL 5-MW reference controller when the peak shaving routine is implemented in ROSCO. This is expected because rotor thrust reductions reduce the wind turbine's power output as well. Notably, the maximum rotor thrust seen is slightly higher than the expected maximum rotor thrust (see Figure 10). This is attributed to the imperfect nature of a peak shaving routine based on a wind speed estimate, and it could likely be improved through an observer-based rotor thrust shaving algorithm or similar. The peak shaving also helps to both mitigate rotor thrusts introduced by the initial ROSCO tuning and reduce them further than those from the simulations using the NREL 5-MW reference controller.

## 6.2 IEA 15-MW on the UMaine Semisubmersible FOWT Results

We compare results from the IEA 15-MW wind turbine on a semisubmersible floating turbine platform for the ROSCO controller with and without the floating feedback and pitch saturation modules enabled (see Figure 3). Larsen and Hanson (2007) suggest that the tuned bandwidth of a rotor speed-regulating collective blade pitch controller should not be higher than the platform's first fore-aft eigenfrequency. This method of "derating" the blade pitch controller has traditionally been employed in baseline FOWT controllers, such as the NREL 5-MW OC3-and OC4-Hywind FOWT models (Jonkman, 2010; Robertson et al., 2014). Though derating the turbine can provide stable platform dynamics, generator overspeeds can generally be very high with this method of control. The standard distribution of the IEA 15-MW wind turbine on the UMaine semisubmersible platform (IEA Wind Task 37, 2021) employs ROSCO, and the pitch controller bandwidth is  $0.2 \text{ rad/srad/s}$ , which is already less than the UMaine semisubmersible's first platform eigenfrequency of  $\sim 0.21 \text{ rad/srad/s}$ . Also, the IEA 15-MW wind turbine uses constant generator torque control in above-rated operation. For this comparison, the floating feedback and pitch saturation modules are either enabled or disabled, and the rest of the controller is not changed at all.

Figure 14 presents results from the DLC 1.1 and 1.3 simulations. With the pitch saturation enabled, slight decreases in power production are seen at near-rated wind speeds. This does, however, correlate to significant reductions of tower fore-aft bending moments and related loads near rated. The presented reduction in platform pitching motion of ~~slightly more than 30~~ about 15% resulting from the floating-specific feedback term has a clear effect on the tower base bending moment as well. The above-rated maximum rotor speed is not expected to change significantly with and without the pitch saturation and floating controller because the standard pitch controller for rotor speed regulation is the same. Similarly, the average power output is expected to drop when peak shaving is introduced, as shown in the bottom right plot of Figure 14.

The maximum platform pitch motions are reduced by approximately ~~47%, from 7.61 to 3.56~~ 20%, from 6.64 to 5.35 degrees, through use of the FOWT feedback term and pitch saturation routines. The annual energy production with complete FOWT tuning is ~~18.2%~~ 1.5% less than that without the pitch saturation terms, ~~though this is~~ which is primarily attributed to the ~~near 20% rotor overspeeds that are seen without peak shaving and fairly aggressive (25%) peak shaving percentage~~ peak shaving



**Figure 14.** Results from DLC 1.1 and 1.3 simulations for the IEA 15-MW wind turbine on the UMaine semisubmersible platform. Output statistics from the platform pitch angles, tower base fore-aft bending moments, rotor speed, and generator power are shown. Simulations using the FOWT feedback loop ( $\beta_{float}$ ) and pitch saturation are compared to those with the pitch saturation or FOWT feedback modules turned off.

600 [routine](#). Lemmer et al. (2020) do a very good job of highlighting the trade-offs between focusing control actuation on regulating rotor speed versus mitigating platform pitch motions. In this work, no specific tuning of the floating feedback term or blade pitch controller gains was done outside of the methods presented in sections 5.5 and 2.5, so overall controller performance could certainly be tuned and improved.

## 7 Conclusions and Future Work

605 We have provided the research community with a reference open-source controller (ROSCO) for fixed and floating offshore wind turbines. The controller structure is similar to many controllers that are seen on industry turbines that function in the field. Generic tuning methods have been developed for the ROSCO controller and made available through the Python-based ROSCO

toolbox. The tuning methods can be implemented easily by the interested non-controls engineer or in a completely automated fashion for use in optimization routines.

610 On the NREL 5-MW land-based wind turbine, we have shown that the generically tuned ROSCO controller performs comparably to the NREL 5-MW reference controller. We have also shown that, through a small amount of additional controller tuning, ROSCO's performance can be further improved to reduce rotor thrusts without significant reductions in power generation. We have also provided the foundations of more modern, industry standard control methods, such as peak shaving and wind speed estimation. A TSR tracking controller is shown to generate below-rated turbine power outputs that are consistent  
615 with the expectation based on the literature without significant power fluctuation or increased tower-base loads. No significant differences have been made to the implementation of the above-rated collective blade pitch controller, but automated tuning methods have been developed to easily generate pitch-dependent gain schedules for the blade pitch controller based on the  $C_p$  surface. A set point smoother has been implemented to improve the transition between the primary blade pitch and generator torque controller regions. A Kalman filter-based wind speed estimator is implemented in ROSCO to enable the TSR track-  
620 ing and blade pitch saturation capabilities. Pitch saturation routines have been implemented to improve power output in low wind speeds and reduce rotor thrust rated wind speeds. A simple shutdown logic has also been implemented to facilitate more realistic wind turbine testing for the IEC DLCs.

Additionally, a FOWT-specific feedback loop is included in ROSCO and has shown improvements over previously published open-source FOWT control methods. The combination of a FOWT-specific feedback loop and a peak shaving routine has been  
625 shown to significantly reduce platform pitch motions and maximum rotor speeds compared to a simple pitch controller with a bandwidth below the first fore-aft natural frequency of the platform. Notably, all the results shown for the IEA 15-MW on the UMaine semisubmersible are shown for the generalized ROSCO tuning values, and there is potential to further improve controller performance through additional fine-tuning of the input parameters to the ROSCO toolbox.

Several other capabilities are also being incorporated in ROSCO and the ROSCO toolbox generic tuning logic. These ca-  
630 pabilities and tuning methods are currently being developed, some of which include individual pitch control, distributed aerodynamic control, and improved FOWT feedback term tuning methods. A number of specific improvements for the control methods discussed in this paper will also be implemented. These include additional functionalities for the blade pitch and torque controller, such as power-reference tracking control and tower resonance-avoidance methods. Improved shutdown and yaw methods are also being actively investigated.

635 Finally, the authors would like to reiterate that ROSCO and the ROSCO toolbox are open-source tools. We invite the research community to download, use, and contribute to these codes in whichever ways they see fit.

*Code availability.*

The ROSCO controller ~~is~~ and toolbox are available for download at:

<https://github.com/NREL/ROSCO>.

640 ~~The ROSCO toolbox is available for download at:-~~

## Appendix A: Filters

Four filters are used in the ROSCO controller. For the filters presented,  $\omega_f$  is a cornering frequency in rad/s, and  $\zeta_f$  is a unitless damping ratio.

### First-order low-pass filter:

$$645 \quad F_{L1}(s) = \frac{\omega_f}{s + \omega_f} \quad (\text{A1})$$

### Second-order low-pass filter:

$$F_{L2}(s) = \frac{\omega_f^2}{s^2 + 2\zeta_f\omega_f s + \omega_f^2} \quad (\text{A2})$$

### First-order high-pass filter:

$$F_{H1} = \frac{s}{s + \omega_f} \quad (\text{A3})$$

### 650 Notch filter:

$$F_N = \frac{s^2 + 2\omega_f\zeta_{f1}s + \omega_f^2}{s^2 + 2\omega_f\zeta_{f2}s + \omega_f^2} \quad (\text{A4})$$

*Author contributions.* Nikhar Abbas developed the generic tuning processes, formalized the control concepts, and collected the theoretical foundations discussed in this article. He also contributed the majority of the code found in ROSCO and the ROSCO toolbox and established them as the tools that they are today. Nikhar Abbas was also the primary contributor to the writing of the article. Daniel Zalkind contributed to much of the testing and verification of the ROSCO toolchain. He has also served in an advisory role during the development of many of ROSCO's modules and reviewed this article multiple times before its submittal. Alan Wright contributed the original theoretical idea behind the tuning of the floating feedback term, served in an advisory role, and reviewed this article multiple times. Lucy Pao served in a supervisory role, guided the theoretical foundations discussed in this article, and reviewed this article extensively.

*Competing interests.* No competing interests are present.

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