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An Update to the National Renewable Energy Laboratory Baseline Wind Turbine Controller

Nikhar J. Abbas[1,2], **Alan Wright**[2], **and Lucy Pao**[1]
[1]University of Colorado, Boulder, CO 80309
[2]National Renewable Energy Laboratory, Golden, CO 80401

E-mail: `nikhar.abbas@colorado.edu`

Abstract. The National Renewable Energy Laboratory's 5-MW wind turbine model is well established as an industry standard and is often used as a comparison model, or a model on which to build upon. Though effective, the legacy controller for the 5-MW wind turbine uses a simple algorithm that is not up to date with many industry standards. Additionally, as the research community has advanced into fast-paced development cycles, as systems engineering tools such as Wind-Plant Integrated System Design & Engineering Model (WISDEM ®) [1] are employed, and as a greater focus on controls co-design practices is encouraged, demand for a generic wind turbine controller has arisen. This work presents updates for the NREL 5-MW controller to a more modern control architecture, and establishes a generic tuning framework that can be easily adapted to various wind turbines. Based on initial results, the updated generic controller eases the automatic tuning process while maintaining or improving the performance of the legacy NREL 5-MW controller.

1. Introduction

The National Renewable Energy Laboratory's (NREL's) 5-MW baseline wind turbine [2] has become ubiquitous in modern wind turbine research. The legacy control algorithm for the turbine controller is largely based on the work presented in [3] and [4]. The legacy controller employs a well-adopted framework that maximizes power generation by controlling the torque below a rated wind speed, and it maintains a constant rotor speed with collective blade pitch control above a rated wind speed. We developed a generic controller that pursues similar goals of the legacy NREL 5-MW controller, albeit through a different control strategy, in order to improve controller performance and integrate modern industry practices.

A number of publicly available reference wind turbine models and controllers exist in the literature. The NREL 5-MW [2] and DTU 10-MW from the Technical University of Denmark (DTU) [5, 6] are perhaps the most regularly referenced turbines. They are both available within the OpenFAST [7] framework, a servo-aero-elastic simulation software tool that is actively developed and maintained by NREL. OpenFAST employs a DNV-GL Bladed-style [8] controller implementation. Researchers at the Delft University of Technology produced an open-source, modular controller framework known as the Delft Research Controller (DRC) [9] that is consistent with the Fortran-based implementation of OpenFAST. The DRC produces a Bladed-style binary file that is compiled once and calls an input file containing controller parameters. We leveraged the modular nature of the DRC to implement the updated generic controller tuning strategy in a streamlined fashion. The updated tuning strategy enables an open-source automatic tuning process that produces the input file to the DRC quickly and algorithmically. We have also expanded the capabilities of the DRC to include controller behaviors that are more consistent with modern industry practices than those of the legacy 5-MW controller.

In the updated generic controller, a proportional-integral (PI) gain-scheduled generator torque controller is used to track an optimal tip-speed ratio in below-rated wind speeds. A PI gain-scheduled blade pitch controller is used in above-rated wind speeds to keep the rotor speed constant. The gain schedules for both of these controllers are formulated analytically and avoid the need for any extensive initialization or aeroelastic linearization routines. The updated generic controller includes logic to transition smoothly between below- and above-rated operation. Using only an OpenFAST turbine model, this framework enables automatic tuning possibilities that make it possible for researchers to implement a feedback controller without an extensive control systems background. Though this work presents the controller formulation within the framework of the NREL 5-MW wind turbine, the algorithm can be applied to a wide range of wind turbines with conventional designs. This enables development of controls co-design practices and tools (i.e., Wind-Plant Integrated System Design & Engineering Model (WISDEM) [1]) for numerous wind turbine models.

In this paper, we first present the legacy NREL 5-MW wind turbine controller for reference purposes. We then develop the necessary theory for the updated generic controller. This theory is the backbone of the controller algorithm and enables the automatic tuning process presented in this work. Finally, we describe the necessary input parameters to the control algorithm and present some preliminary results of the controller performance as compared to the legacy NREL 5-MW controller. The result of this is an open-source code base for generic controlling tuning. With six controller input parameters, we define a functioning controller for standard wind turbine designs. The controller tuning process is available through NREL's Reference Open-Source Controller (ROSCO) toolbox:

`http://github.com/NREL/ROSCO_toolbox`.

The NREL ROSCO toolbox writes the input file called by the DRC [9] to provide the updated NREL generic controller.

2. Legacy NREL 5-MW controller

We offer a brief overview of the legacy NREL 5-MW controller that is presented in [2]. The controller is divided into three primary regions of operation. In region two, the blades are pitched to the fine pitch angle to maximize power. The generator torque is defined by

$$\tau_g = K\omega_g^2. \tag{1}$$

K is a coefficient defined as [3]

$$K = \frac{\pi \rho R^5 C_p}{2\lambda^3 N_g^3}, \tag{2}$$

where ρ is the air density, R is the rotor radius, C_p is the power coefficient, λ is the tip-speed ratio, N_g is the gearbox ratio, and ω_g is the generator speed [3]. To calculate K, λ and C_p are defined as the power-maximizing tip-speed ratio and associated power coefficient, respectively. This formulation theoretically guarantees that for any generator speed, the power-optimizing generator torque is defined.

Region 3 begins when the rotor speed reaches rated rotor speed. The generator torque is defined by

$$\tau_g = \tau_{g,r} = \frac{P_r}{\omega_{g,r}}, \tag{3}$$

for constant torque operation. In (3), $\tau_{g,r}$, P_r, and $\omega_{g,r}$ are the rated generator torque, power, and generator speed, respectively. The blade pitch controller is a PI, gain-scheduled controller that collectively pitches the blades to maintain generator speed. In order to define the linear gain schedule, the sensitivity of the aerodynamic power to the rotor-collective blade-pitch angle is necessary, and it is generally found through linearization routines available through aeroelastic design tools such as OpenFAST [7].

The transition between Region 2 and Region 3 is commonly referred to as Region 2.5. In the legacy NREL 5-MW controller, the generator torque in Region 2.5 is defined by a simple linear interpolation between an operating point in Region 2 and the beginning of Region 3. This, along with some basic switching logic, prevents the blade pitch and generator torque controllers from conflicting.

3. Generic controller overview

The updated NREL wind turbine controller attempts to achieve similar goals as the legacy controller through a number of changes to the underlying logic. The goal of the below-rated generator torque controller is still to maximize power, but is facilitated through a PI controller rather than through the law defined in (1). In above-rated operation, the blade pitch controller still regulates the rotor speed, but the gains are calculated analytically. The transition region is updated to incorporate commonly adopted industry practices, providing a more up-to-date reference controller for the research community. A high-level block diagram of the updated generic controller is shown in Figure 1.

In below-rated operation, the legacy generator torque control law (1) presents two challenges. In simulation, the calculation of K in (2) can be done fairly well. In practice, the calculation of K is highly subject to modeling error. Additionally, (1) does not offer any ability to tune the generator torque response characteristics. For these reasons, we employ a wind speed estimator to implement a tip-speed ratio tracking generator torque PI controller in below-rated operation.

In above-rated operation, the legacy blade pitch controller PI gain-schedule formulation necessitates a number of aeroelastic simulations to find wind turbine performance characteristics. We use a numerical linearization of the generator speed dynamics to schedule the PI gains for

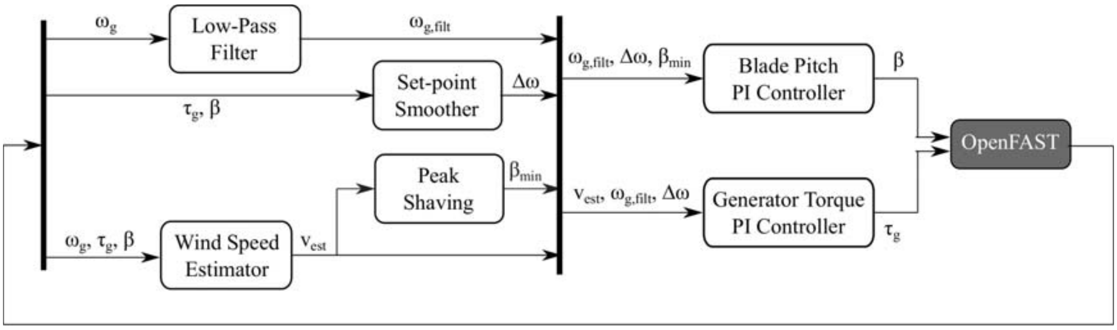

Figure 1. A block diagram showing the general controller logic: ω_g is the generator speed, τ_g is the generator torque, β is the blade pitch angle, v_{est} is the estimated wind speed, and $\Delta\omega$ is a controller set-point shifting term.

the blade pitch controller, facilitating an algorithmic tuning process that can be completed in a negligible amount of time with standard computational power.

The Region 2.5 routine in the legacy 5-MW controller uses a simple linear interpolation between wind turbine control regions. We employ a set-point smoothing logic that separates generator torque and blade pitch controller reference points, discouraging the controllers' interaction and mitigating transients that occur during rapid switching from one controller to another.

Finally, a low-pass filter on the generator speed is employed with a corner frequency of one-third of the first edgewise natural frequency of the turbine blades.

4. Plant model

In order to establish the gain schedules for the torque and pitch controllers, a first-order model of the wind turbine is used [10]

$$\dot{\omega}_g = \frac{N_g}{J}(\tau_a - N_g\tau_g), \tag{4}$$

where J is the rotor rotational inertia and τ_a is the aerodynamic torque. The aerodynamic torque is further defined as

$$\tau_a = \frac{1}{2}\rho AR\frac{C_p(\lambda,\beta)}{\lambda}v^2, \quad \text{where } \lambda = \frac{\omega_g R}{N_g v}. \tag{5}$$

In (5), A is the rotor swept area, β is the blade pitch angle, and v is the effective wind speed at the rotor. The first-order linearization of (5) at some nominal steady-state operational aerodynamic torque τ_a, generator speed $\omega_{g,0}$, blade pitch angle β_0, and wind speed v_0, is

$$d\tau_a \approx \left.\frac{\partial\tau_a}{\partial\omega_g}\right|_{OP} d\omega_g + \left.\frac{\partial\tau_a}{\partial\beta}\right|_{OP} d\beta + \left.\frac{\partial\tau_a}{\partial v}\right|_{OP} dv, \tag{6}$$

where "OP" denotes the expected, steady-state operational ω_g, β, and v for any linearization point. Equation (4) can then be re-written in a linearized form as

$$d\dot{\omega}_g = A(v_{OP})d\omega_g + B_{\tau_g}d\tau_g + B_\beta(\beta_{OP})d\beta + B_v dv, \tag{7}$$

where changes in blade pitch angle, $d\beta$, and generator torque, $d\tau_g$, are the controllable inputs to the system. We are able to parameterize A by v_{OP} because ω_{OP} and β_{OP} can both be parameterized by v_{OP}. Similarly, we parameterize B_β by β_{OP} only, as β_{OP} can be parameterized by v_{OP}. Equation (7) is subsequently the plant model used to define the generator torque and blade pitch controller PI gains. The definitions of B_{τ_g} and $B_\beta(\beta_{OP})$ will be discussed in later sections. B_v, the disturbance (dv) input matrix to the system, is set to 0 for the current controller design's gain-scheduling calculations.

4.1. Steady states

The terms that define $A(v_{OP})$ and $B_\beta(\beta_{OP})$ in (7) are dependent on the value of $C_p(\lambda_{OP}, \beta_{OP})$ at steady-state operating points. In below-rated conditions, we strive to operate at a maximum C_p by operating at a C_p-maximizing tip-speed ratio. In above-rated conditions, the steady-state $C_p(\lambda, \beta)$ is defined by [11]

$$C_p(\lambda_{OP}, \beta_{OP}) = C_{p_r}\left(\frac{\lambda_{OP}}{\lambda_r}\right)^3, \tag{8}$$

where C_{p_r} and λ_r are the power coefficient and tip-speed ratio at rated wind speed, respectively. From (8), we are able to define $\beta(v)$, which provides a mapping from wind speed, v, to blade pitch angle, β, and facilitates calculation of the values in (7).

5. Controller gain scheduling

We used a first-order analytical model based on basic turbine parameters to schedule the PI controller gains. By employing the plant model and analytical linearization established in Section 4, the updated generic controller does not require numerically linearizing a higher-order turbine model in OpenFAST [7] or similar code, easing the automation of the tuning process. Through use of a wind speed estimator and a Region 2.5 smoothing regime, we are able to employ an updated generic controller that can be implemented with minimal control systems knowledge or experience.

In order to tune the above- and below-rated controllers, we define the PI controllers to be of the form

$$C(s) = K_p + \frac{K_i}{s}. \tag{9}$$

Combining (9) with (7) in a standard negative feedback loop results in the closed-loop transfer function

$$H(s) = \frac{d\Omega_g(s)}{d\Omega_{g,ref}(s)} = \frac{B(K_p(v)s + K_i(v))}{s^2 + (BK_p(v) - A(v))s + BK_i(v)}, \tag{10}$$

where B is either B_{τ_g} or $B_\beta(\beta_{OP})$, depending on if the turbine is in below- or above-rated operation, respectively. We note that B is negative in below- and above-rated operation, so K_i and K_p are generally negative.

Equation (10) looks similar to a standard second-order system, so we define the PI gains as

$$K_p(v) = \frac{1}{B}(2\zeta_{des}\omega_{des} + A(v)), \tag{11}$$

$$K_i(v) = \frac{\omega_{des}^2}{B}, \tag{12}$$

where the closed-loop response is characterized by a desired natural frequency, ω_{des}, and damping ratio, ζ_{des}. We assume constant blade pitch or constant generator torque in below- or above-rated operation, respectively. As a result, defining ω_{des} and ζ_{des} for the above- and below-rated operating regions are the only four parameters that need to be defined to tune the generator torque and blade pitch controllers.

5.1. Below-rated tuning

In below-rated operation, we assume that the blade pitch is held constant at fine pitch, so $d\beta = 0$ in (7). This means that $B = B_{\tau_g}$ in equations (11) and (12), where

$$B_{\tau_g} = \frac{-N_g^2}{J}. \tag{13}$$

Because $A(v)$ is dependent on the wind speed, a wind speed estimator is employed to estimate v. We can then calculate $A(v)$ and equations (11) and (12) are redefined for the variable-speed torque controller to be $K_{p,vs}(v)$ and $K_{i,vs}$. Note that $K_{i,vs}$ is independent of v because B_{τ_g} is constant.

5.2. Above-rated tuning

In above-rated operation, we assume that the torque is held constant at rated torque, so $d\tau_g = 0$. Consequently, $B = B_\beta(\beta_{OP})$ in equations (11) and (12), where

$$B_\beta(\beta_{OP}) = \frac{N_g}{J}\frac{\partial \tau_a}{\partial \beta} = \frac{N_g}{2J}\rho A R v_{OP}^2 \frac{1}{\lambda_{OP}^2}\Big(\frac{\partial C_p(\lambda_{OP}, \beta_{OP})}{\partial \beta_{OP}}\lambda_{OP}\Big). \tag{14}$$

By investigating the C_p surface and equation (8), we can find the blade pitch angles, $\beta(v)$. This enables us to redefine $A(v)$ to be $A(\beta)$. Equations (11) and (12) are then defined for the blade pitch controller to be $K_{p,pc}(\beta)$ and $K_{i,pc}(\beta)$.

6. Set-point smoothing

The regions of control are separated by defining the generator speed set point differently for the blade pitch and generator torque controllers. The generator torque controller and blade pitch controller generator speed set points are defined as $\omega_{ref,\tau}$ and $\omega_{ref,\beta}$, respectively. We implement a smoothing methodology [12] [3] to separate the controller set points and prevent unnecessary switching between controllers.

6.1. Torque controller set point

We define the torque controller generator speed set point as

$$\omega_{ref,\tau} = N_g \frac{\lambda_{opt} v}{R}, \tag{15}$$

where λ_{opt} is the C_p-maximizing tip-speed ratio. We saturate $\omega_{ref,\tau}$ such that

$$\omega_{min} \leq \omega_{ref,\tau} \leq \omega_{rat} \tag{16}$$

where ω_{min} is the cut-in rotor speed and ω_{rat} is the rated rotor speed. This ensures that the set point is defined as the C_p-maximizing generator speed in below-rated operations, and that the torque controller is saturated in above-rated operation.

6.2. Blade pitch controller set point

The blade pitch controller set-point is always defined as

$$\omega_{ref,\beta} = \omega_{rat}. \tag{17}$$

In below-rated operation, the rotor speed is less than the rated rotor speed, so the blade pitch angle, β, saturates at $\beta = \beta_{min}$. In above-rated operation, the pitch controller set point is the rated rotor speed.

6.3. Transition region (Region 2.5)

If the generator torque and blade pitch set points are only defined by (15) and (17), then the controllers will be in conflict with each other in near-rated operation. To account for this, we employ a set-point smoother regime that is akin to a Region 2.5 controller observed in the legacy NREL 5-MW controller. The general idea is to shift the rotor-speed set point of the saturated controller to prevent actuation while the unsaturated controller is active. By shifting the set point for one controller in the correct direction, we can guarantee that the controller stays saturated while the other controller actuates, and vice versa, without conflicting signals [12].

We first define a perturbation to the rotor speed set point, $\Delta\omega$, as

$$\Delta\omega = \underbrace{(\beta - \beta_{min})}_{\Delta\beta} K_{vs} - \underbrace{(\tau_{g,rat} - \tau_g)}_{\Delta\tau} K_{pc}. \tag{18}$$

In (18), K_{vs} and K_{pc} are tunable gain factors that define the magnitude of the effect of the set-point perturbation on the torque and pitch controllers, respectively. Both K_{vs} and K_{pc} are greater than 0. Notably, in below-rated operation, $\Delta\beta = 0$, and in above-rated operation, $\Delta\tau = 0$. We then employ a piece-wise logic to shift the controller set point, such that

$$\omega_{ref,\tau} = \begin{cases} \omega_{ref,\tau} - \Delta\omega & \Delta\omega \geq 0 \\ \omega_{ref,\tau} & \Delta\omega < 0 \end{cases} \quad \text{and,} \quad \omega_{ref,\beta} = \begin{cases} \omega_{ref,\beta} & \Delta\omega \geq 0 \\ \omega_{ref,\beta} - \Delta\omega & \Delta\omega < 0 \end{cases}. \tag{19}$$

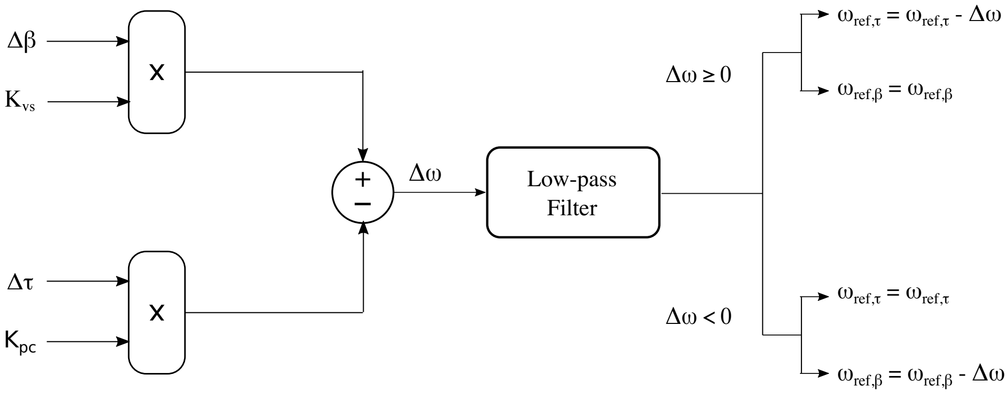

Figure 2. A block diagram of the set-point smoother logic. The term $\Delta\omega$ shifts the blade pitch or generator torque controller to help avoid unwanted controller interactions.

Figure 2 shows a block diagram displaying the set-point smoother logic. The smoother shifts the saturated controller's set point linearly depending on how "far away" it is from rated operation. Notably, the factors K_{vs} and K_{pc} are two tuning parameters that are somewhat turbine-dependent and must be chosen by the control designer. Future work includes normalizing Equation (19) so that K_{vs} and K_{pc} are turbine-agnostic.

7. Wind speed estimator

We employ a wind speed estimator inspired by [13] that is based on a continuous-discrete Kalman filter - an extension of the extended Kalman filter. The specifics of the continuous-discrete Kalman filter used in this work is further detailed in [14]. The work developed in [13] uses informed definitions of the covariance matrices based on the expected wind fields to estimate the rotor-effective wind speed, v. The prediction updates 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. See [13] for detailed formulations of the covariance matrices in the Kalman filter and [14] for a more in-depth formulation of the continuous-discrete Kalman filter for this purpose.

8. Results and analysis

A selection of time-domain simulation results is presented to provide some initial results of the performance of the generic controller as compared to the legacy NREL 5-MW controller. These results are meant to show a high-level overview of the basic functionality of the updated generic controller; future publications regarding this work will include a more rigorous analysis of the controller performance from both control theory and wind energy systems perspectives. The simulations were done in OpenFAST and with all fixed-bottom wind turbine degrees of freedom enabled.

In the results presented, the torque controller is tuned with a closed-loop damping ratio of

$\zeta_{\tau,des} = 1$ and natural frequency of $\omega_{\tau,des} = 0.3\ \frac{rad}{s}$, where the subscript, $_\tau$, denotes the generator torque controller. The blade pitch controller is tuned such that the closed-loop damping is $\zeta_{\beta,des} = 0.7$ and natural frequency is $\omega_{\beta,des} = 0.6\ \frac{rad}{s}$, where the subscript, $_\beta$, denotes the blade pitch controller. We chose the blade pitch tuning to be consistent with [2], whereas the generator torque controller tuning parameters were chosen empirically to give smooth generator torque actuation. For the set-point smoother, the tuning parameters were chosen empirically and defined as $K_{vs} = 30\ \frac{1}{s}$ and $K_{pc} = 0.0001\ \frac{rad}{kNs}$. Future work includes normalizing the set-point smoother logic to be turbine-agnostic. Finally, the wind speed estimator has a number of tuning parameters and initial conditions. Fortunately, the tuning values are related to the wind field and are independent of the turbine model.

Step responses for below- and above-rated operation are simulated with rapid wind changes, as shown in Figures 3 and 4. In below-rated operation, a noticeable offset between the legacy controller and updated generic controller generator torque signal exists. This is likely attributed to a small difference in the wind speed estimate from the rotor-effective wind speed. The wind speed estimate is used for the tip-speed-ratio tracking controller, whereas the rotor-effective wind speed directly defines the generator torque in the legacy controller. This torque offset does not, however, significantly affect the generated power. In simulations with turbulent wind, shown in figure 5, we see negligible differences in generator torque and power production. Notably, the characteristics of the generator torque response were empirically defined by $\omega_{\tau,des}$ and $\zeta_{\tau,des}$ and are yet to be tuned through a more intensive process.

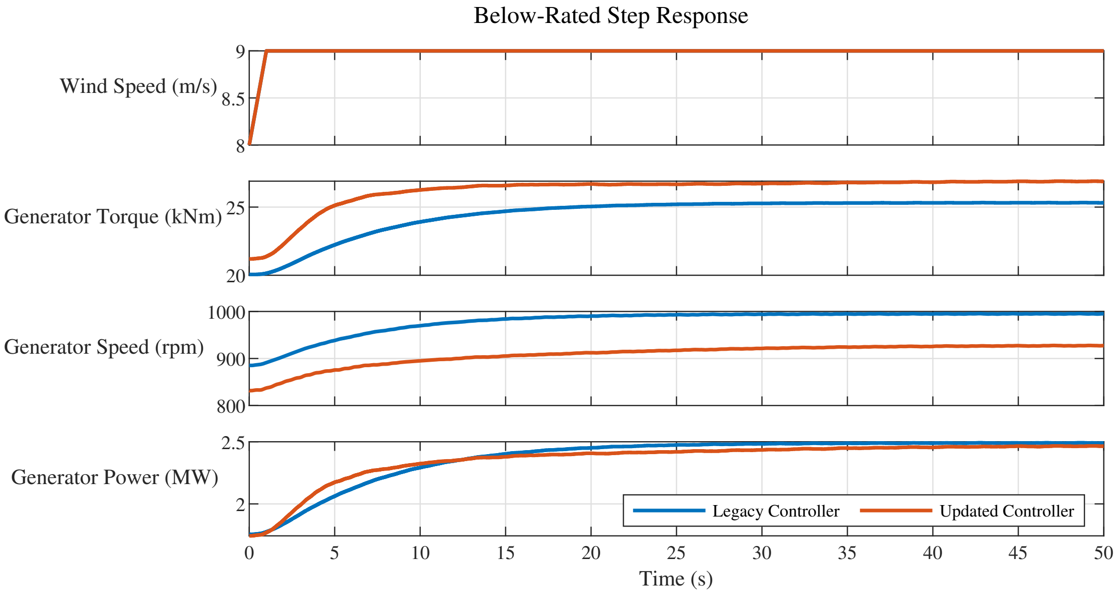

Figure 3. Below-rated response to a rapid 1-m/s increase in wind speed for the NREL 5-MW land-based wind turbine.

The above-rated step response dynamics (Figure 4) show a noticeable difference between the legacy NREL 5-MW controller and the updated generic controller. It is well understood that the full-state simulation dynamics of a wind turbine can differ somewhat significantly from those defined for a reduced-order model [15]. Because the legacy controller was tuned based on a full-state linearization, the blade pitch gain schedule differs slightly between the legacy and updated generic controllers. The PI gains for the blade pitch controller when the blades are pitched to 5 degrees are shown in Table 1. Noticeably, the generator speed with the updated generic controller is more tightly regulated in Figure 4, at the cost of more blade pitch fluctuation. For the sake of comparison, we have chosen the same $\zeta_{\beta,des}$ and $\omega_{\beta,des}$ for the updated blade pitch controller as the legacy controller. Further work includes investigating the optimization of $\zeta_{\beta,des}$ and $\omega_{\beta,des}$ to maximize various performance metrics using WISDEM.

Table 1. Blade pitch controller PI gains when $\beta = 5$ deg.

	Legacy	Generic
Kp [s]	-0.0132	-0.0105
Ki [-]	-0.0062	-0.0045

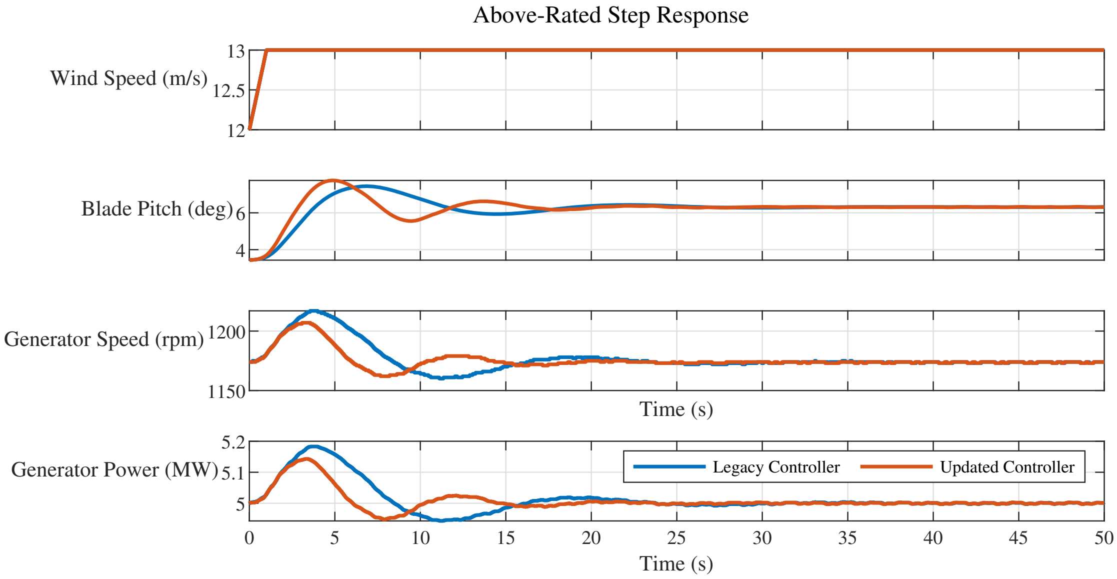

Figure 4. Above-rated response to a rapid 1-m/s increase in wind speed for the NREL 5-MW land-based wind turbine.

Figure 5 shows a below-rated simulation. The NREL 5-MW wind turbine is simulated in turbulent wind conditions with an average wind speed of 8 m/s. Power production is nearly identical between the two controllers, though modified tuning of the torque controller gains and wind speed estimator parameters can result in power production changes in the range of ± 1-5%.

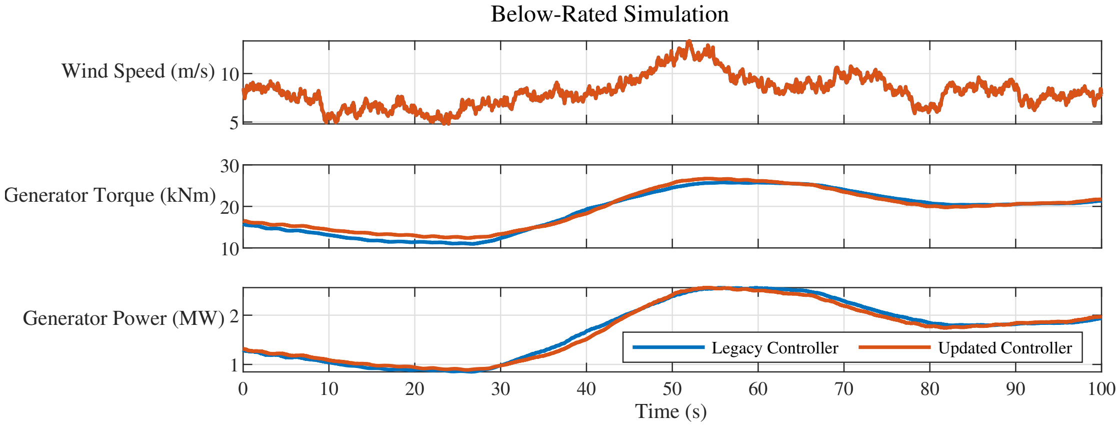

Figure 5. Below-rated simulation results of the NREL 5-MW land-based wind turbine in an incident wind field with an average wind speed of 8 m/s and International Electrotechnical Commisssion (IEC) normal turbulence.

Figure 6 shows time-domain results of a simulation in a turbulent wind field with a mean wind speed of 12 m/s. We observe that any controller-induced periodic switching between the two controllers is avoided, which is desired. Because of the absence of a Region 2.5 and implementation of the set-point smoother, we see fewer erratic drops in generator torque when the turbine shifts to below-rated operation, as observed near the 55- and 85-s marks.

In above-rated operation, we see results comparable to those found using the legacy NREL 5-MW controller. Increased blade pitch actuation is observed in the first 50 seconds of the near-rated simulation results shown in Figure 6 and throughout Figure 7. Figure 7 shows improved generator speed regulation through increased blade pitch actuation. The resulting generator speed standard deviation using the updated generic controller is approximately 12 rpm, which is nearly 50% less than the standard deviation of approximately 22 rpm using the legacy controller. This result is, of course, dependent on the specific choices in tuning $\omega_{\beta,des}$ and $\zeta_{\beta,des}$ and is specific to the simulation shown.

The collective energy output with the updated generic controller for all three of the cases shown in Figures 5-7 is within 0.01% of the energy output using the legacy NREL 5-MW controller. A more extensive analysis of the specific advantages and disadvantages of the generically tuned controller is pending.

9. Controller implementation

The Reference Open-Source Controller toolbox for tuning the generic controller is available as of November 2019 at

`http://github.com/NREL/ROSCO_toolbox`.

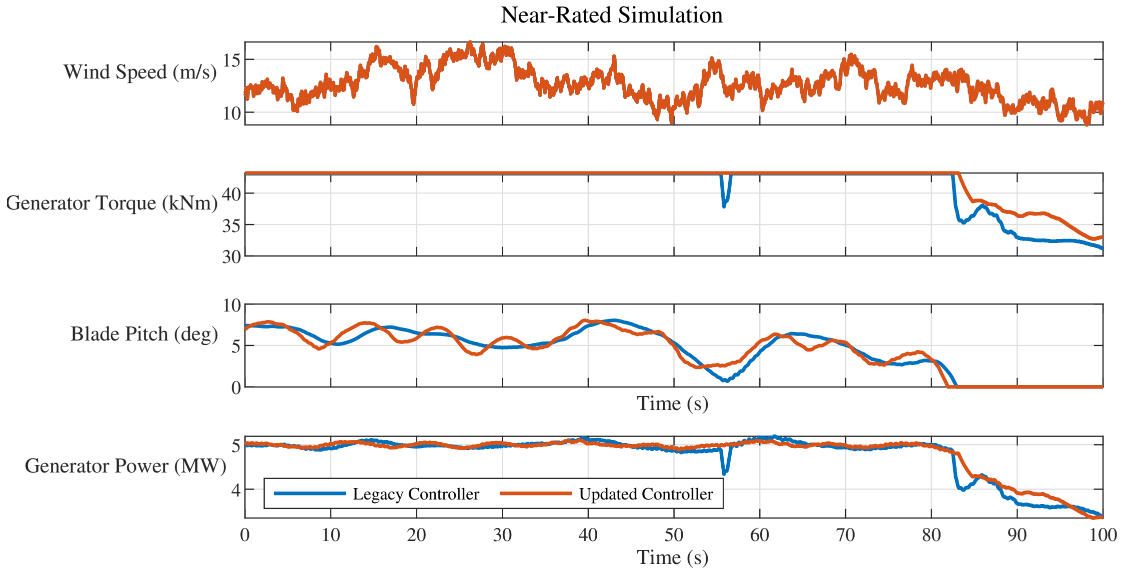

Figure 6. Near-rated simulation results of the NREL 5-MW land-based wind turbine in an incident wind field with an average wind speed of 12 m/s and IEC normal turbulence.

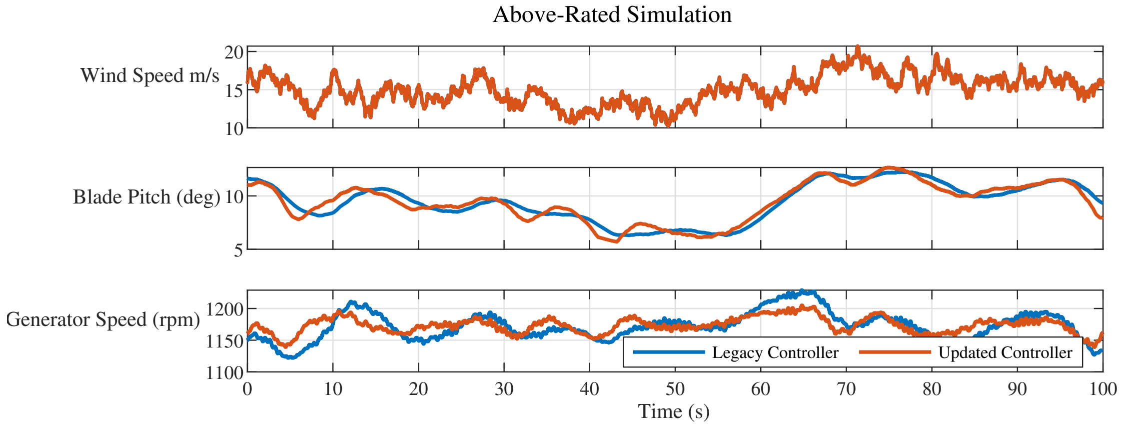

Figure 7. Above-rated simulation results of the NREL 5-MW land-based wind turbine in an incident wind field with an average wind speed of 15 m/s and IEC normal turbulence.

The presented formulation of the above- and below-rated PI controller gain schedules allows for a control algorithm that removes the need for intensive tuning. Six total controller input parameters are needed to tune the controller: ω_{des} and ζ_{des} for the below- and above-rated PI controllers, and K_{vs} and K_{pc} for the set-point smoother. The gain schedules can be found quickly using turbine parameters readily available in an OpenFAST turbine model and a C_p-surface that can be quickly and easily generated using CCBlade [16], other blade element momentum solvers, or OpenFAST. With these input parameters, we are able to solve for equations (11) and (12) quickly and algorithmically. The immediate next steps of this research include removing the need for K_{vs} and K_{pc} in (18) to be tuned.

If a user does wish to modify the controller behavior for a turbine model, simple step response analysis is generally sufficient. For a step wind change, increased values of $\omega_{n,des}$ will decrease rotor speed response time, whereas increased values of ζ_{des} will decrease the amount of rotor speed overshoot. There are associated trade-offs with changing the desired controller behavior significantly (i.e., more erratic blade pitch behavior may result when attempting to more quickly regulate rotor speed). Chapter 3 of [17] offers a much more extensive review of the effect of the damping ratio, ζ_{des}, and natural frequency, ω_{des}, in second-order systems.

10. Conclusions and future work

In this paper, we present an updated version of the NREL 5-MW controller for fixed-bottom wind turbines. By shifting the control objective in below-rated operation to track an optimal tip-speed ratio, there is no longer a need to find the ideal K in the $\tau_g = K\omega_g^2$ law. Additionally, an updated methodology to prescribe PI gains in above- and below-rated operation removes the need for linearized aeroelastic wind turbine models, and it makes the tuning process seamless and more accessible to the non-controls engineer. Despite added complexity that is introduced by the need for a wind speed estimator, controller performance is generally on a par with standard baseline controllers that are being employed within the research community today. The major advantage of this methodology is the ease of automating a tuning process for a wind turbine controller. This approach can decrease wind turbine design cycle times and offer a capable reference controller that is easy to implement.

There is certainly continued investigation necessary to further validate and verify the merits of the updated generic controller. A rigorous analysis of the controller performance from both control theory (i.e., stability analysis) and wind turbine (i.e., design load cases) perspectives is necessary. The updated generic controller has also been tested and evaluated on the DTU 10-MW [5, 6] wind turbine with similar results. Additional testing of the automatic tuning on turbines other than the NREL 5-MW and DTU 10-MW wind turbines is necessary to further validate this “generic” controller. Further capabilities for controlling a floating offshore wind turbine will be implemented and validated in an extensive study. A noninclusive list of additional controller features that are actively in progress or planned in the future includes:

- Normalizing set-point smoother parameters
- Implementing rotor thrust peak shaving routine
- Providing individual pitch control
- Implementing power resonance avoidance and tower-top damping.

The DRC controller implementation provides the opportunity to compare multiple types of controllers and easily implement and modify a number of different filters and feedback loops, all without the necessity of compiling code between iterations or employing Simulink [18] as a tool.

We plan to continue to grow this framework and integrate it into NREL's wind turbine simulation tool(s). Collectively, this work provides a wind turbine controller that can be modified by wind energy researchers or modern optimization tools, such as WISDEM [1].

11. Acknowledgements

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