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UNICO: an open-source controller optimized for stall-regulated wind turbines

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Abstract. Stall regulation turbines still represent the preferred solution for small wind turbines. In stall-controlled rotors the controller plays a key role but, differently from pitch-based ones, no open-source controller was available to date. The study presents the UNICO (UNIfi research COntroller) controller, which has been specifically developed for variable speed stall-regulated turbines. The controller has been developed in MATLAB® Simulink® and a dynamic link library (.dll) has been generated, which can be coupled with common simulation codes such as OpenFAST and QBlade using a Bladed-style interface. UNICO includes features that are specifically tailored to variable-speed stall-regulated turbines. For below-rated conditions, the controller employs either the commonly used k-ω^2 law or a tracking of the optimal tip speed ratio. For above-rated conditions, a PI controller is used to track a user-imposed reference speed. The reference speed is set to decrease linearly with wind speed, providing a safety margin for turbine operation at higher wind speeds. UNICO has been tested on a 50-kW stall-regulated reference turbine. Preliminary results show how the proposed controller can achieve better overall performance in comparison to the simplified control laws implemented in state-of-the-art codes. Additionally, the rotor speed can be controlled in above-rated conditions, providing an increased run away safety margin.

Keywords: controller, small wind, stall control, open source.

1. Introduction

While all modern utility-scale wind turbines now feature variable-speed blade pitch control, there are still many turbines around the world that make use of stall regulation. In particular, this is the case of small wind turbines, in which, as discussed in [1], the use of pitch control is generally discarded due to three main reasons: 1) higher capital cost, concurring to a high LCOE; 2) higher complexity, and increased maintenance requirements; 3) reduced space in the nacelle and hub to host pitch motors. When designing stall-controlled turbines, specific challenges must be addressed to strike a compromise between the maximization of aerodynamic performance and the onset of stall in the desired conditions. In addition, the control system, which can act only on the generator torque and shaft braking, must guarantee that the turbine stalls in above-rated conditions. Despite the pivotal role of the controller for stall-regulated turbines, to the best of the author's knowledge there is still no open-source controller available specifically designed for stall-regulated turbines, significantly hampering research on small wind turbines. This study aims to fill this gap by developing an open-source controller for stall-regulated wind turbines named UNICO. While UNICO is a general-purpose controller, the routines for pitch control are mainly devoted to didactic and research scopes, and are similar to other state-of-the-art open-source controllers [2–4]. On the other hand, UNICO features a stall-control version that has been developed from the ground-up for stall-regulated turbines by implementing both traditional and ad-hoc control strategies for below- and above-rated conditions. This represents the most significant difference between UNICO and the other currently available controllers, which do not include specific control strategies for stall-controlled turbines. In fact, the Reference Open-Source Controller (ROSCO) [3] developed by NREL, the Delft Research controller (DRC) [4], and the DTU Wind Energy Controller (DTUWEC) [2], can employ control strategies for individual and collective pitch control, but no logics have been implemented yet for operating stall-controlled turbines. The study is structured as follows. Section 2 provides a description of the control logics implemented in UNICO. A simplified methodology to tune the UNICO controller is presented in Sect. 3, and the methodology used to test the controller is provided in Sect. 4. The results of the controller tests are summarized in Sect. 5, and the main conclusion and outlook of this work are discussed in Sect. 6.

2. Controller implementation

UNICO has been developed in MATLAB® Simulink®. To allow for simple interfacing with common wind turbine simulation and design codes, UNICO con be compiled into a dynamic link library (.dll), that can be coupled with simulation codes such as OpenFAST [5] and QBlade [6] using a Bladed-style [7] interface. Direct links to the Simulink model of the controller and the compiled .dll are made available on GitHub (see "Data Availability"). Although UNICO has been tested in both QBlade and OpenFAST, all the development and results presented herein are obtained through coupling to OpenFAST. The controller receives the filtered wind speed and generator speed through the controller interface, which are used to determine the operating conditions and the controller response. For the investigation presented herein, the wind speed is obtained from turbine simulation using a digital twin implemented in OpenFAST, while in real-life applications the wind speed must be measured with dedicated sensors, e.g., with corrected nacelle-mounted anemometers, or estimated based on the turbine's performance and operating condition through dedicated wind speed estimation algorithms. To this end, several methodologies have been proposed in the literature to estimate the wind speed, such as transfer functions or Kalman filters [8]; however, the investigation of such methodologies is out of the scope of the current work.

As per common practice, depending on the generator speed and wind speed, the controller response is split into different regions, as the control objectives are different in below-rated and above-rated conditions. Above the cut-in wind speed, the controller needs to maximise the energy extracted from the wind. Instead, in above-rated conditions, the controller must guarantee stable turbine operation and avoid turbine runaway due to sharp increases in rotor speed and aerodynamic torque. UNICO defines several regions and sub-regions, as described below. Fig. 1 shows an overview of the control regions in UNICO. Lastly, UNICO is a research controller. As such, in its current form, it doesn't include supervisory control routines and can handle only standard operation. A turbine shutdown mode for wind speeds above the cut-off value is under study but not implemented yet.

2.1. Region 1 and 1.5

In Region 1 the wind speed is below the cut-in value. The generator does not produce any power, and no controller action is required for these operating conditions (Fig. 1). However, an intermediate region is usually defined, referred to as "1.5", where the controller does not target optimal performance but tracks a minimum rotational speed to avoid the low-frequency modes of the tower. To this end, UNICO uses a PI controller in Region 1.5 to track the minimum speed set by the user, rather than optimal performance. In this region, the generator torque is calculated as in Eq. (1):

$$Q_g = k_p\left(\omega_g - \omega_{ref}\right) + \frac{k_i}{T_i}\int_0^t \left(\omega_g(\tau) - \omega_{ref}(\tau)\right) d\tau\,, \tag{1}$$

where k_p and k_i are the proportional and integral gains, respectively, which must be tuned by the user to achieve the desired performance. The variable ω_{ref} is the reference generator speed tracked by the controller. In Region 1.5, the reference speed is equal to the minimum rotational speed.

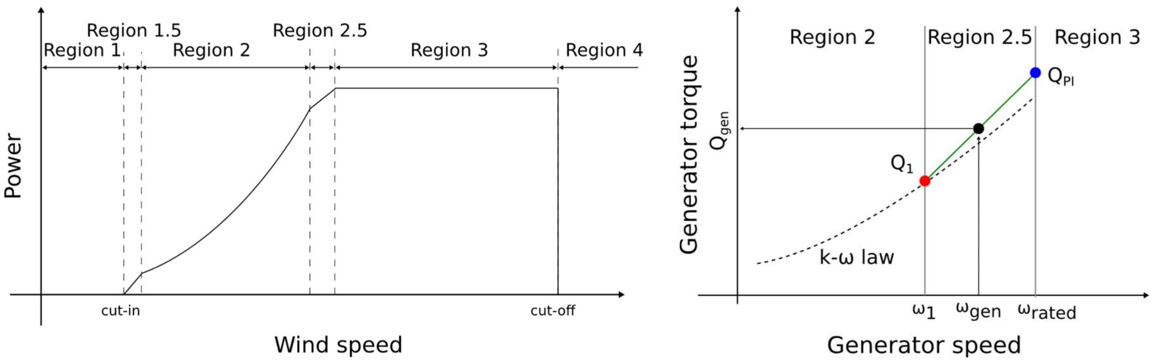

Figure 1. Typical operating conditions of a wind turbine (left), and control strategy for Region 2.5.

2.2. Region 2

In Region 2, the wind speed is between the rated and cut-in values, and the objective of the controller is to maximize power extraction. Within UNICO, two different control strategies, already proposed in the literature [3,8], can be employed, namely the k-ω^2 or the optimum TSR tracking.

The most used approach is the k-ω^2 law. In fact, this control strategy is more robust, as it does not require the estimation of the wind speed and the generator torque is computed as in Eq. (2):

$$Q_g = K\omega_{gen}^2 \tag{2}$$

where ω_g is the generator speed and K is a constant defined as:

$$K = \frac{\frac{1}{2}\rho\pi R^5 Cp_{max}}{\left(TSR_{opt}\right)^3} \tag{3}$$

where ρ is the air density, R is the rotor radius, Cp_{max} and TSR_{opt} are the maximum power coefficient and corresponding tip-speed ratio. In this way, Eq. (2) represents the locus of the maximum power coefficient as a function of tip-speed ratio.

An alternative strategy is also available in UNICO, whereby the optimum TSR can be tracked in Region 2 using a PI controller, as shown in Eq. (1). In this case, the reference speed is calculated from the measured wind speed to achieve the optimal tip-speed ratio as $\omega_{ref} = TSR_{opt}RU_w$. This strategy requires adequate tuning of the controller but can significantly improve the performance in case of aerodynamic performance deterioration or changes in external conditions. In fact, differently from the k-ω^2 law, this control strategy is independent on air density, hence a different tuning is not required when the turbine is operating at different altitudes (often the case for small wind turbines [1]) or far from standard conditions.

2.3. Region 3

Region 3 identifies the operating condition of the turbine between the rated and cut-off wind speeds. For a stall-regulated turbine, the controller modifies the generator torque to limit the energy extraction from the wind to the rated value and to guarantee that the rotor speed remains within the operational limits. The UNICO controller employs a PI controller as in Eq. (1), determining the generator torque required to track a user-imposed generator speed. Note that a different set of PI gains can be set for regions 2 and 3 when using TSR-tracking in both regions, allowing for improved performance of the controller in both regions, as explained in detail in Section 3.

The reference speed is set to decrease linearly with wind speed (v), providing a safety margin for turbine operation at higher wind speeds. The reduction in reference speed is set by the user by defining the slope m (Eq. 4).

$$\omega_{ref} = \omega_{rated} - m(v - v_{rated}) \tag{4}$$

2.4. Transition regions

When the k-ω^2 law is used in Region 2, a critical aspect of wind turbine control is represented by the switch between Regions 2 and 3, as switching between the PI controller and the k-ω^2 law may cause sharp changes in generator torque. For this reason, an additional region is usually defined, identified as "2.5", to provide a smooth transition between the control strategies employed in these two regions. In UNICO the value of the generator torque in Region 2.5 is obtained as a linear interpolation (Eq. (5)) between the value in Region 3, obtained by the PI controller tracking the rated rotational speed, and the k-ω^2 value at the beginning of Region 2.5 (Fig. 1).

$$Q_g = Q_1 + \frac{Q_{PI} - Q_1}{\omega_{rated} - \omega_1}(\omega_g - \omega_1) \tag{5}$$

Analogous to Region 2.5, a switching method is required between Regions 1.5 and 2, if the k-ω^2 law is used in Region 2. In UNICO, the same approach used in Region 2.5 is used, where the generator torque is calculated as a linear interpolation of the generator torque obtained from the k-ω^2 law and the output of the PI controller, which is tracking the minimum rotational speed (Eq. (6)).

$$Q_g = Q_1 + \frac{Q_{PI,min} - Q_1}{\omega_{rated} - \omega_1}(\omega_g - \omega_1) \tag{6}$$

3. PI controller tuning

UNICO employs a PI controller to track a reference generator speed in Regions 1.5, 2 and 3, as described in Sect. 2. Before operation, the PI gains must be tuned by the user to guarantee controller stability and adequate performance. To select the values of the proportional and integral gains, k_p and k_i (Eq. (1)), multiple approaches have been proposed in the literature. Holistic methods like the Ziegler-Nicholson [9] can be used to obtain the first attempt values that can then be fine-tuned for improved performance. Otherwise, more advanced approaches like the one proposed by Garpinger et al. [10] can be employed to determine the gain values.

While the investigation of the tuning methods for a PI controller are outside of the scope of this work, a simplified method based on the analysis by Abbas et al. [3] can be used to determine the gains. The method involves the linearization of the closed-loop wind turbine system with a PI controller. The wind turbine is described as a second order system (Eq. 7):

$$(I_r + n_g^2 I_g)\ddot{\phi} = Q_a - \frac{1}{\eta}Q_g \tag{7}$$

where I_r, n_g, and I_g are the rotor inertia, gearbox ratio and generator inertia, respectively,ϕ is the rotor azimuth, $\ddot{\phi}$ is the rotor acceleration, Q_a is the aerodynamic torque, and Q_g the generator torque. For a fixed-pitch, stall-regulated turbine, the aerodynamic torque is a function of the wind speed V and rotor speed, Ω. Performing a first order linearisation of Eq. (7) around a set of defined working conditions, *op*, the equation can be rewritten as (see Abbas et al. [3] for the complete derivation):

$$(I_r + n_g^2 I_g)\ddot{\phi} - \left.\frac{\partial Q}{\partial \Omega}\right|_{op} + \frac{1}{\eta}\Delta Q_g = 0 \tag{8}$$

where ΔQ_g is the output of the PI controller:

$$\Delta Q_g = k_p\dot{\phi} + k_i\phi \tag{9}$$

Substituting Eq. (9) into (8), and $\Omega = \dot{\phi}$, the second order equation is rewritten as:

$$(I_r + n_g^2 I_g)\dot{\Omega} + \left(\frac{1}{\eta}k_p - \frac{\partial Q}{\partial \Omega}\bigg|_{op}\right)\Omega + \frac{1}{\eta}\mathrm{k_i} = 0 \tag{10}$$

To determine the first-attempt gains, $\frac{\partial Q}{\partial \Omega}\big|_{op}$ can be neglected for simplicity. In this way, Eq. (10) represents a second order system, characterized by natural frequency, ω_Ω, and damping ratio, ζ_Ω:

$$\omega_\Omega = \sqrt{\frac{\frac{1}{\eta}k_i}{I_r + n_g^2 I_g}}, \; \zeta_\Omega = \frac{\frac{1}{\eta}k_p}{2(I_r + n_g^2 I_g)\omega_\Omega} \tag{11}$$

The natural frequency and damping ratio are chosen by the user depending on the desired controller performance. The PI gains are then calculated as in Eq. (12):

$$k_p = 2\eta\zeta_\Omega\omega_\Omega(I_r + n_g^2 I_g), \qquad k_i = \eta\left(I_r + n_g^2 I_g\right)\omega_\Omega^2 \tag{12}$$

Typical values of the natural frequency and damping ratio for a wind turbine torque controller are 0.1 Hz and 0.7, respectively [11]. These values can be used as first guess and then iteratively adjusted until the controller reaches the desired behavior. As a general guideline, by increasing the natural frequency, the speed of the controller is increased, achieving a better tracking of the reference velocity. However, increasing natural frequency too much may lead to increased oscillatory behavior or even unstable response, and higher loading on the drivetrain. Instead, increasing the damping ratio generally leads to reduced rotor speed overshoot, even though the controller may achieve steady-state operating conditions after a longer time delay, reducing the accuracy of the reference speed tracking. An exmaple of the effect of natural frequency and damping ratio on rotor speed and generator torque is shown in Fig. 2).

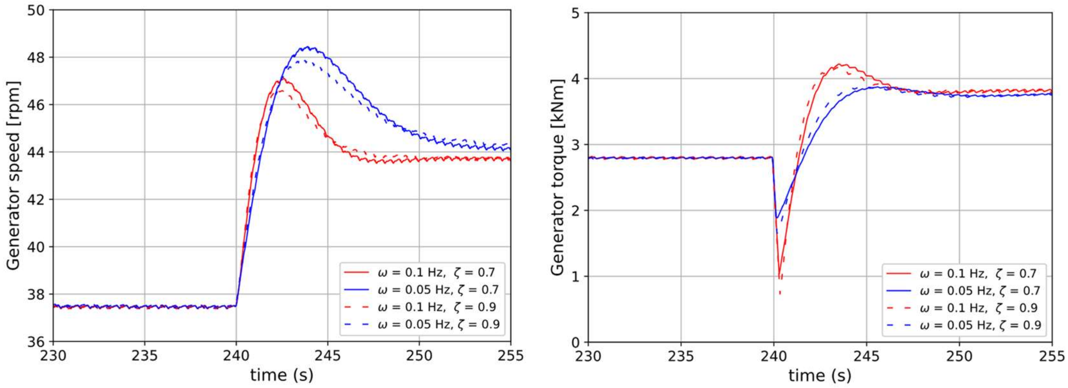

Figure 2. PI controller response with varying natural frequency and damping ratio. (left) Generator speed, (right) Generator torque.

Equation 12 can be used to tune the gains in regions two and three. However, the objectives of the PI controller in the two regions are different, and while a single set of gains might achieve stability of the controller in both regions [12]; the performance of the controller will not be optimized. In fact, adequate performance is generally achieved in Region 2 with moderate values of the natural frequency and damping ratio [12]. In fact, as the value of the reference speed changes with the wind speed, tracking the high-frequency velocity components can lead to improved performance but also increased stress on the drivetrain. Hence, the selection of the controller gains represents a trade-off between the optimization of the rotor performance and preservation of the drivetrain. On the other hand, in Region 3 the controller needs to achieve accurate tracking of the reference speed, as increases of the turbine speed could cause a significant rise of aerodynamic torque and runaway. For this reason, the control response in this region should be faster, requiring higher values of the natural frequency and consequently larger proportional and integral gains (see Eqs. (11) and (12)). Preliminary tests performed using UNICO in the test case presented herein showed that, as a rule of thumb, the natural frequency should be increased by about a factor of three to achieve adequate performance in Region 3 (see Sect. 4 for further details). For this reason, two sets of integral and proportional gains are defined in UNICO, one for below rated conditions and one for above rated conditions and a smoothing function is employed to guarantee adequate switching between the different gain values.

4. Validation and verification

The stall-control-oriented implementation of the controller was tested on the open-source UNIFI 50kW RWT designed by the Wind Energy Group at the University of Florence [13]. It is a horizontal-axis, fixed-pitch stall-regulated turbine. The main turbine parameters are summarized in Table 1.

Table 1. Summary of parameters of the UNIFI 50kW RWT.

Parameter	Value	Parameter	Value
Number of blades	3	Cut-in/Cut-out wind speed	3.2 – 20 m/s
Rotor diameter	16 m	Rated wind speed	12 m/s
Hub radius	0.5 m	Rated rotational speed	56 rpm
Hub height	25 m	Total drivetrain inertia	4279.345 kg m^2
Rated power	50 kW	Gearbox ratio	1

The performance of the controller has been tested in combination with the OpenFAST model of the turbine. A .dll of the controller (available on GitHub) was compiled using MATLAB® and coupled with OpenFAST using the bladed-style interface. Initially, UNICO was tested by simulating the RWT under a uniform wind step test, where the wind speed is increased using a unit step every 60 seconds. The controller was evaluated using both the TSR tracking and k-ω^2 law to underline the differences between the two control algorithms. Results were used to identify an adequate setup of the controller. Then, the performance of the turbine achieved using UNICO was tested under turbulent inflow conditions spanning from cut-in to cut-out conditions. In this way, the controller was applied to more realistic inflow conditions. Results were compared with those obtained using the simplified control logic implemented in the ServoDyn module of OpenFAST, which currently represents the only available open-access option to simulate stall-regulated turbines in above rated conditions. This comparison is carried out to underline the main advantages of the proposed implementation of UNICO. Tests were carried out both with the TSR tracking and k-ω^2 control logics, and the results compared in terms of power output and generator speed.

Table 2. Summary of the UNICO controller setup.

Region	Symbol	Definition	$k-\omega^2$	TSR tracking	Unit
R1.5	ω_{min}	minimum rotational speed	25		rpm
	ω_1	rotational speed @ R1.5 end	27		rpm
R2	K	$k-\omega^2$ law coefficient	184.81	n/a	N m rad^{-2}s^2
R2.5	ω_1	rotational speed @ R2.5 start	54	n/a	rpm
R3	$k_{p,br}$	below rated proportional gain	n/a	-3161	N m s rad^{-1}
	$k_{i,br}$	below rated integral gain	n/a	-1419	rad^{-1} N^{-1} m^{-1}
	$k_{p,ar}$	above rated proportional gain	-9485		N m s rad^{-1}
	$k_{i,br}$	above-rated integral gain	-12770		rad^{-1} N^{-1} m^{-1}
	m	reference speed reduction slope	-0.02		rad m^{-1}

The controller was first tuned to achieve stable operation and adequate performance in all the operating regions. The tuning of the PI controller is performed using the linearization described in Sect. 3. Starting from natural frequency and damping rations proposed in the literature [11], a trial and error approach was used to determine the values that guarantee stable response of the controller and adequate performance. As described in Sect. 3, the controller bandwidth should be higher in above rated conditions compared to below rated. Hence, for below rated conditions the natural frequency was chosen as 0.1 Hz and the damping ratio to 0.7, while in above rated conditions, the natural frequency was increased to 0.3 Hz, keeping the damping ratio constant. In this way, the oscillations of the rotor speed around the reference value are minimized, reducing the risk of run away (see Sect. 5.2).When the k-ω^2 law is used in Region 2, the rotational speed used to switch between the different control strategies must be defined. In this case, stable operation and smooth controller output were obtained by performing the switch between the two control strategies over a rotational speed range of 2 rpm.

5. Results

The performance of the UNICO controller using both the TSR tracking and k-ω^2 control logics for the uniform wind step test and for turbulent inflow conditions is shown in Sects. 5.1 and 5.2, respectively.

5.1. Uniform wind step tests

To compare the k-ω^2 law and TSR tracking strategy implemented in UNICO, the results are analysed for a uniform wind step test, from 3 m/s up to 15 m/s. Comparing the two control strategies for Region 2, the k-ω^2 law leads to reduced overshoot of the controller during a step increase of the wind. In fact, the analytical k-ω^2 law, which estimates the generator torque from the generator speed. Instead, the PI controller tracks the reference speed leading to an initial reduction in generator torque and consequently faster generator acceleration. To reduce the rotational speed overshoot, the speed of the controller could be further increased, however limitations in the maximum torque rate that can be applied by the generator will lead to controller instability, in addition to increasing the mechanical stress on the drivetrain.

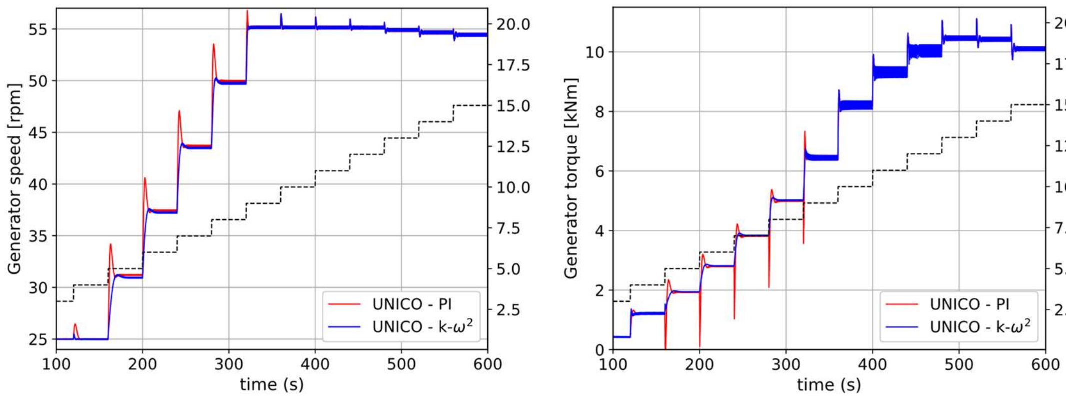

Figure 3. Controller response to wind inflow step test from 3 to 15 m/s. (left) generator speed, (right) generator torque.

The critical aspect of the k-ω^2 law concerns the switching between Region 2 and the PI controller, between 10 and 12 ms^{-1} wind speeds. In fact, the generator torque shows larger oscillations compared to the TSR tracking case, as the generator switches continuously between the two control strategies. Beyond the 12 ms^{-1} treshold, when the controller switches to Region 3, the proposed strategy achieves minimal overshoot of the generator speed.

At low wind speeds, the controller tracks the minimum speed successfully for both the TSR tracking and k-ω^2 control strategies. Even when the k-ω^2 law is employed, the proposed switching strategy (see sect. 2.4) achieves the tracking of the minimum speed correctly, and a smooth transition is observed between the two control regions.

Finally, Figure 3 shows the correct tracking of the linearly decreasing reference speed in Region 3, with minimum overshoot of the rotational speed. The reduced overshoot for the PI controller is due to the faster controller response imposed in this region.

5.2. Turbulent inflow tests

To provide a more representative test of the controller performance, the UNIFI 50kW RWT was coupled with UNICO and simulated for a turbulent inflow. Figure 4 shows the generator torque response as a function of generator speed for UNICO compared to that obtained with ServoDyn. Results show how in Region 3 UNICO can reduce the rotational speed as a function of the wind speed; by doing so, an increased safety margin is guaranteed at high wind speeds. It must be noted that, when using the simple torque control strategy implemented in ServoDyn, the turbine is effectively operated in Region 2.5 when the wind speed exceeds its rated value, and it is not allowed to enter Region 3. If the turbine is operated in this region, where the generator torque as a function of turbine rpm is constant, any increase in rotor speed (leading to an increase in aerodynamic torque) would not be met with an increase in generator torque, causing the turbine to run away. Moreover, this simplified strategy does not allow for precise rotor speed control, making the power curve increase rather than decrease at 20 m/s (see Figure 5), while UNICO provides here a more consistent behavior.

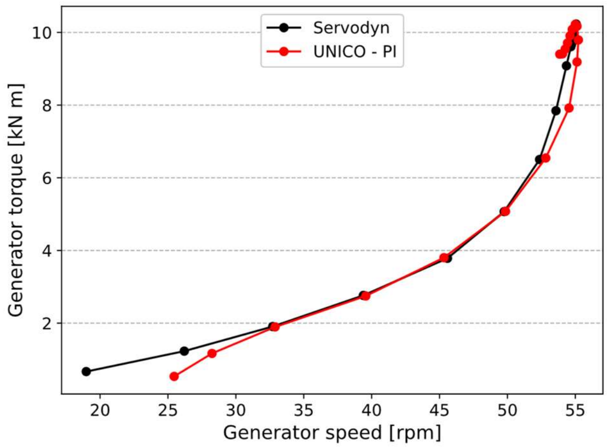

Figure 4. Controller torque response for ServoDyn module and UNICO employing the TSR tracking in Region 2.

Comparing the power curves obtained with the ServoDyn module and UNICO using the $k-\omega^2$ law and TSR tracking approach in Region 2 (Fig. 5), the results show improved performance of the controller between 10 and 12 m/s, where ServoDyn operates in Region 2.5, resulting in a 2% increase in power output. However, despite the improved performance, UNICO shows larger power and speed oscillations when the PI controller is used to track the optimal TSR in Region 2, as the standard deviation is increased for these two metrics. This result confirms the larger speed and torque overshoots observed during the step test of the PI controller in comparison to the k-ω^2 law. On the other hand, when employing the k-ω^2 law in Region 2, the performance of the controller is analogous to ServoDyn up to wind speeds of about 7 ms^{-1}. Discrepancies between UNICO and ServoDyn increase when the wind speed is between 7 and 12 ms^{-1}, as the controller operates at a higher rotational speed, closer to the optimal TSR value. Additionally, the power and speed oscillations increase. These differences are due to the switching law implemented in Region 2.5. In fact, for turbulent inflows, as simulated in this study, the controller may work in Region 2.5 even for lower wind speeds due to sudden wind gusts, which cause the rotor to accelerate beyond the rotational speed threshold imposed for Region 2.5 (see Table 2). The increased rotational speed of the generator in these conditions is due to the switching strategy employed in Region 2.5, as the PI controller is tracking the rated rotational speed rather than the optimal TSR (see Sect. 2.4).

Despite these differences, results show how the controller achieves a smooth transition between regions, as no excessive power or generator speed oscillations are observed.

At low wind speeds, the UNICO controller tracks a higher rotational speed in comparison to ServoDyn to achieve the minimum rotational speed. This results in sub-optimal operation; however, this is a control objective, as, in this way, the low frequency modes of the tower are avoided.

In Region 3, the ServoDyn module achieves a constant rotational speed at the rated value with minimal oscillations. However, due to the implemented control logic this may result in unstable response in case of a sudden rotor acceleration. In contrast, UNICO employs the PI controller to track the linearly decreasing rotational speed. Results show how selected controller gains do achieve the tracking of the reference speed with minimal oscillations of the generator power and rotational speed. This underlines the necessity of using two different sets of gains for the below and above rated conditions. In fact, a slower controller would lead to excessive rotor speed oscillations and possibly run away, for example for sudden wind gusts.

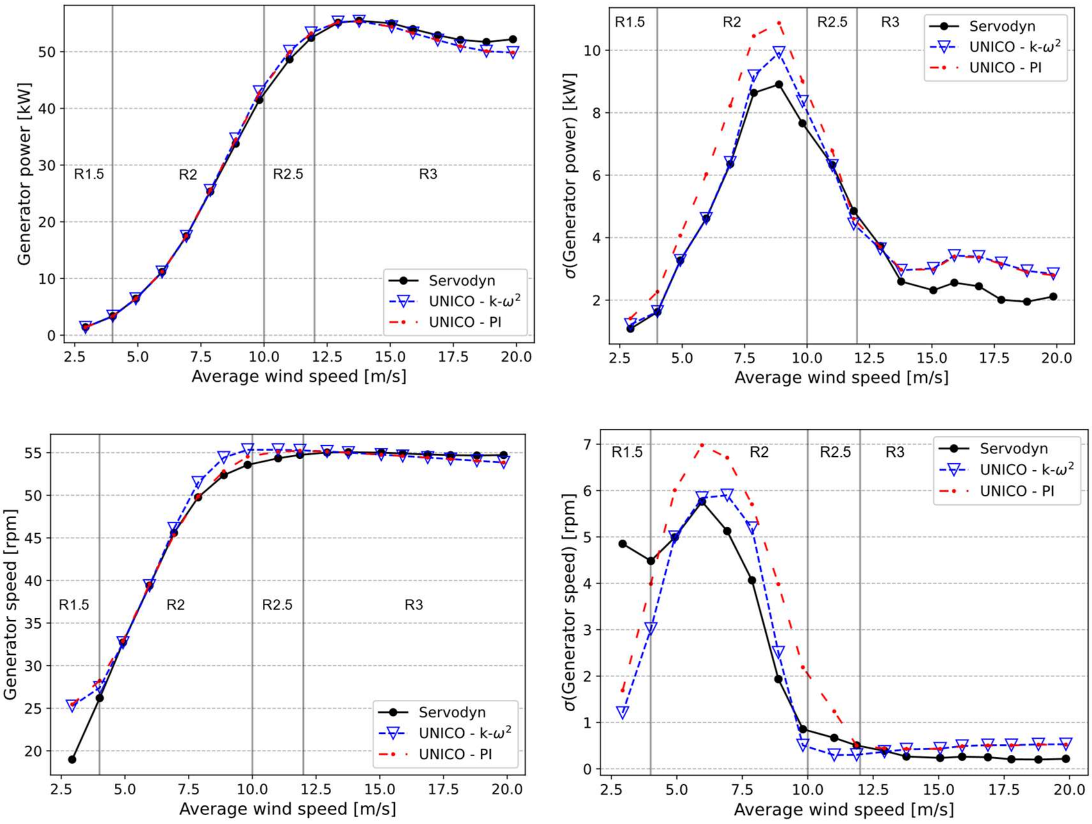

Figure 5. Comparison of ServoDyn module response and UNICO controller using the k-ω^2 law or the TSR tracking control strategy in Region 2. (Top left) Generator power, (top right) Standard deviation of the generator power, (bottom left) Generator speed, (bottom right) standard deviation of generator speed. The grey vertical lines identify the edges of the controller operating region in uniform wind.

6. Conclusions

In the present study, the new open-source UNICO controller is presented. The controller includes PI generator speed tracking above rated wind speed; a feature currently unavailable in other open-source research controllers, which allows for wind turbine stall-regulation. UNICO can be easily coupled to widespread wind turbine simulation software, taking advantage of its open-source nature and bladed-style interface, greatly easing future research efforts on small stall-regulated wind turbines. Additionally, two different control strategies have been implemented for Region 2. The first one is the commonly employed k-ω^2 law. In this case, ad-hoc smoothing strategies have been implemented to achieve improved and stable performance when switching between the different torque control strategies in Regions 2 and 3. The second control strategy employs a PI controller to track the optimal tip speed ratio, which could allow for a significant improvement in performance in case of aerodynamic performance deterioration or changes in external conditions. If PI control is used in both regions 2 and 3, UNICO employs two different sets of PI gains, which can allow the optimisation of the controller response in all operating conditions.

The controller performance was tested in OpenFAST for a small 50-kW reference wind turbine (UNIFI 50kW RWT) and compared with the control logics currently implemented in the ServoDyn module present in OpenFAST. Results showed how both the TSR tracking method and the k-ω^2 law (which is here implemented using a novel switching strategy between Regions 2 and 3) can achieve a 2% increase in power production in near-rated conditions. Additionally, results showed how employing a PI controller to track a reference speed in Region 2 or Region 3 can lead to increased power and generator speed oscillations. Such oscillations, which could be detrimental for the turbine performance and reliability, can be reduced using UNICO by scheduling two different sets of controller gains in above-rated and below-rated conditions.

In the current implementation of UNICO, the PI controller assumes the inflow wind speed known. A key area of future development is the addition of an algorithm capable of estimating the inflow wind speed to provide a more realistic application of the controller.

Data availability

UNICO controller can be downloaded at the address: https://github.com/UNIFI-Wind-Energy/UNICO. DOI: 10.5281/zenodo.10809105.

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