A Structured Wind Turbine Controller Evaluation Process Embedded into the V-Model for System Development

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Abstract. Controller design is always accompanied by an evaluation of control performance. However, for wind turbines, there is only a diffuse consensus on what a good controller constitutes, and no clear method to evaluate overall controller performance. Most evaluations, which can be found in wind turbine control literature, follow similar approaches. However, details such as the models used, the scope of simulation or the result evaluation metric, can change the validity of results greatly. We sort these different evaluation approaches and align them with the V-Model for system design. This yields a structured process which defines requirements within three major domains: Stable automated operation, energy production and structural loads and limits. By following our proposed process, an impartial control evaluation scheme can be setup. Doing so, the complexity of evaluation and validation is handled in a systematic way. We give a clear indication which requirements need to be specified and show which difficulties arise when setting up an evaluating method. Furthermore, the influence of different evaluation parameters on the resulting controller quality measures is shown by evaluating results in slightly different ways. Thereby, the importance of the careful selection of quality measures is emphasized considering the high complexity of the task.

1. Introduction
The design of wind turbine controllers is an art in itself. They need to fulfill basic controller requirements, e.g. stability or robustness, but they also need to operate the turbine so that it produces maximum power with minimum loads. Unfortunately, these objectives compete with one another. A balance needs to be found by a detailed and impartial evaluation of controller quality. Thus, we present a structured process to examine controller quality for multiple domains. The evaluation of controller quality needs to include all controller design objectives and ideally quantifies their fulfillment. In this way, facts replace engineering judgment. Additionally, if all objectives can be expressed as numerical values and their computation is completely automated, mathematical optimization, possibly even multiobjective optimization, becomes feasible. At first though, the process of controller quality evaluation needs to be defined and setup. This is a multi-step procedure that is specific to each turbine and its controller.

We base our proposed structured process on the V-Model for system design according to VDI standard 2206 [1]. It consists of two linked tasks: Development and Verification. Both are based on pre-defined requirements with an iterative process that continuously verifies development.
steps. In order to identify the current state of the art for control evaluation, control literature was reviewed. We focus on identifying common evaluation methods and tie these into our structured process. With this in mind, the paper directly commences with the proposed structured process in Section 2. Afterwards, an application example is analysed in Section 3. We end with a conclusion in Section 4.

2. Controller Design and Evaluation According to the V-model
Over the last decades, numerous papers about new controller developments have been published. Controller quality has been assessed to show their improvement compared to the current state-of-the-art, but the methods used for quality evaluation are rarely more than an afterthought. Review papers usually summarize the current status of new control methods, see e.g. [2, 3, 4, 5], but neglect the evaluation entirely. In [6] and [7], a development process for different types of wind turbine controllers including load reduction methods are described. In [8], a scope of verification is recommended, but not extensively discussed. The paper clearly addresses suitable simulation setups and evaluation methods at different stages of the development process. The authors give some clear advise which dynamics should be included in linearized models for controller tuning and how the controller performance of the PI-pitch controller can be evaluated. They recommend signals that should be included in more complex nonlinear simulations to evaluate the controller performance with respect to loads. The focus of the paper is the design process of a controller without explicitly discussing the applied evaluation methods. Therefore, the paper provides a good starting point for the discussion of existing methods and their integration to a clearly defined process. In order to do so, present control literature is examined. All literature that was reviewed is included in Table 1 and Table 2 at the end of this Section. The literature study includes various different controller designs, e.g. a classical combination of torque and PI-pitch control, but also model predictive control (MPC) or classical controllers including individual pitch control (IPC).

However, instead of looking at the control design itself, we are only interested in the respective control quality evaluation. It became clear that the two major differentiating elements are the complexity of the system model and the evaluation methods. Next, we categorized wind turbine controller evaluation according to its aim. Three major domains were identified: stable automated operation, energy production and structural loads and limits. These form the requirements against which a controller is evaluated.

2.1. Controller Requirements
The specific requirements as well as applied methods, simulations and models always depend on the developers and their specific goals. The development process according to [1] builds on these requirements. The most important requirement is to ascertain safe operation without structural failure. Below this, maximum energy production is required. The lowest step will always be to require basic operational functionality.

(i) Structural loads and limits – When a wind turbine is designed, all components must function reliably for a pre-defined operating time of e.g. 25 years. The influence of the operating controller in interaction with the wind turbine on a component and its failure mode varies strongly. Therefore, the first step for the definition of requirements for a wind turbine controller ideally consists of a selection of relevant components and their specific failure modes. Afterwards, a reliability measure for each selected component failure mode needs to be defined and requirements for this measure are deduced. This can e.g. be strict limits, which must not be exceeded, or a desired reduction of fatigue or ultimate loads. In a subsequent step, the developer decides which evaluation methods are needed to assess the reliability measure, i.e. the models, what simulations need to be performed and what
external conditions (wind characteristics, wave characteristics for offshore turbines, grid connection etc.) are assumed. However, available resources, computational effort, extra work and expected improvement of the control solution will also influence the choice of the measure. Requirements and evaluation methods need to be balanced.

In a late development stage, the controller needs to fulfil the requirements of standards before going into field testing. IEC standard [9] addresses fatigue and ultimate loads by the definition of design load cases (DLCs). These consist of numerous simulations under different wind and operating conditions. However, component specific reliability measures are not clearly defined. For fatigue loads, [9] recommends to use ”appropriate fatigue damage calculation” and mentions Miner’s rule, i.e. the calculation of damage equivalent loads (DEL), which is considered as state-of-the-art for structural components.

(ii) Energy production – The main goal for a wind turbine is energy production. Thus, the major aim of controller development is to produce as much energy as possible throughout the lifetime of a turbine. When load reducing controllers are developed, the possible trade-off to the loss in energy needs to be considered and balanced.

(iii) Stable automated operation – A stable and automated operation is a basic requirement for any controller. The actuating variable controls the system output to follow a set point, despite system perturbations. Therefore, the requirements for the evaluation can in principle be derived from classical control theory. Additionally, this also depends on the selected controller design. For example, the theory for single-input-single-output (SISO) controllers, e.g. standard PI-pitch controller or PI-implementations for IPC, differs from the multiple-input-multiple-output controllers like MPC. Additionally, the particularity of wind turbines, where the wind is converted into electric power but at the same time can be regarded as a disturbance input for the controller, needs to be considered in all of the implemented controller designs.

2.2. Description of the V-model

To cope with these three major domains, the well-known V-model [1] is adapted to the wind turbine controller development process, see Figure 1. At the bottom of the V-model, a specific controller design is selected by the developers. Our model addresses the validation of the specific controller design based on models and simulations. The identified domains of requirements are displayed on the left hand side of Figure 1. At top level of the V-model, the controller is ready to use for field testing based on the requirements of the wind turbine operator and international or national guidelines. Even though the application of a controller on a real wind turbine in the field will always be the final goal, the requirements for a controller in earlier development stages or on research level will differ from the final requirements for an industry level controller. At a lower level, more specific requirements within specific domains need to be defined to be able to verify specific objectives, compare different concepts with each other or to show improvements compared to the current state-of-the-art.

The main reason for using less complex models at a lower level within the V-model is their lower computational time. The use of turbulent wind fields as input for dynamic load simulations often requires a large number of simulations in order to reduce the influence of the specific random seed which is used to create the wind field. Deterministic wind fields allow for fast comparison of different controller designs. However, some effects can only be captured when stochastic wind fields are used as simulation input. Especially fatigue loads can only be evaluated with full aeroelastic simulations for wind conditions that are close to reality. The response of the controller to the incoming wind plays an important role in all three domains of requirements. In Figure 1, increasing model and simulation complexity is summarized as system complexity.
2.3. Evaluation Methods
On the right hand side of the V-model, suitable evaluation methods for all three domains of requirements need to be selected. With increasing complexity, the scope of verification of the controller is extended. Additionally, evaluations performed with lower system complexity need to be confirmed at an advanced development stage. Whereas on a lower level, a large number of different parameters of the controller might be compared using efficient simulations, only a few parameter combinations of the final version can be used when system complexity is increased.

Current literature can be integrated in our proposed model by grouping it into the three domains of the scope of verification:

(a) **Controller performance metrics** – If linear or linearized models of the wind turbine are used for the design, classical controller tuning measures can be applied. Such measures are also recommended in [7] as "useful measures of performance" for a PI-pitch controller. "Gain and phase margins", "the crossover frequency", "pole positions of the closed loop poles", "step responses" and "frequency responses" are explicitly mentioned (p. 223). The authors also state that these techniques allow for a rapid process of controller tuning and that a verification by performing "non-linear simulations using a three-dimensional turbulent wind input" is necessary (p. 233). Analysis in the frequency domain are found as power spectral density (PSD) for rotor/generator speed [10, 11], pitch velocity [10], power [12] and frequency response plots for pitch angle [13] and tilt- and yaw moment [13].

In general, the controller response to wind speed changes is more important than changes in the setpoint. Before using turbulent wind input, step-wise increasing wind speeds are used with complex nonlinear aero-elastic models of wind turbines. When a step response is simulated, quantities like the maximum overshoot and the settle time are evaluated. When more complex simulations with turbulent wind input are used for the quantification of controller performance metrics, the standard deviation of quantities like the rotor speed [10, 14, 11], the power [10, 14] and also the pitch angle [10] are used as measure.

Another performance measure that is frequently used in the literature consists of the visual inspection of a simulated time series. Often rotor/generator speed [15, 16, 17, 18, 19, 12, 20, 10, 14], generator torque [16, 12, 10, 14], pitch angle [21, 17, 12, 20, 10, 14] and tilt- and yaw moments for IPC [8] are considered for performance evaluation. Visual inspection is used to demonstrate stable operation of a complex system including high fidelity wind turbine models with turbulent wind input. Also, two controllers can be compared using this method. However, implicitly the developer will resort to a visual estimation of measures like overshoot or variation of the signal.

(b) **Energy** – The energy yield can be computed from simulation results. However, the scope of these simulations is of major importance for result validity. During early stages of the
development, an estimation based on the power curve might be sufficient. Later on, results need to be obtained for realistic wind conditions. Only these can show the advantages of maximum power point tracking or efficient yaw controllers. In general, the evaluation of power only plays a minor role in the present literature. Measures in the literature are the mean value [16], root mean squared [12], the standard deviation [10, 14] and the annual energy production [10, 22, 23, 24]. Moreover, visual inspection of time series is applied for power production [16, 18, 19, 12, 20, 24] to analyze the energy production for specific events.

(c) Loads – In order to quantify the influence of the controller on wind turbine loads, it is important to select the model complexity according to the requirements. In [7], some features for aero-elastic wind turbine models are recommended for the evaluation of the control performance with respect to loads. This includes "drive train rotational and torsional dynamics", "the generator response", "blade vibrational dynamics", "tower vibrational dynamics", "power or speed transducer response", as well as the "pitch actuator response" (see p. 243). In addition, some basic suggestions for the incoming turbulent wind field are given (see p. 243, [7]). However, it is neither discussed how many simulations should be performed, which wind speeds or specific wind models should be used nor how the output signals should be evaluated.

Quantification of controller performance should ideally be independent of external parameters, e.g. the incoming wind. During load evaluations, the deterministic turbine model is simulated. This is only possible with a pre-computed wind field. To obtain this, a realization of the stochastic variable wind is created using a random number generator that requires a seed value. The seed value has a major influence on the loads obtained from the simulation. To reduce this influence, a large number of seeds and simulations is required. These yield long computation times or large numbers of simulations, which might be feasible for the final evaluation of the controller at top level of the V-model, but more efficient methods are desired at a lower level to allow for comparison between different controller configurations or numeric optimization.

Visual inspection or comparison of load time series is frequently used. In this case, only one or very few incoming wind conditions can be considered and only a qualitative evaluation is possible. Common variables for visual inspection are tower deflection [21, 18, 19, 10], blade root bending moments [17, 8, 14], pitch acceleration [20] and nacelle velocity [17]. The evaluation of load time series in the frequency domain can be a useful measure to identify oscillations. These can help to find frequencies to be damped by the controller or to design a filter. Moreover, it gives indication for further analysis. The usual approach is PSD analysis, it shows the spectral energy distribution of a signal. Common load variables are tower top/base bending moments [15, 11], blade root bending moments [15, 8, 14, 25], pitching yawing moment of the rotor [14], shaft bending [8], yaw bearing [8] and pitch acceleration [11]. Another frequency related measure is e.g. the violation of a power limit [26]. It could indicate the aggressiveness of the controller. A high frequency could imply high loads. Nevertheless, specific quantitative measures for each component allow for much more substantiated statements about the controller performance.

The calculation of mean values and standard deviation can help in understanding the overall effect on load variables. The mean value is computed in [26] for tower displacement, drive train twist rate and power variation. The use of standard deviations can be found for blade root bending [19], tower deflection [11] and pitch acceleration [11]. Both measures neglect the sequence of load cycles and should only be used carefully. A common measure to evaluate the pitch activity is the actuator duty cycle (ADC), which is applied in e.g. [22] and [26]. However, a more detailed cycle analysis of the specific movement patterns of the pitch bearing has to be applied for the evaluation of pitch bearing loads [27].
The description of requirements mentions DELs as the state-of-the-art for fatigue load evaluation. Therefore, this measure is frequently found in the literature as a measure for controller performance. When this measure is used, an awareness of the dependency of this measure on the number of turbulent wind realizations is important. Usual variables are tower top/base bending moments [15, 28, 17, 12, 10, 22, 25, 24], blade root bending moments [15, 17, 8, 10, 14, 22, 25, 24, 23], shaft bending moments [8, 10, 22, 24, 23], yaw bearing [8, 24], hub bending moments [25] and rotor speed [28].

As a summary, categorization of the literature into system complexity and evaluation domain is presented in Table 1. The columns of the table show three evaluation domains, which are described above. The rows describe the system complexity. We found four major levels of complexity. Linear models are obtained for early developments. Linearized models are derived from aero-elastic code at certain operating points. These models can be used to analyze the stability of the system or for low level load assessments. Aero-elastic models can cover the nonlinear dynamics of the wind turbine in interaction with the wind. Such models are frequently used, since they give a good compromise between computational effort and accuracy. In the case of aero-elastic code, a distinction is made by the applied wind field. These wind fields can be grouped by their formulation, which is deterministic or stochastic. Deterministic wind includes no randomness and usual profiles are constant, sinusoidal, step wind or extreme operating gusts. Stochastic wind fields are designed to represent the wind turbulence as realistic as possible. The use of computational fluid dynamics (CFD) and wake models are listed separately because they are mainly use for wind farm controller development. The wind is modelled differently than in other non-linear approaches. The wind turbine model can also differ. It can be described by an actuator disk or include aero-elastic formulations.

A second overview is given in Table 2 regarding the evaluation methods. Here, the rows describe the three evaluation domains from above. The columns group the evaluation methods. We specifically address the methods and not the variables for the sake of clarity. First, there are the visual inspection and statistics of a time series. By statistics we refer to mean, standard deviation, maximum and minimum of a time series. Other post processing methods address the AEP for the energy domain and DELs or ADC for the load domain. All frequency based evaluations are combined by the frequency domain column.

Most studies can be placed at the aero-elastic level with stochastic wind modeling. Linear and linearized models are less often used than aero-elastic formulations. The focus of evaluation is found by performance and load measures. Energy production is not always considered.

Table 1: Categorization by modeling complexity and evaluation domain

| System complexity | Performance metrics | Energy | Loads |
|-------------------|---------------------|--------|-------|
| Linear            | [16, 13, 18]        | [16, 18] | [13, 18] |
| Linearized        | [2, 21, 13, 15, 10] | - | [2, 21, 13, 15, 10] |
|                   | deterministic       | [6, 17, 20, 10, 11] | - | [17, 10] |
| Aero-elastic      | [2, 6, 19, 17, 12, 8, 20, 10, 14, 22, 11] | [26, 19, 17, 12, 10, 14] | [2, 6, 28, 26, 19, 17, 12, 8, 10, 14, 22, 25, 11] |
| stochastic        | -                   | [23, 24] | [23, 24] |
| CFD, Wake-Models  | -                   | - | - |
Table 2: Categorization by evaluation domain and method

| Evaluation     | Time series | Other post processing | Frequency domain |
|----------------|-------------|-----------------------|------------------|
| Performance metrics | [6, 16, 21, 15, 18, 19, 17, 12, 8, 20, 10, 14, 29] | 10, 14, 22, 11 | [2, 13, 17, 10, 11] |
| Energy         | [16, 18, 19, 12, 29, 24] | [26, 17, 10, 14, 29, 23] | 23, 24 | - |
| Loads          | [2, 21, 15, 18, 17, 10, 14, 29] | [26, 19, 28, 17, 12, 8, 10, 14, 23, 24, 25] | 6, 13, 15, 17, 8, 22, 25 |

CFD and wake modeling gained interest, especially for wind farm studies.

The applied evaluation methods focus on performance metrics and load evaluation. The preferred method is the visual inspection of a time series for performance metrics. Energy evaluation is considered by visual and statistical analysis of time series. For load evaluation an almost even distribution between the methods is found.

It becomes obvious that the more complex the controller or the model is, the more careful the selection of appropriate controller requirements has to be as well. The very first step is to clearly define the objectives of the controller. Basic controller performance according to Step (a) has to be checked in every case. For most controller requirements, the main driver for model complexity is the evaluation of loads, i.e. Step (c). A more detailed evaluation of power produced, i.e. Step (b) is a welcome byproduct.

3. Application Example

We will evaluate the implementation of a cyclic individual pitch controller (IPC) which was designed as a PI controller according to [8]. The controller is implemented for the generic direct-drive wind turbine IWT 7.5 [30]. IPC can be added to a standard torque-pitch controller of a wind turbine. We start from an existing controller which uses $k \omega^2$ as torque reference in partial load and a PI collective pitch controller in full load. We assume that this controller design is finished and that it fulfills its specific design requirements. It is subsequently referred to CPC controller.

The main purpose of IPC is to reduce loads which are introduced by the asymmetric wind inflow on the rotor disc. For a controller evaluation according to the V-model, this purpose needs to be translated into specific requirements within the three domains that were described in section 2.1. More specifically, IPC aims at reducing fatigue loads of the rotor blades at the blade root. At the same time, loads on other components should ideally not increase at all or only to a reasonable extent. For pitching motions, the main concern is with the pitch bearing. Component specific damage measures are required for these components. The requirements for structural loads and limits (domain (i)) are thus to reduce the blade loads as much as possible, but to keep the pitch system loads within reasonable limits. Since IPC works by pitching the blades away from their aerodynamic optimum, a negative effect on energy production has to be expected. The loss in energy needs to be outweighed by reduced material or operating costs which can hardly be considered during control design. The corresponding requirement for energy production (domain (ii)) is to keep the loss of energy as low as possible. Before these requirements can be addressed, the IPC controller needs to be designed such that it guarantees a stable automated operation in combination with the original CPC controller at all times (domain
(iii)). This process is located at the bottom of the V-model. It is the starting point of a controller
development once higher level requirements are defined.

A complex aero-elastic model of the IWT 7.5 is available in MoWiT [31]. This model is
used for load simulations when higher level requirements are assessed. In order to evaluate
controller performance metrics, the complexity needs to be reduced by limiting the number of
degrees of freedom using rigid elements for the blades and the tower. The process we employ
in order to ensure stability of an IPC controller is based on the analysis of Eigenvalues. Basic
stability theory indicates that a closed-loop system with positive real Eigenvalues is unstable.
To determine the Eigenvalues, linearization of the reduced-complexity model is employed. In a
first step, the model is linearized for several wind speeds. This yields system matrices for a state-
space representation. To reduce the effect of azimuth-dependent nonlinearities, linearizations for
at least 12 evenly spaced angular positions are used. Then, non-necessary states are removed.
This is e.g. the rotor azimuth angle, which is not required but always unstable. Rotating
degrees of freedom are transformed to non-rotating degrees of freedom according to [32]. This is
augmented to compensate for time-delay between transformations according to [33]. To remove
azimuth dependent nonlinearities, system matrices are averaged over all angular positions. With
this approach, a separate open-loop plant model for each wind speed is obtained. This is then
coupled with the transfer function of the controller. From this, the analytically-obtained closed-
loop transfer function is parameterized. We then analyze the transfer function’s Eigenvalues.
The closed-loop model is linear and time invariant. As such, its validity is strictly limited to
small perturbations from the linearization point. A stability analysis is also only valid within
the same constraints. However, with sufficiently granular wind speed steps and azimuth angles,
the remaining risk becomes acceptable. The computational effort of this approach does not
allow an instant evaluation, but since it can be employed unattended it does not significantly
slow down controller development. Additional, lower level evaluations have been performed to
gain a deeper understanding of the control behaviour and its performance. This includes step
responses and frequency analysis using the full aero-elastic model of the turbine. An evaluation
of the power spectral density of the flapwise bending moments, as suggested by [8], shows that
the peak at the 1P frequency is eliminated by the controller.

The evaluations in [27] are generally a prime example for the assessment of loads based on
specific measures for the components which are mainly influenced by IPC. In this paper, the
impact of pitch motions on the blade bearing is investigated. For this, we employ the method
introduced in [27]. Additionally, fatigue loads of the blades are evaluated using DELs. Here,
we pay additional attention to the wind fields as an influencing factor.

By performing load simulations for DLC 1.2 according to [9] with MoWiT, the mentioned
component specific measures can be evaluated and the impact on energy production can be
assessed. According to [9], it is recommended to use ”at least six 10-min stochastic realizations
(or a continuous 60 min period) for each mean, hub-height wind speed” (p. 40) to account for
the uncertainties. We use 12 different turbulent wind seeds of 10 min for each mean wind speed
from 3 to 27 m/s with a resolution of 2 m/s. For both controllers, CPC and IPC, the same wind
fields are used as input. Instead of evaluating all 12 results together, the simulations for each
mean wind speed are subdivided into two separate sets of 6 simulations. At first, the energy
yield is evaluated for each mean wind speed and both separate sets. The relative change in
energy is shown in figure 2. The energy output of the turbine decreases for all wind speeds
except for 3 m/s mean wind speed. This wind speed bin is very close to cut-in and wind speeds
below cut-in wind speed, with turbine operation stopped, are common. Also, the absolute value

1 Note that there is a major difference between the IPC controller that was used in [27] and the version used in
this paper. The present version uses IPC within the complete range of wind speeds, i.e. also below rated, whereas
the other controller is only activated when the CPC pitch angle is above 2.3°, i.e. only above rated wind speed.
The underlying CPC controller is also different.
of energy is very low compared to the other wind speeds so that the increase is negligible. At mean wind speeds of 5, 7 and 9 m/s, the loss of energy lies around 1% and the difference between the two separate sets of seeds is measurable but seems statistically insignificant. When the total energy is scaled with a Weibull distribution of IEC class A using simulations with all 12 seeds for each wind speed, the total reduction of energy is 0.42%, which seems to be justifiable cost for a significant blade load reduction.

To evaluate the fatigue loads of the rotor blades, DELs of the flapwise blade root bending moments (flapwise BM) are selected as component specific measure. A major parameter for DEL computation is the Woehler-coefficient, which is a material parameter for fatigue life. We assume a value of 10, which is commonly used for rotor blades. For industrial applications, a more precise value from experiments would be beneficial. A further discussion of this measure would go beyond the scope of this application. Figure 3 shows the relative change in DEL for each mean wind speed of the IPC controller compared to the CPC controller exemplary for two out of three blades. A reduction of DEL can be seen for all mean wind speeds and both blades. Again, the simulations were subdivided into two separate sets. In Figure 3a, at 13 m/s wind speed, a DEL-reduction of about 17 % can be observed with the first subset of seeds compared to a 10 % reduction with the second subset. In Figure 3b, the reduction of DEL at 9 m/s constitutes of only 4 % with the first subset compared to about 10 % with the other subset of seeds and the results of blade 1. These results suggest that 6 seeds, as required by [9], are not necessarily a sound basis for a fatigue life evaluation.
A more detailed analysis is shown in Figure 4. Here, stochastic distributions for DEL for one of the three rotor blades are computed for each mean wind speed and each turbulent wind seed. All results are normalized to the average DEL of the CPC controller at mean wind speed of 11 m/s. Despite individual DEL values for one controller being well within the range of results of the other controller, DEL for CPC and for IPC controllers can be separated quite well.

Concluding the findings above, one can clearly state that this IPC controller significantly reduces the DELs of the flapwise blade root bending moments. However, quantitative statements to the amount of reduction in the reliability measure should only be made with an awareness to the remaining uncertainties and the methods that were used for evaluation. Uncertainties can be reduced with a higher number of simulations and the controller developer needs to determine a trade-off between acceptable uncertainty and simulation effort. In this case, the lifetime DEL of the flapwise BM is reduced by about 13 % when all 12 seeds are taken into account for each wind speed. Again, the Weibull distribution (IEC class A) was used for this measure.

In order to evaluate the influence of the IPC controller to the blade bearings, the algorithm from [27] is applied. A range pair algorithm counts the number of pitch cycles, which are then grouped by their double amplitude. In addition to the number and amplitude of the cycle, their sequence and also the resulting bending moments can influence the risk of rolling contact fatigue and wear of pitch bearings. However, further research is required to draw detailed conclusions regarding a specific risk or fatigue measure. More details regarding the impact of different influencing factors can be found in [27]. The cycle amplitudes are still an essential part for the evaluation of the pitch bearings because the risk of wear is increased by a high use of small pitch cycles. Figure 5 shows the total number of pitch cycles for the IPC controller compared to the CPC controller scaled with the already mentioned Weibull distribution. It can clearly be seen, that the number of pitch cycles increases strongly for all amplitude ranges but for the lowest range. Between 0.05° and 0.55°, it is decreased by almost 30 %. In total, the pitch operation time is increased by 188 %. This is mainly because IPC is operating during partial load when the CPC controller does not operate at all. In Figure 6, the number of cycles is shown for three
different mean wind speeds for CPC and IPC controller. The activity of the CPC controller is dominated by very small load cycles between $0.05^\circ$ and $0.55^\circ$ and between $0.55^\circ$ and $1.05^\circ$ to some extend. In the IPC controller, a shift from a higher use of small amplitudes to an increased use of high amplitudes can be seen with increasing wind speed. In total, it is not yet possible to draw clear conclusions on the influence of the controller on the bearings. A positive effect is definitely evoked through the reduction of very small pitch cycles during full load production.

It becomes apparent that an impartial evaluation becomes possible when requirements are clear and evaluation methods can be selected. Still, the example shows how much evaluation results depend on the choice of evaluation methods as well as on the chosen system complexity.

4. Conclusion
The evaluation of the quality of a controller for wind turbines poses quite a few challenges, which are not only unique to wind turbines, but also make comparison between different controllers extremely difficult. The differences between specific control methods, turbine simulation tools, turbine models and controller design objectives are too great to be covered by a single universal comparability process or metric. Therefore, the a structured process with clearly defined requirements is of high importance. We presented a literature overview on wind turbine controller evaluation methods. By classifying the different methods into a defined structure, similarities could be found.

By combining the classification with the V-Model for system design, we could show that the major requirements stable automated operation, energy production and structural loads and limits, which can be distinguished clearly, can be ascertained separately in different stages of controller development. For this, different model complexity is required. With increasing complexity also comes increased computational expense. At the lower end of the complexity spectrum lie linear or linearized models, whereas at the complex end full aero-elastic models are used. These rely on turbulent wind fields, which further impede efficient evaluation. This is mainly due to their direct effect on wind turbine simulations and resulting loads. We show this effect with an application example that highlights the complexities for controller evaluation.

In order to setup an individual evaluation approach, a control engineer needs to be aware of these difficulties. We aid by showing what measures are commonly evaluated for what purpose. Our proposed V-Model with the three distinct domains can be used as a guide towards an impartial evaluation where the first and most important step is the clear definition of requirements for the controller.
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