Closed-loop supervisory control for defined component reliability levels and optimized power generation

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Abstract. Wind turbines are commonly designed for an operating life of approximately 20 years. During development, loads based on a standardized wind site are assumed and the components are designed accordingly. During manufacturing, variance between components and deviations from the nominal component properties cannot be avoided. During operation, loads experienced by a turbine might differ significantly from those assumed during development. Combined, these effects lead to changed actual time to failure. Turbines are either overloaded, making them fail before the end of their design life, or they are running with lower than possible performance and some load bearing capacity is wasted at the end of their service life. To better adapt turbine operation to the actual loads experienced by an individual turbine, we propose the use of reliability control. It is based on a closed-loop adaptation process which changes operating parameters such that performance is maximized, but reliability requirements are met. We present the basic concept and give a detailed introduction to reliability control for wind turbines. We also highlight the current challenges for deployment, which mainly lie in the field of condition monitoring.

1. Introduction

Multi-Megawatt-wind turbines are large, flexible structures employed in rough, changing and strongly site-specific environmental conditions. A common requirement is continuous operation over a time span of 20 or even 25 years with very high availability. At remote sites, e.g. offshore, access to the turbines is limited and very costly. Therefore inspection, maintenance and repair need to be planned carefully. Currently, maintenance is planned based on statistical information about component failure behavior augmented with detailed information about the current state of the main turbine components. This can be obtained from a condition monitoring system that collects measurement data from the turbine and estimates the failure state or predicts the time to failure. However, this planning is still reactive: Predicted or existing failures in the turbines drive the maintenance schedule. Instead, a more flexible approach with planned unavailability during periods with low wind would be preferred.

Main drivers for wind turbine failures, i.e. cases in which the component life is shorter than the design life, are the dynamic loads which can be partly influenced by the operational mode, e.g. by operating at reduced power. To compensate for uncertainties in the actual turbine loads and the load bearing capacity of components, partial safety factors are used during design of the turbine and its individual components. In practice, deliberate overdesign is used as means to avoid early failures and to guarantee safe operation under defined worst case scenarios. However, fixed safety factors in combination with site specific and varying external conditions as well as limited use of knowledge about existing load bearing capacities lead to overly strong designs. As the reduction of cost of energy is the main driver of the industry, optimal usage of the turbine and its components must be a development goal, which directly conflicts with overdesigned components. Our novel approach to cope with these challenges is to combine the possibilities of influencing load levels through changed operating modes with the estimation of current remaining load bearing capacity into a closed-loop reliability control on supervisory control level. Reliability control uses the current remaining load bearing capacity of each component together with a-priori knowledge about failure causes, modes and models as well as system performance and maximizes energy production while keeping a desired reliability or required residual life. It changes loads on the turbine, and in turn the rate at which components are aging, by adapting the operating mode accordingly.

Figure 1 shows the effect of individually adjusted operating modes for each turbine. In the figure on the left, the current situation is illustrated. Stress for each wind turbine in a wind park can be approximated by stress probability distributions, which are similar for all wind turbines in a wind park. Due to tolerances in the turbines' component geometries, differences in their material properties and variations in the production process, strength follows a probability distribution as well. Two turbines out of this strength distribution are depicted exemplarily: a strong turbine and a weak turbine. For both turbines, damage accumulates approximately at the same rate. This in turn leads to an earlier critical failure probability for the weak turbine. On the right side of Figure 1, which corresponds to the proposed situation with implemented reliability control, individually adapted operating modes are used. The strong turbine is used at higher performance and thus has a higher degradation rate, while the weak turbine is derated and has a lowered degradation rate. In this way, individual stress is applied to both turbines, which leads to a levelled time to failure despite their differing strengths.

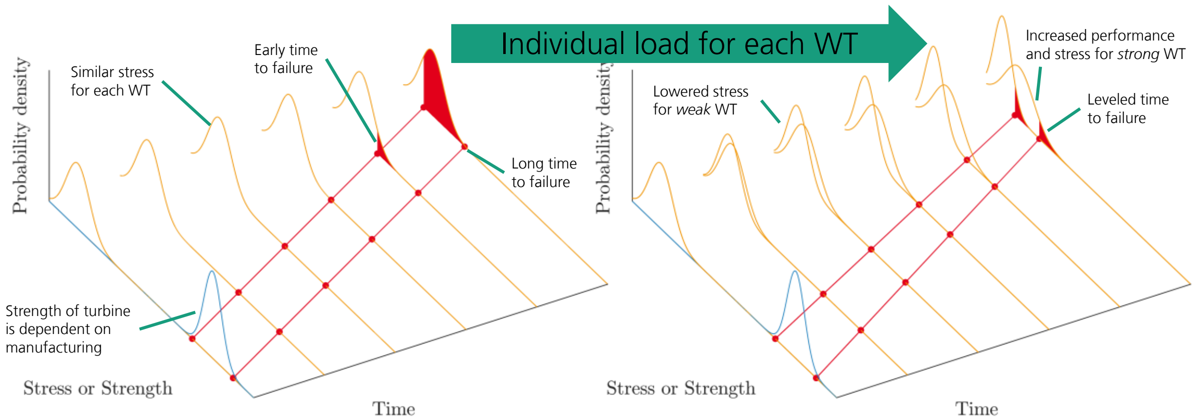

Figure 1. Stress and strength of a large number of turbines are random distributions. Individual turbines have pre-determined strength, by means of changed degradation rate, time to failure can be leveled.

1.1. Structure of this paper

The remainder of this paper is organized as follows: In the next section, we give an overview over currently used methods for wind turbine control. Also included is a brief introduction to reliability control and an overview over other related approaches for lifetime control. Section 3. illustrates the benefit that can be obtained when using reliability control, while Section 4. gives an in-detail-introduction to reliability control for wind turbines. A major aspect is detection of current degradation, and for this reason an overview over condition monitoring and its applicability is given in Section 4.4. This paper ends with a conclusion of our work and an outlook to future work in Section 5.

2. Current state of the art

In research, two means to reduce aging of wind turbines are commonly discussed: controllers that reduce fatigue damage in a turbine itself and operating strategies that reduce turbulences experienced by downwind turbines in wind farms [1]. A common approach to reduce fatigue damage is to include a measure in real-time control directly and to influence this by means of e.g. [2], derating or individual pitch control [3]. A common approach for turbulence reduction is wake redirection by means of yaw misalignment [4], or individual pitch control [5]. All individual strategies can also be combined. A common problem with any damage-reduction or turbulence-redirection method is that power generation, i.e. system performance, is reduced [1]. During a twenty-year operating period, fatigue damage cannot be avoided but a suitable balance between damage rate and system performance needs to be found. The main question, which remains unanswered in recent research results, is thus: What compromise between performance and damage rate needs to be selected such that performance is maximized, but fatigue damage is limited to meet the pre-defined reliability goals for the turbine?

As solution to this demanding problem, we propose the use of reliability control. It is based on model-based self-optimization for system behavior adaptation [6]. This method has been developed independently of specific systems. It has already proven suitable for reliability control of automotive components [7] and quality control of manufacturing processes [8] and is considered to have high potential for application in wind turbines.

Reliability control forms an outer control loop on supervisory process control level. It is separate from power-, pitch- and yaw-controllers, which directly interact with the structure of the turbine by means of sensors and actuators. While these dynamics controllers run in real-time and on a PLC inside the turbine, reliability control runs on a slower time scale and can be implemented on a separate system for the whole wind farm. It interfaces with the dynamics controllers by means of their configuration. A controller configuration can consist of control law parameters, e.g. PI gain values or individual pitch influence and set points such as yaw misalignment or reduced power, or other similar parameters that can be changed during operation.

2.1. Reliability control for wind turbines

In order to adapt the dynamics controllers, several possible configurations together with knowledge about their impact on turbine performance and degradation need to be available. Reliability control then selects a configuration according to the current system state, which is obtained from a condition monitoring system. The whole loop is outlined in Figure 2.

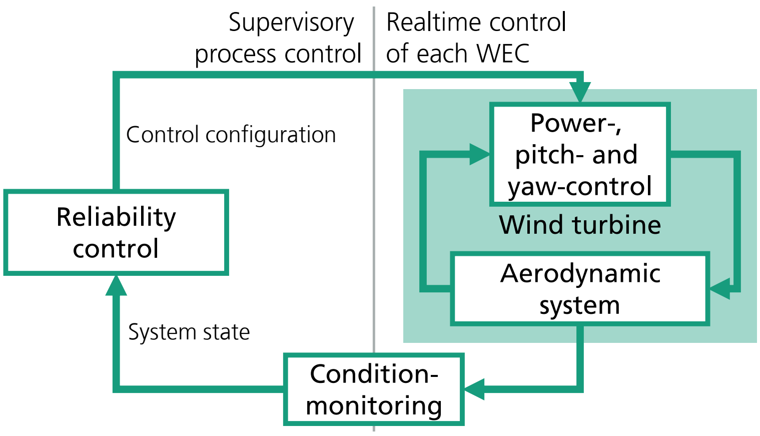

Figure 2. Basic outline of reliability control loop.

Since reliability control only influences actual system behavior through a selection process among predetermined possible configurations, each configurations suitability and safety can be validated before operation. In order to find such suitable configurations, model-based multiobjective optimization is employed [9]. For wind energy reliability control, models of turbine or wind park performance, loads and specific component degradation are used. These are augmented with quantifiable objectives. At least two objectives are required: One for performance, which usually equals power output, and one for reliability, which usually corresponds to fatigue damage rate or loads. These are implemented to evaluate simulation results and return one single value for each objective.

To employ numeric multiobjective optimization algorithms, the models, simulation tools and objective function algorithms are combined into a set of objective functions. The optimization algorithm then tries to optimize all objective functions by means of parameter adaptations. Parameters that can be adapted are e.g. controller parameters such as gain parameters or set points such as yaw misalignment angles or reduced power. Commonly, performance and reliability objectives contradict one another and make it impossible to find one single optimum configuration. Instead, the result from multiobjective optimization is a set of all possible optimal compromises for which an improvement of one objective necessitates impairment of other objectives. For certification, the number of configurations can be reduced and each can be certified individually. Changes between configurations that only require setpoint changes do not need further certification procedures. If controller parameters are changed, it needs to be ascertained that the change itself does not impair system safety or integrity, but existing control engineering methods can be employed [10].

The result from multiobjective optimization is the Pareto front, which contains all optimal objective compromises, and the corresponding parameters, which are called Pareto set. Using this set of optimal configurations, damage rate can be adapted by a reliability controller by selecting a compromise that is suitable for the current situation, then changing the controller parameters or setpoints of a turbine or the whole wind farm accordingly. For closed-loop reliability control, the current state of each individual turbine or component is fed back into the reliability controller. State estimation can be conducted using contemporary condition monitoring or structural health monitoring methods. These take over the role of a sensor in a classical control loop. The interaction of multiobjective optimization, Pareto optimal solutions, turbine model and actual turbine is depicted in Figure 3.

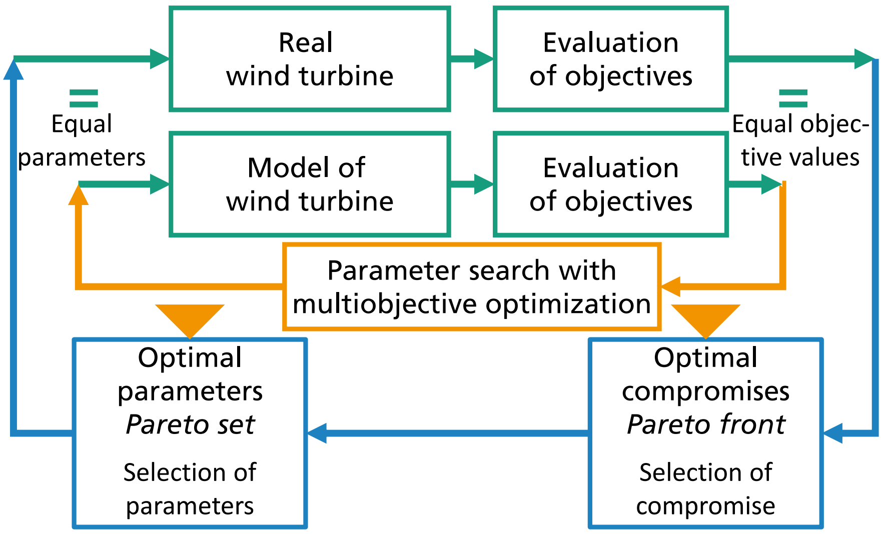

Figure 3. Numerical multiobjective optimization as basis of behavior adaptation during operation.

System adaptation is then conducted in several individual steps. At first, condition monitoring information is compared to the accepted and desired degradation state at the current time. To this end, a sophisticated condition monitoring which outputs continuously updated information about the current degradation state is required. Then, the priority of reliability and performance objectives is adapted to align actual degradation with desired degradation. The Pareto optimal configuration is selected and the configuration of the turbine or wind farm is set accordingly. In the next time step, new condition monitoring information is available and the adaptation cycle is conducted again. This is conducted on a supervisory level, not directly in the real-time turbine dynamics control. The separation into two layers allows for further safety checks and fast real-time reaction on turbine level while reducing the computational load caused by reliability control, which can be run on a much slower and longer time scale.

2.2. Related approaches to control wind turbine reliability

Existing approaches for wind farm or wind turbine reliability control integrate fatigue life limiting features into the dynamics controllers themselves, e.g. by using model predictive control including a fatigue progression model [11]. However, this approach requires extensive knowledge about degradation mechanisms and a fatigue lifetime model. This limits their applicability to components where such a model is available for the actual component on an individual turbine. If only lifetime models for a component with nominal properties are available, a compensation of individual strength deviations is difficult to impossible.

Especially for wind farms, complete real-time control including fatigue life becomes a computationally expensive task. If using model predictive control, during each time step, the fatigue life for each turbine along with turbine dynamics and interactions would need to be simulated. This is possible on a lab scale, but not feasible for large, multi-Gigawatt wind farms. In effect, the computational complexity of model predictive control including fatigue damage control limits applicability to small-scale problems and is not suitable for full wind farms.

3. Effect of reliability control on turbine reliability

Figure 4 illustrates the advantage that can be achieved using reliability control by showing exemplary reliability functions of wind turbines with different operating strategies. Turbines with today's static control configuration show large variance in time to failure; to obtain 95% reliability, maintenance has to be conducted long before the mean time to failure (MTTF) or the turbines have to be designed with a mean time to failure much higher than the intended operating time. The higher load bearing capacity of *strong* turbines is wasted in this case. Reliability control increases the time to failure of *weak* turbines by reducing loads and increases the performance of *strong* turbines, which increases their power output but uses up their load bearing capacity faster. These two aspects combined lead to a reduced variance in the time to failure, but do not change the mean time to failure. This allows for later maintenance close to the actual failure time and reduces wastage of load bearing capacity. Changes in the required lifetime are realized by changing the control configuration of reliability controlled turbines, which is shown in the curve $R_e(t)$ in Figure 4. Changing the required lifetime can be used to better align turbine degradation with the maintenance plan. This way, maintenance planning does not need to purely react on turbine degradation, but can also take availability of material, personnel and other assets into account. However, changes in required lifetime also come with changed performance. A reduction in required lifetime, e.g. due to a scheduled early replacement, makes a sole focus on performance possible, while an extended turbine lifetime or extended maintenance intervals due to e.g. inclement weather, lack of maintenance personnel or in order to facilitate logistics, come at the price of decreased performance.

By allowing for better maintenance planning, availability is increased by increasing the time to failure, but more importantly by reducing the time to repair. At the same time, component life is fully utilized without increasing the risk of early failures. This allows for lowered safety margins in the design, which reduces material usage and logistics efforts. Combined, these effects significantly contribute to a lowered cost of energy and increase revenue.

4. Application of reliability control to wind energy systems

Several prerequisites need to be fulfilled in order to employ reliability control for wind turbines successfully. While many of these must be fulfilled in any system to which reliability control is applied, several specific challenges arise for wind turbines.

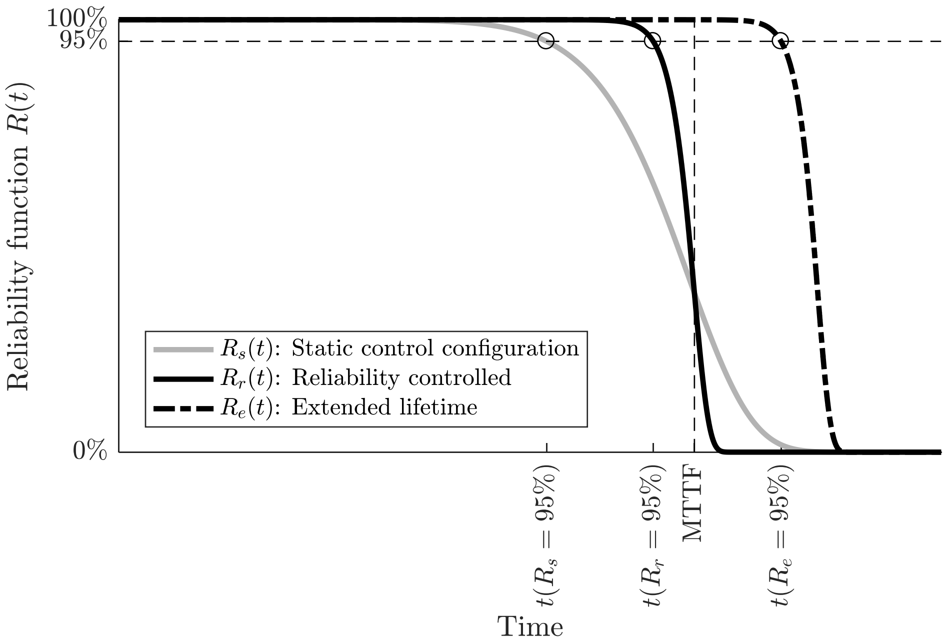

Figure 4. Reliability functions of the same turbine operating with different operating strategies. 'Extended lifetime' denotes turbines with reliability control, but changed desired lifetime.

4.1. Model of dynamic behavior including loads

For model-based multiobjective optimization, a model of the system to be controlled is required. If the reliability of a single wind turbine is to be controlled, a model for this turbine is required. It usually consists of structural dynamics, the interacting mechanical and electrical drivetrain components, aerodynamics of the structure and blades, system controllers, wind and, for offshore turbines, waves. Such a model is usually set up for load calculation and can be adapted to suit multiobjective optimization needs. If multiple turbines in a wind farm are controlled by one common supervisory reliability controller, all turbines and their interactions need to be included in the simulation model. This model is considerably more complex and needs to be set up separately, but simplified wake models are sufficient to find suitable configurations.

To evaluate a configuration's feasibility, objective functions that evaluate simulation results must be defined. For multiobjective optimization with the aim to find a trade-off between regular operation and reliability, at least two objective functions are required: one for intended operation objectives, i.e. power generation, and one for reliability. To allow for easier formulation of reliability-related objective functions, loads are used in favor of damage. This allows for simulations without a damage progression model. Damage progression models are difficult to set up and may need simulations over a long period of time. We assume that by reducing loads, which would serve as input to a damage progression model, damage rate is reduced as well and system lifetime is increased. This way, knowing that a relationship between certain loads and the damage progression rate of a component exists is sufficient. Reliability control then influences the damage progression rate indirectly.

If multiple turbines or turbine components are supervised by reliability control, one objective function for each turbine or component is required. With multiple reliability-related objective functions, trade-offs not only between intended operation objectives and reliability but also between reliability of individual turbines or components become possible.

In order to find optimal operating points, parameters that can be changed during operation need to be provided to the multiobjective optimization algorithm as optimization parameters. While there exists a multitude of multiobjective optimization algorithms, it is common for all of them that in an iterative process, the algorithm selects a set of parameter values, simulates the system, and evaluates all objective functions for the simulation result. Between iterations, it compares the objective function values to other objective function values that were found for other parameter values and in turn converges to the optimal solutions. For this to be possible, optimization parameters need to be identified. Good candidates are controller parameters such as gains of classical PI pitch controllers, which influence response speed of the pitch system, set points such as yaw misalignment, desired overload or reduced power production, or complex parameters such as weights of turbine-level model-predictive control e.g. for individual pitch control.

The final result of a model-based multiobjective optimization is a set of optimal compromises between all objectives. For each compromise, parameter values and corresponding objective function values are given.

4.2. Adaptation means

The behavior of the wind turbine or wind farm is adapted during operation by selecting a suitable compromise from the optimization results and then setting the parameters and setpoints accordingly in the turbine or wind farm. For this to be possible, the parameters that were used as multiobjective optimization parameters must have directly corresponding parameters in the actual turbine or wind farm, and it has to be possible to change these during operation. Generally, this is the case for parameters of controllers running on a computer based process controller, but not e.g. for geometric parameters of turbine components or low-level controllers that are implemented in hardware.

4.3. Automated evaluation of optimal compromises

The current state of certification does not permit arbitrary behavior adaptations during operation. Instead, simulations for all relevant load cases are conducted and evaluated to find loads on the turbine components. Blades, tower and other structural components are then designed accordingly. Novel behavior adaptation strategies have to take this certification process into account.

Certification simulations for extreme loads and other discrete events are run for each optimal compromise. This way, the multiobjective optimization results are proven to not compromise structural integrity of the turbine. For the normal certification process, fatigue load simulations are required as well. With behavior adaptation, worst-case estimations could be conducted by either running fatigue load simulations for all parameter sets or for those parameter sets that create the highest loads on the turbine. These worst-case estimations would give a lowest expected lifetime of the structure. In real use, however, reliability control would rarely select a compromise with these worst parameters. Instead, the purpose of reliability control is to keep the damage progression of an individual turbine within certain limits, thus also enabling active fatigue control.

While the worst-case estimations or also nominal-case estimations can give valuable insights into the strength of the structure, a condition monitoring system has to monitor the actual damage progression.

4.4. Condition monitoring

The condition monitoring plays a key role in the implementation of the proposed reliability-control approach, as it serves as a “health sensor” providing input into the behavior control loop. At the same time, it is a critical point for the realization of such control and requires substantial further development in order to meet the strong requirements with respect to component coverage and detection performance as well as continuity and dynamics of detection.

Condition-monitoring systems (CMS) are well established and successfully applied in a variety of industries. Their use is motivated by the fact that the large majority of equipment failures are preceded by indications that a fault is developing and a failure is impending. This makes CMS central facilitators for condition-based maintenance.

Also the majority of MW-class wind turbines is equipped with at least one type of CMS. Compared to other industrial sectors, however, the condition monitoring of wind turbines is challenging as their operation is characterized by strongly varying loads and rotational speeds as well as by changing environmental conditions, all of which typically have a disturbing influence on the measured CMS data. In wind turbines, the monitoring of structural components such as the support structure or the rotor blades is typically referred to as structural health monitoring (SHM), while systems monitoring other turbine components, in particular the turbine drivetrain, are called CMS. In this paper, for the sake of simplicity, the term CMS is used independently of the monitored turbine component.

In addition, it is common to differentiate between online and offline monitoring methods: Online condition monitoring occurs by means of permanently installed monitoring equipment, the CMS. Offline condition monitoring, in contrast, is based on regular inspections, measurements or analyses. In wind turbines, e.g. the sampling and subsequent lab analysis of gearbox oil or the inspection of rotor blades can be considered as offline condition monitoring. Due to the requirements of continuous monitoring and fast detection of changes in the degradation state, only online monitoring methods are applicable for use in reliability-controlled systems.

CMS applied in wind turbines are predominantly vibration-based systems monitoring the rotating drivetrain components, such as the main bearing, the gearbox with its bearings, shafts and gearwheels as well as the generator bearings; in addition, these systems often measure the oscillations at the top of the tower. Some systems are also capable of detecting damages in the yaw system. Vibration-based drivetrain CMS have reached widespread application in wind turbines, have proven their practical usefulness in many cases and are therefore recommended as standard equipment for multi-MW and offshore wind turbines today [11]. Particle counters are gaining importance as complementary systems for gearbox oil monitoring. Furthermore, several wind-turbine rotor-blade monitoring systems have entered the market during the past decade and monitoring experience is accumulating at fast pace. While the main focus has been on the detection of potentially damage-initiating influences or incidents such as lightning strikes, icing or rotor imbalance, some of the systems are claimed to detect also deterioration of the structural integrity, due to e.g. fatigue of the composite laminates, buckling in sandwich panels or bond-line failure. The latter capability to monitor degradation of the structural health is the key for utilization in the proposed reliability-control approach.

The development of SHM systems for the support structures of both onshore and offshore wind turbines is subject of ongoing work. First monitoring products are commercially available. These range from sensors over data acquisition systems to comprehensive condition-monitoring packages for towers, onshore foundations and offshore foundations. Their suitability for employment in reliability control, however, is strongly dependent on the monitoring technique. The prevailing method consists of load counting and a comparison of the experienced loads to the design assumptions in order to calculate the current consumption of allowable fatigue life. But as the real strength of an individual component typically differs from its deterministic design strength, the true degradation state cannot be detected by means of this approach. It can nevertheless serve as an interim solution until more suitable methods, capable of identifying the real state of health e.g. by monitoring the structures' modal properties, are applicable.

The continued trend towards larger turbines, which goes hand in hand with an increasing concentration of asset values, as well as the increasing installation of wind parks at remote sites with limited accessibility drives the extension of condition monitoring to further wind-turbine components. Dedicated CMS for electrical and electronic components, such as the main power converter, for pitch and yaw systems are subject of research and development work, but are not commercially available yet. Novel approaches under investigation seek to move from the monitoring of single components to a holistic CMS covering the turbine as a complete system, making use not only of measurements by

CMS-specific sensors but also of the multitude of high-frequency signals available in the turbine control system.

A key method in condition monitoring is trend analysis: The temporal evolution of suitable condition indicators, which are derived from the CMS raw data, is compared to historic values measured in (presumably) intact, non-deteriorated conditions. For illustration, Figure 5 shows two envelope-analysis based trend curves obtained from a vibration-CMS monitored wind-turbine generator bearing, with a developing fault and subsequent bearing replacement.

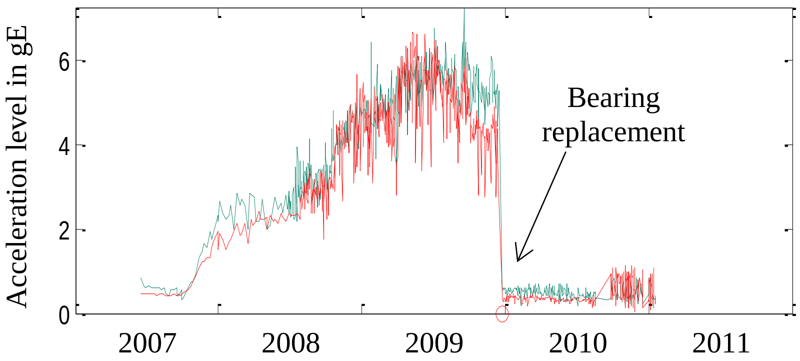

Figure 5. Example of fault detection in a wind-turbine generator bearing by means of trend analysis [12]; curves based on measurements in a low-speed bin (red) and a high-speed bin (green).

A detailed description of the scope, monitoring techniques, instrumentation and analysis methods applied in wind-turbine CMS together with an evaluation of user experiences is found in [13], a summary of the state of the art and recognized challenges in wind-turbine condition monitoring in [14]. Among the challenges, which were identified based on a comprehensive literature review and a survey among wind-turbine operators with accumulated experience from >2600 CMS-equipped turbines, is the limited (and among the monitoring systems strongly differing) detection performance, i.e. the occurrence of both false alarms and missed faults, the latter of which result in unforeseen failures. Another challenge lies in the fact that at present, condition monitoring is limited to certain components of the wind turbines, while others, facing frequent and/or expensive failures as well, remain unmonitored.

Additional challenges creating a need for further research and development work arise from the intended employment of CMS in the proposed reliability control:

(a) Trend-analysis based condition monitoring is typically afflicted with slow detection dynamics. This conflicts with a quick behavior adaption of the turbine.

(b) At present, detection (in the sense of measuring, not by means of load counting) of accumulating fatigue degradation is limited to damage detection that is large enough to e.g. change the vibration pattern by generating characteristic defect frequencies or to modify the modal properties of a structure. At this stage, however, failure mitigation by means of behavior adaption might require a compromise that has a large impact on other objectives or might not be possible at all anymore.

(c) Today's CMS typically provide condition-indicator values which are related to damage, but do not quantify the degree of damage, i.e. do not estimate a health index. The example from vibration-based CMS given in Figure 5 illustrates this: The vibration trend increases significantly but does not provide information about the severity of the damage. In addition, the condition indicator decreases from some point before the bearing replacement, in spite of the further progress of bearing damage. Reliability control, on the other hand, requires a measure for remaining health or accumulated damage. This measure needs to be monotonically decreasing or increasing, but may not be fluctuating. To provide this, a mapping that translates the condition-indicator values from CMS into a "health index" (moving from 100% = fully intact to 0% = failed) or a "damage index" (moving from 0 to 100%) is necessary. Such a mapping can be achieved only by a combined evaluation of comprehensive CMS and failure data, if possible also of the corresponding inspection reports, from the field.

(d) Due to the required expert knowledge, CMS data is usually evaluated in condition monitoring service centers by professional analysts, in some cases additionally by personnel at the wind-turbine operators. In case of abnormal observations, the operator is informed by means of a diagnosis report. Subsequently, the operator typically initiates an inspection to verify the diagnosis and to assess the severity of the damage in order to decide about maintenance measures. In this way, the current process depends on both human judgement and human action, which is not compatible with an automated reliability-control concept.

In conclusion, currently available condition monitoring systems form a good basis for reliability control, but due to the high degree of automation of behavioral adaptation, additional work is required. This mainly includes unsupervised yet highly reliable condition monitoring that gives a continuously changing health or damage indicator. This value then serves as sensor input to the behavior control loop.

5. Summary and outlook

We presented an approach for control of turbine operation such that reliability requirements are met and performance is maximized. It builds on reliability control, which changes operating parameters during operation based on currently consumed lifetime of the components. We introduced the concept and its application in detail and highlight the challenges and difficulties that need to be overcome. One major requirement is a condition monitoring system that detects actual health of main components. Using reliability control, turbine operation is adapted to the individual state of health and the required lifetime is reached.

As a welcome and very important side-effect, an individual wind turbine with reliability control also adapts to site-specific wind loads. This makes it possible to automatically fine-tune system operation of non-site-specific hardware to optimally cope with the wind experienced. This also facilitates adaptation of an existing wind turbine design to a specific site without requiring a specific hardware design or modification, which seems to be a current customer driven trend in the wind industry. With the above described capability, e.g. wind turbines with hardware rated for wind class IEC I or II could be used at sites where wind conditions correspond to wind class II or III to generate higher revenues with a more aggressive power curve than originally specified. In contrast, it also helps to operate a turbine if the wind conditions at a specific site threaten to slightly overload the turbine, which normally would result in a shorter time to failure and in turn to reduced availability. Reliability control reduces loads if the experienced loads result in more accumulated damage in the turbine than anticipated in the design phase. This way, reliability control allows for more flexible deployment of standardized components across a multitude of different site conditions without increasing the risk of catastrophic failure.

While the path towards reliability controlled wind turbines is clear, there is still more work to be done before commercial deployment becomes possible. Fraunhofer IWES is currently working on the specific challenges in order to unlock the potential for the wind energy industry.

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