Component maturity check for superior turbine reliability

F. Langmayr, C. Gray, N. Haselgruber

Uptime Engineering, Schönaugasse 7/3, 8010 Graz
t: +43-316-711921-22; m: +43-664-73 878 497; e: f.langmayr@uptime-engineering.com

Abstract

Turbine reliability is key to the lifetime profitability of wind farms. Standards give a guideline for the proper selection of components with respect to expected wind conditions, i.e. primarily to cope with different levels of fatigue load. Failure statistics show that a wide range of failure modes occur in the field. Not all of them are well reflected by wind speed classification.

The contribution of turbine test operation to lifetime demonstration is limited due to a lack of acceleration potential. Component testing can play a major role in maturity demonstration if special test rigs are used. There is further potential for risk reduction through the use of dedicated material tests. In any case a detailed understanding of potential failure mechanisms is necessary to identify useful tests and quantify their contribution to reliability demonstration.

A reliability improvement program for wind turbines is proposed. As usual it starts with the investigation of risks, including consideration of technical, quality and organizational aspects. The resulting recommendations cover a variety of risk mitigation tasks: load case simulation, failure mode investigation, quality system review, supplier assessment, etc. Input data quality is critical: time logs of wind and climate conditions, grid quality, site location, failure statistics, technical specifications of turbine candidates are necessary in a reasonable quality. Lack of knowledge or low quality data can represent the major risk during early project phases.

Proper component testing is based on the understanding of component failure modes. Therefore, in a consecutive step the potential failure mechanisms of turbine components have to be analyzed in full detail. If this bottom-up analysis is performed strictly failure mode related, it identifies damaging operation conditions and boundary conditions. These correlations can be used for describing damage kinetics with physics of failure models, based on observable operation and climate data logs. Such models have been successfully used for test development, for adaptation of test procedures to field conditions, for evaluation of test acceleration with respect to certain failure modes. Examples are presented for mechanical and thermal fatigue, for abrasive wear and for fretting.

In the context of validation assessment, these models are used to evaluate the overall demonstration potential of a turbine validation program. Such an assessment delivers weak-points as well as over-testing. It identifies particularly aggressive conditions for a given location with respect to certain failure modes and checks whether complementary measures have to be taken for risk mitigation.

The process described above has been applied successfully to various industries during recent years. The potential for wind turbines is illustrated by showing results of a particular analysis, with details given for the turbine blades. It shows clearly the potential of dedicated test rigs to generate real life fatigue load conditions while further test procedures are required to cover a variety of failure modes. A corresponding component maturity demonstration plan is presented.

Introduction

Reliability is the major parameter, which dictates whether a turbine is a good investment or not. It is therefore of utmost importance to drive product reliability to the maximum, achievable during development. Only under this precondition can availability targets be achieved within an optimized O&M strategy. Relevant for on-shore installations, this will be decisive for future off-shore investments.

New designs exhibit reliability growth during the first years after product launch. Un-reliability rises with product complexity, up-scaling of size and power, rising power factors, changing load spectra and climates. As long as the development methodology is not perfect, some of the resulting changes and effects are not foreseen or not correctly quantified. This is in particular difficult for lifetime limiting failure modes, due to the high effort is necessary for validation.

Demonstration of component functionality is well established during product development. It is based on a function related system analysis, like FMEA, to grant for a comprehensive verification of functionality. However, field operation shows a large variety of failure modes, which result generally from a gradual degradation of components over time. Several types of wear, thermal and chemical aging, chemical and galvanic corrosion, deposition, pollution, mechanical and thermal fatigue are the most common failure modes. Reliability demonstration requires lifetime validation against all these failure modes, provided there is a reasonable chance for them to occur.

Published statistics on turbine reliability do not contain the details, which are necessary to assign faults to failure modes. Thus, very little is generally known about the root causes of faults. On the other hand there is an enormous amount of distributed expert knowledge on these topics from science and from practise in manufacturing, failure analysis, O&M activities, turbine monitoring. Expert reasoning on lifetime limiting failure modes is an effective analysis approach. It takes functional verification for granted and investigates those detrimental effects, which eventually lead to end of life for a component or for the whole turbine. It is not an encyclopaedic collection of failure modes but rather an investigation, to identify those topics, which are relevant according to the design and with respect to future operation and climate conditions. Operation and climate are driving component deterioration.

The various damaging effects are investigated in order to design adequate tests for reliability demonstration against all the relevant mechanisms. Their large number forbids that each failure mode has a dedicated test. Vice versa it is reasonable to ask what each test contributes to validation against each of the failure modes. This approach leads to a minimum set of validation test procedures to cover the whole variety of failure modes. When the root cause analysis uncovers the physics or chemistry of the failures, only a relatively small number of damage drivers remain. Each of them is linked to operation and/or climate conditions, which consequently must be present in validating tests. Their severity and duration has to be adequate to the future operation conditions for the turbine under development. Thus, data on future operation conditions are essential for tailored durability tests.

As the typical development period for turbines is less than 20% of the lifetime, a reliability test to cover this target must show an acceleration factor larger than 5. This is possible, but only for dedicated tests, with large overload factors for certain failure modes. Such tests can only be performed with components, as the turbine load is fixed by the wind speed. Accelerated lifetime (or warranty time) testing of components is the most effective way to raise the reliability at least against the subset of failure modes, which can be tested with components. Turbine test operation can only address load characterisation and reliability growth. As a second step in a test sequence it is based on the availability of components whose endurance against as many failure modes as possible is proven. Without component reliability demonstration, frequent faults lead to long delays, as the failing components have to be improved. Thus, component maturity demonstration is the key to turbine reliability.

The Validation Process

Efficient validation starts already during the concept phase of product development [1]. Fig. 1 gives an overview. For adequate validation, initially the validation targets have to be identified with respect to the expected load spectra. Based on the system targets a risk based distribution is performed to achieve the corresponding list of targets for modules and components. The risk filter is a top-down analysis, to identify which types of risk are expected for which components. This approach results in a mitigation plan, addressing risk-specific measures to be taken. This approach is in particular powerful for highly innovative designs or for distributed development.

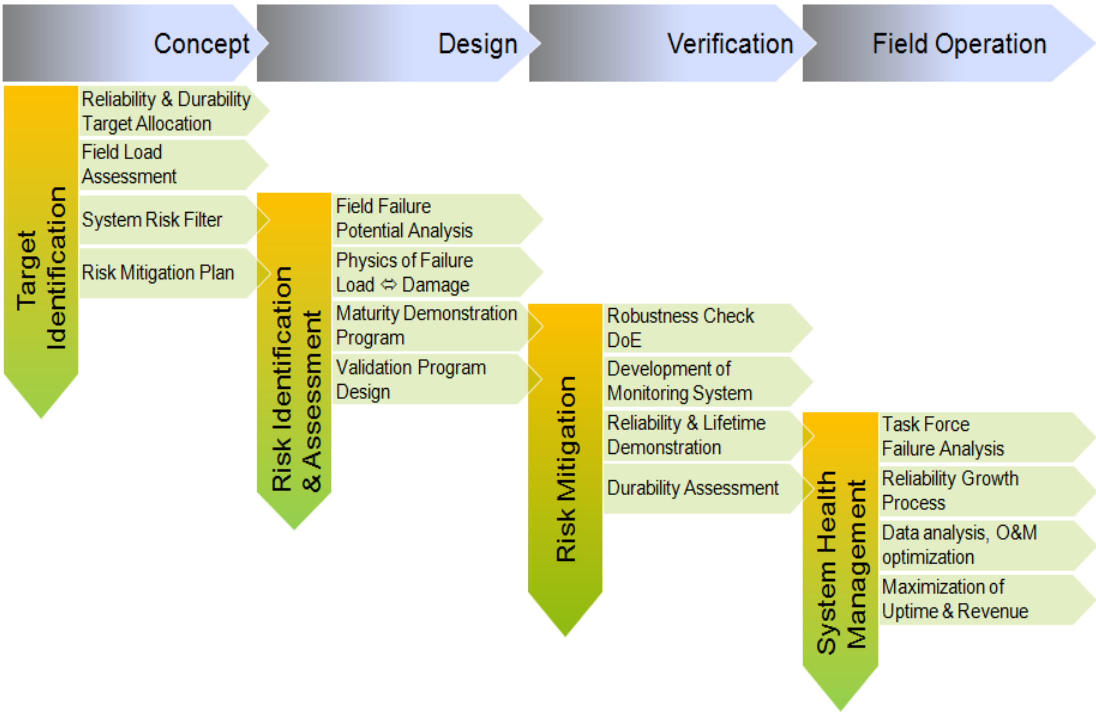

Fig. 1: Risk reduction along the product development process

Technical risks are assessed during the design phase in order to derive the corresponding component maturity demonstration and validation plan. While demonstration of component functions is a widely accepted practise, there is still a large potential for the comprehensive demonstration of reliability at the component level. This potential is investigated during failure potential analyses, which will be described below.

During the verification phase robustness checks are used to identify and eliminate weak points. A monitoring system for field operation load is defined. The focus is on indicators and precursors of lifetime limiting failure modes. Reliability demonstration is the primary target of validation activities. A failure mode related test hierarchy is applied, starting with material qualification. After that component and module durability testing demonstrates maturity against certain failure modes. Finally turbine operation is required for reliability growth of the system.

As reliability growth of wind turbines requires years of operation, it is normally not complete by the start of production. Therefore system health management is necessary as an integrated part of turbine operation. Acquisition and analysis of load data delivers the foundation for an adapted O&M strategy, the basis for high turbine uptime and revenue.

The Validation Process: Reliability Failure Potential

When all functions have been verified the question of how components would fail during long term operation in the field typically still remains. These lifetime-limiting failure modes are the subjects of a structured reasoning method, which can be considered as an extended a-priori fault tree analysis. An example is shown in Fig. 3 for failure modes of turbine blades.

Component	Failure Mode	Failure Location	Root Cause / Effect chain	Damage Promoting Operating Mode	ENLIGHT Analysis Package	Smallest Test Probe	Component Test	Typical Scope of Replacement
Internal structure - laminates	debonding	sandwich panels - face to core: main spar web	global deformation of blade cross section generates inward bending of pressure side and tension of suction side - resulting in main spar shearing - defect formation - debonding - buckling	fluctuating wind speed	tmf(wind speed, k_tmf = 12)	Internal structure - laminates	stress or strain controlled HCF tests: 1) pulsating bending at high mean stress/strain, 2) pulsating torsion at high bending mean stress	Blade
Internal structure - laminates	HCF	main spar laminates towards suction side	suction side is subject to tension across the blade (pressure side is less critical because of compressive mean stess across blade) leading to shearing of the main spar box - microcracking and delamination	high wind speed and turbulences plus cyclic gravitational forces and gyroscopic forces from yaw movement	tmf(wind speed², k_tmf =12)	Internal structure - laminates	stress or strain controlled HCF tests: pulsating bending at tension-compression and pulsating torsion	Blade
Internal structure - laminates	HCF	main spar web towards pressure side	(cyclic) strain under tensile pre-load - fibre cracking	high wind speed and turbulences plus cyclic gravitational forces and gyroscopic forces from yaw movement	tmf(wind speed², k_tmf =12)	Internal structure - laminates	stress or strain controlled HCF tests: pulsating bending at tension-compression and pulsating torsion	Blade
Lightning protection	therm. overload	around receptor and tip cables	lightning strike at extreme voltage leads to arc formation low humidity reduces conductivity of air, leads to higher potential differeces before lightning, off-shore lightning frequency 3-4 times higher than on-shore	thunderstorm	threshold (stroke energy)	Lightning protection	lightning stroke test	Blade
Lightning protection	abrasive wear	interface to slip-rings at bearings	overheating of C-brushes, oxidation, wear, etc.	thunderstorm	time @ thunderstorm	Lightning protection	lightning stroke test	Blade
Skins - laminates	HCF	Skin - sandwich panels - face to core, skin laminates	tensile mean stress due to bending of blade, alternating tension-compression from rotation, torsion due to shock load from wind gust, wake operation	wind speed fluctuating around v_nominal, wind direction resulting in wake-operation	tmf(wind speed², k_tmf =12)	Skins - laminates	stress or strain controlled HCF tests: 1) tension-compression under torsional mean load 2) tension-compression plus pulsating torsion	Blade

Fig. 3: Possible fault cases are investigated to derive an adequate test program

The analysis is performed as an expert reasoning. It starts with the definition of an unwanted, lifetime limiting event, i.e a fault case, which is considered to be reasonably possible during long term operation of turbines. For each of these cases the corresponding cause-effect chains (possibly more than one) are constructed in order to identify the root causes. The cause-effect reconstruction has to be defined carefully and in full detail in order to identify damage driving operation modes and boundaries. Moreover, understanding the physics or chemistry of failure is essential as it delivers the basis for a quantitative assessment of load spectra with respect to various failure mechanisms. Comparison of load spectra and durability test candidates is based on damage models. Common examples would be the Woehler model for mechanical fatigue, the Manson-Coffin model for thermal fatigue, the Arrhenius model for thermal aging [2, 3, 4]. These models are indicated in Fig. 3 as "Analysis package".

Reliability demonstration should start with the smallest probes and the simplest test. This allows for front-loading of risk reduction through cost-effective component testing. Tests are specified for each failure mode if technically/economically reasonable. The objective of component testing is maturity demonstration for a well defined subset of failure modes in order to reduce the failure risk during system durability test operation. Further derivatives of this analysis are failure mode related:

- specification of component properties
- fault precursors and inspection methods for durability assessment and service

- instrumentation for optimized failure detection

The Validation Process: Component Maturity Demonstration

The potential for component maturity demonstration is shown in Fig. 4 for the example of the blades. Aging effects, induced by temperature, UV and ozone can be tested on material samples by using relatively simple exposure tests at aggravated conditions. For modelling of aging under real conditions, interactions between damage drivers have to be checked and the activation energies for aging mechanisms should be evaluated. Once the applicability of a model like Arrhenius is verified, accelerated tests can be performed in a quantified manner and coverage of lifetime or warranty period is possible within a few months.

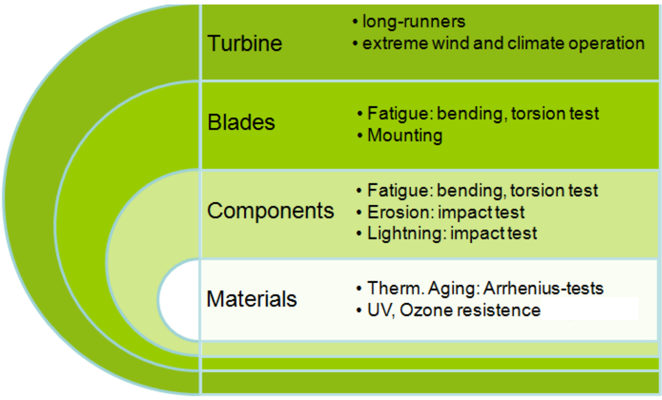

Fig. 4: Validation hierarchy for turbine blade as a result of component maturity demonstration approach

Sections of blades are necessary for the next level of testing. Erosion can be simulated in wind tunnels with dust containing air. If momentum transfer from particle to blade is the proper failure model, accelerated testing is possible via particle fraction and wind speed. Lightning impact is to be tested with high voltage test equipment primarily in order to quantify the effect of a lightning event on the surroundings of the protection wires. Lifetime demonstration is possible by rising the frequency of lightning events during testing.

Proper fatigue testing requires load input from FEA. The specimen must be instrumented in order to control the strain distribution during fatigue testing. Load superposition is actually damaging at critical blade locations. With closed loop strain control this can be applied easier to blade sections than to large scale full blade test rigs. Test acceleration is achieved via increased strain amplitudes. The sensitivity of materials to rising load amplitudes is extremely high. Therefore, in order to avoid misinterpretation of results the fatigue endurance including the scattering have to be measured in parallel.

In modern test facilities, blades are used for fatigue testing under pulsating bending load. Torsional load is also possible. Superposition of both is a difficult non-standard task. With the fatigue results from blade sections, the large scale blade tests fulfil the final validation step prior to turbine test operation. Systematic testing of blade section fatigue is not only relevant as a contribution to reliability demonstration but also as a basis for blade test assessment. While blade fatigue tests are typically single amplitude tests, real load spectra consist of a distribution of load amplitudes of stochastic sequence. The transfer between these two cases is based on several load capacity material properties: a fatigue lifetime curve including scattering bandwidth, linear accumulation of damage, robustness against load sequence, quantified effects of mean load and load superposition (bending, tension, torsion), negligible detrimental effects from aging. These aspects are clarified efficiently on blade segments or laminations specimens to form a reliable basis for assessment of blade fatigue test results.

As described above for the blade also for the other components the majority of failure modes can be addressed by specimens of different system integration level.

For some isolated failure modessuch as aging, the demonstration of reliability targets is possible with component testing only. For testing of interactions, higher system integration (the rotor, the drive train) is necessary. Nevertheless for the majority of failure modes component testing contributes significantly to reliability demonstration and verifies the prerequisite for turbine testing,i.e. durable components. In this context representative operation under realistic yet severe conditions remains the primary objective for turbine prototype operation. Interaction between components, load and climate effects and detection of a-priori unknown failure modes are the primary targets for turbine testing.

Risk Mitigation - Action Plan - Blade

Subsystem	Component	Failure mode	Failure location	Load Case Simulation	Load Case Measurement	Load Capacity Assessment
Internal structure						
	internal laminates	debonding	adhesive layer joining skin and main spar at pressure side	eigenmode analysis to identify critical areas	strain measurement for FEA calibration	HCF testing of blade section - lifetime curve (Wöhler)
	internal laminates	debonding	sandwich panels - face to core: main spar web	eigenmode analysis to identify critical areas	strain measurement for FEA calibration	HCF testing of blade section - lifetime curve (Wöhler)
	internal laminates	fatigue	main spar laminates	eigenmode analysis to identify critical areas	strain measurement for FEA calibration	effect of aging (thermal, UV, ozone) on fatigue endurance of laminates
	internal laminates	fatigue	main spar - pressure side	eigenmode analysis to identify critical areas	strain measurement for FEA calibration	HCF testing of blade section - lifetime curve (Wöhler)
Lightning protection						
	tip cables	arc formation	around receptor	heat transfer from conductor to surroundings	electric power of lightning stroke	number/energy of lightning strokes to failure
	slip-rings at bearings	wear	running surface	thermal condition during lightning stroke	electric power of lightning stroke, temperature	variation of wear rate with current, temperature and humidity, investigation of failure mode
	C-brushes	wear	running surface	thermal condition during lightning stroke	electric power of lightning stroke, temperature	variation of wear rate with current, temperature and humidity, investigation of failure mode
	C-brushes	wear	running surface	thermal condition during lightning stroke	electric power of lightning stroke, temperature	variation of wear rate with current, temperature and humidity, investigation of failure mode
Paint and coatings						
	gel-coat	cracking, debonding	-	blade surface temperature (rotating, stationary)	UV intensity, blade surface temperature (rotating, stationary)	exposure to UV, temperature, Arrhenius lifetime tests
	paint	aging	-	blade surface temperature (rotating, stationary)	UV intensity, blade surface temperature (rotating, stationary)	exposure to UV, temperature, Arrhenius lifetime tests
	paint	erosion	leading edge	CFD momentum transfer of particle stream	particle freight in air (season, location)	CFD assessment of erosion on uplift, measurement of erosion effect on power curve
Skins - laminates						
		fatigue	Skin - sandwich panels - face to core; skin laminates	eigenmode analysis to identify critical areas	strain measurement for FEA calibration	HCF testing of blade section - lifetime curve (Wöhler)
		fatigue	leading and trailing edge adhesive layer, joining the pressure and the suction side	eigenmode analysis to identify critical areas	strain measurement for FEA calibration	HCF testing of blade section - lifetime curve (Wöhler)
		fatigue	skin and main spar at pressure side	eigenmode analysis to identify critical areas	strain measurement for FEA calibration	HCF testing of blade section - lifetime curve (Wöhler)
		pollution	leading edge	CFD momentum transfer and flow re-direction, deposition	particle freight in air (season, location)	wind tunnel, polluted air, deposition
		erosion	leading edge	CFD momentum transfer of particle stream	particle freight in air (season, location)	CFD assessment of erosion on uplift, measurement of erosion effect on power curve
T-bolt/root inserts						
		fatigue	threat ground, stud basis - pressure side	FEA of stress under critical load superposition	strain measurement for FEA calibration	HCF testing of mounting zone and stud
De-icing system						
		local overheating	surrounding of heating wires / hot air channels	heat transfer from conductor via surroundings to ice layer	heating rate	cyclic freezing-de-icing lifetime test

Fig. 5: Action Plan for risk mitigation – example turbine blade

During development there is lack of knowledge or data for certain failure modes. This limits the chance to identify critical operation modes or climate aspects, which drive the evolution of faults. In order to overcome this limitation, subsequent to the failure potential analysis an action plan is set-up to generate failure mode specific data and know-how, see Fig. 5 for the blade.

Within expert workshops an investigation is carried out to ascertain whether the failure relevant load types are understood and quantified. If this is not the case the necessary simulation and measurement are identified. In addition to the identification of critical loads, data relating to the load capacity is also required. In particular for innovative systems this is the risk focus as reliable data and technical specifications typically cover only part of the relevant failure modes. Sufficient details of failure mode interactions are rarely available, such as the fatigue of aged material or chemical plus thermal aging. The situation is aggravated if there is no reference for the long term behaviour of a material or component under the expected load spectra and climate conditions. An action plan is followed in order to generate measurement or simulation data – stresses, strains, corrosion kinetics, etc. – as input for the damage models.

Validation Process: Assessment of Component Validation Potential

Validation against high cycle fatigue is used to illustrate the procedure of test assessment for the blade. Fig. 6 shows two time logs of wind speed and ambient temperature for high and for medium wind class IEC I and II plus a corresponding load sequence, representing a standard pulsating bending fatigue load case.

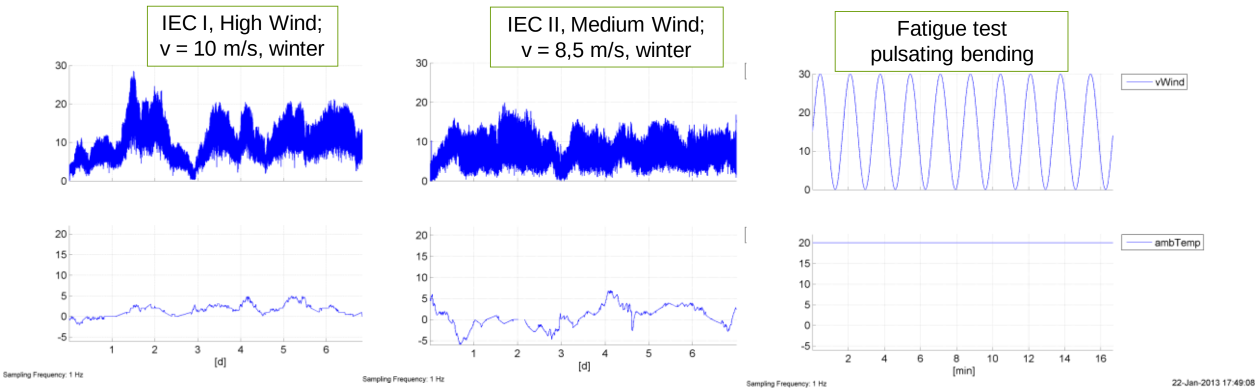

Fig. 6: Wind speed time logs for high and medium wind class and a load cycle for a pulsating bending fatigue test.

These wind spectra represent typical load situations for the indicated wind classes with ca. 30 m/s as maximum. For test acceleration a fatigue test is performed under pulsation bending with 15 m/s load amplitude. This is a very severe – yet realistically possible - load case, which results in significant acceleration of the addressed fatigue damage kinetics. Test acceleration *A* for a certain failure mode is defined as the relation of damage kinetics between a test and a reference: $A = K_{test} / K_{ref}$. The equivalent time of a test with respect to a certain failure mode t_{equ} is the actual test time *t* multiplied by the acceleration factor A; i.e the acceleration is a failure mode specific weighting factor for assessment of the severity of test conditions.

Adequate and comprehensive testing should cover the lifetime damage for all the failure modes, identified during failure potential analysis, as described in Fig. 3. System validation is a realistic target if for each failure mode at least one test exhibits the equivalent lifetime with respect to the reference field loading.

The assessment task is therefore to evaluate the damage kinetics. For high cycle fatigue this is performed with the classical strain based life model [2]. The number of cycles to failure N_f decreases with an increase in e_a, the strain amplitude of a cycle: $e_a = c * N_f^{\,b}$. It is equivalent to write the damage increment $d=1/N_f$ per cycle rises with the strain amplitude. The relation between damage and cyclic strain is highly non-linear, the exponent *b* being taken as -0.08 according to literature [2]. For damage calculation it is assumed that strain is proportional to load, which is justified to a good approximation for standard load situations [6].

Cumulative damage is evaluated for the turbine lifetime or 20 years with 33% operation time as reference. 50h is assumed for fatigue test rig operation. Fig. 7 shows the corresponding lifetime coverage. The IEC II reference load spectrum as shown above is taken as reference for normalization of the cumulative damage during the indicated duration. Comparison shows that there is a difference between the reference and another load cycle of the same wind class, equivalent to about 70% higher fatigue damage. This is due to the fact that within the current used standard wind classification there is a largedegree for freedom, leading to different amounts of damage.

A significantly higher equivalent fatigue damage occurs for or the high wind class IEC I, indicating a load situation, with a factor of 20 higher cumulative damage than IEC II class. Debonding load for sandwich panels is simulated based on the assumption that damage is proportional to the square of the wind speed, resulting in a very high coverage of the fatigue test due to the large number of high strain amplitudes. The shear forces of laminates are modelled as proportional to wind speed, which brings a factor of 28, still a level which allows lifetime validation with a few samples.

Failure Mode	Fatigue Test	IEC II	IEC II	IEC I	Complementary Test
Duration [h]	50	58400	58400	58400	
Debonding of sandwich panels (HCF)	18230,0	1,0	1,7	21,2	-
erosion and deposition of paint and coating	0,0	1,0	1,0	1,3	wind tunnel test with deposing and abrasive materials on blade segments
Debonding of laminates, shear forces (HCF)	28,4	1,0	1,8	28,5	-
Local overheating around de-icing system	0,0	1,0	1,0	1,1	cyclic icing de-icing test on blade segments
Thermal aging of coating	0,0	1,0	1,0	1,1	UV and thermal aging of blade segments
Thermal aging of laminate	0,0	1,0	1,1	1,1	UV and thermal aging of laminates

Fig. 7: Coverage of turbine lifetime by fatigue durability testing for various blade failure modes

Fatigue failure modes are well represented by a pulsating bending test, indicated by the high equivalent lifetime that can be achieved. On the other hand the fatigue test does not address any of the other identified failure modes. Therefore complementary durability tests have to be performed. As indicated in Fig. 7 there are test candidates for each failure mode, allowing for comprehensive maturity demonstration via component lifetime testing. Detailed test design has to be based on the respective load date from duty cycles for future turbine sites and conditions. If aging is well represented by Arrhenius models also for this failure mode accelerated tests are possible. Also for erosion and overheating a high degree of reliability demonstration can be achieved via aggravated tests.

In any case component tests are simplified models of the reality and accelerated testing bears the risk of induced artefacts. Therefore adequate test design requires validated and calibrated models, which describe the damage effect of load histories. For accelerated tests it is essential to verify that the excited failure mode is not modified and that no critical superposition with other failure modes occurs. These tasks have to be fulfilled within the action plan for risk mitigation (Fig. 5).

Even though component durability tests are quite efficient for the majority of failure modes, conclusive system validation require long term turbine tests. This is due to the fact that interfaces and interactions between modules are not addressed by component tests. Tests performed on a complete operational turbine are beneficial since representative operation exposes the turbine to all possible failure modes. Complementary component testing resulting from test design is used to efficiently address a-priori known failure modes and the respective critical conditions.

Conclusion

Validation of complex technical systems typically consumes the majority of development time and budget. Effective reliability demonstration requires lifetime equivalent testing for all relevant failure modes. This is rarely achieved for wind turbines due to their long lifetime and the fact that the load situation is fixed by the wind at turbine site; i.e. no significant acceleration of turbine testing is possible. Moreover, test turbines are prone to failure from immature components, which do not fulfill their reliability targets.

These limitations can be overcome through the application of a hierarchical validation test strategy. Systematic and comprehensive component maturity demonstration is used as a powerful initial step towards turbine reliability validation. In this context the role of component testing is not only the classical demonstration of functions. It is rather durability testing against lifetime load. Analysis shows that this can be achieved for a subset of failure modes. The approach offers front-loading of reliability demonstration. Cost effective component durability tests are normally dedicated to certain failure modes. They can be highly accelerated and performed in parallel at various component suppliers.

The set-up of load-adequate validation tests has to be performed with respect to the long-term failure modes to be addressed. For quantitative test acceleration and for protection against artifacts the physics of failure have to be understood. This is investigated during a failure mode analysis, which identifies the correlation between failure modes and operation conditions. Models are developed for quantitative assessment of test severity with respect to all the identified failure modes.

Adequate tests need a reference which has to be constructed from turbine duty cycle load histories as measured e.g. by SCADA systems. In this context "load history" has to be understood in the generalized form: the variety of failure modes, occurring during long term field operation, needs to be characterized. Due to lack of data during development this is performed practically by a combination of system simulation, transfer functions from met-mast data, data from forerunners and from prototype turbines.

Turbine durability tests are necessary to address a-priori unknown failure modes, interactions and interfaces. Lifetime demonstration is not possible using operational turbines as tests are hardly ever accelerated. Even the demonstration of warranty targets is challenging. The combination of high reliability demonstration from component maturity testing and reliability growth from turbine operation is the test strategy, which bears the highest potential for system validation.

The damage models, based on the analysis of lifetime limiting faults, deliver a basis for optimization of embeddedcondition monitoring systems capable of early detection of failure mode precursors. With the adaptation of data processing and classification, a cost effective system for maximum turbine availability can be achieved as a positive side effect of the described validation program.

Literature

1. C. Gray, N. Haselgruber, F. Langmayr. Method for testing the reliability of complex systems. Patent application EP12180254.0, 2012

2. S. Suresh. Fatigue of Materials 1998, Cambridge

3. W.Q. Meeker, L.A. Escobar. Reliability: The other dimension of quality. Qual. Tech. & Quant. Management. **1**, 1, 1-25, 2004

4. C. S. Gray, S.J. Watson. Physics of failure approach to wind turbine condition based maintenance. Wind Energy online, DOI: 10.10002/we.360, 2009

5. J.W. Holmes, B.F. Sörensen, P. Bronsdsted. Reliability of wind turbine blades: An overview of materials testing. Wind Power Shanghai 2007, proceedings