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A Limited-Scope Reliability-Centred Maintenance Analysis of Wind Turbines

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Abstract

This paper presents results from a limited-scope Reliability-Centred Maintenance (RCM) analysis of the wind turbines Vestas V44-600kW and V90-2MW. The RCM analysis has been carried out within a workgroup involving a wind turbine owner and operator, a maintenance service provider, a provider of condition-monitoring services and wind turbine component supplier as well as researchers at academia. The study forms the basis for the development of quantitative models for maintenance strategy selection and optimization.

Taking into account both the results of failure statistics and expert opinion, the analysis focuses on the most critical subsystems with respect to failure frequency and consequences. The analysis provides the most relevant functional failures and their failure causes as well as suitable measures to prevent either the failure itself or to avoid critical secondary damage. In this paper, results for the subsystems gearbox, generator and rotor current control / converter are presented.

Challenges identified by the RCM workgroup which are considered to impede the achievement of cost-effective operation and maintenance of wind turbines are discussed together with proposed solutions. Standardized and automated collection of in-depth failure and maintenance data, enhanced training of maintenance personnel, and the utilisation of quantitative methods for decision support in wind turbine maintenance are identified as important steps to improve the reliability, availability and profitability of wind turbines.

Keywords: Reliability-Centred Maintenance, RCM, wind turbine, failure, FMECA

1 Introduction

Wind power plays a central role for the development of a sustainable electric power supply system. In view of climate change and limited primary energy resources, ambitious goals have been set to promote a strong increase of wind energy utilisation: From 75 GW installed wind power capacity in Europe at the end of 2009, an increase to 230 GW by 2020 is targeted of which a minimum of 40 GW is supposed to be installed offshore [1, 2]. However at present, the maintenance costs for wind turbines which are required to ensure their technical availability are usually high. This impedes the increase in wind power utilisation necessary to reach the targets. Wind turbines typically achieve an availability of about 95% to 99% today [3]. But up to ten faults per turbine and year cause unplanned downtimes [4]. This results in high cost due to extensive maintenance efforts and production losses. Suitable countermeasures are improvements in wind turbine design, but also systematic solutions for maintenance management. Research has shown that the present maintenance, in both on- and offshore installations, is not optimized. It has revealed that there are large potential savings by optimizing maintenance decisions over the lifetime to reduce the total cost (a) for maintenance activities and component failure, and (b) costs due to production losses, especially for large offshore wind parks [5-10].

To reach cost-effective maintenance for wind power plants by means of data-based, quantitative methods is the main objective for research in the Wind Power Asset Management (WindAM) research group at Chalmers University of Technology in Gothenburg. This is carried out in close cooperation with wind turbine operators and industrial maintenance service providers. The main approach applied herein is the concept of

Reliability-Centred Asset Maintenance (RCAM) which combines the proven method of Reliability-Centred Maintenance (RCM, explained e.g. in [11, 12], so far applied to wind turbines in [13]) with quantitative maintenance optimization techniques (described e.g. by [14, 15]). Originally developed for the application on electric power distribution systems [16, 17], this combined method provides a promising framework also for the maintenance strategy selection and optimization of wind turbines, as was described by the authors [18]. Figure 1 shows a detailed logic diagram of the RCAM method. It illustrates the different stages and steps in the method as well as the systematic process for analysing the system components and their failure causes.

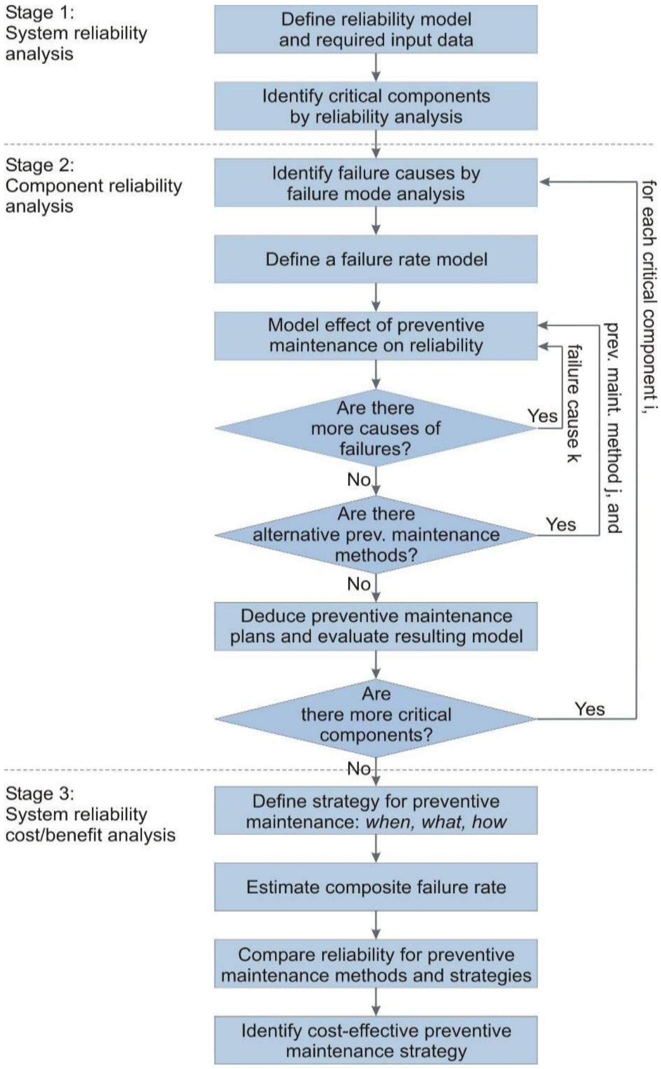

Figure 1: Logic diagram of the RCAM method (adopted from [17])

The three main stages of the RCAM approach are the following [17]:

Stage 1: System reliability analysis; defines the system and identifies critical components

Stage 2: Component reliability modelling; analyses the components in detail and, based on appropriate input data, defines the quantitative relationship between reliability and preventive maintenance measures

Stage 3: System reliability and cost/benefit analysis; places the results of the component level analysis (Stage 2) in a system perspective and evaluates the effect of component maintenance on system reliability and cost

While sole RCM as a qualitative method is limited in determining which maintenance strategy is the most cost-effective option, mathematical maintenance optimization techniques alone do not ensure that maintenance efforts focus on the right components. By merging these two approaches, the RCAM method provides an instrument for the quantitative assessment and comparison of maintenance strategies.

The limited-scope RCM analysis presented here is an essential part in the implementation of RCAM. Its purpose in the context of RCAM is to reveal the components, the failure modes as well as the major underlying failure causes which are most relevant for the system reliability and availability, and to identify suitable preventive maintenance measures. In this way, the RCM study forms the basis of RCAM; it ensures to focus the subsequent development and application of mathematical models on the practically relevant items and failures.

In the following, the RCM analysis of two wind turbine models is described. These are

(1) the Vestas V44-600kW, a turbine with an early, limited variable-speed capability, the design of which was state of the art in the mid 1990s but with a number of 35 turbines in operation in Sweden and more than 300 turbines still operating worldwide, and
(2) the Vestas V90-2MW as a variable-speed wind turbine of contemporary design, with 124 turbines in operation in Sweden and approx. 2800 delivered worldwide [19, 20].

The RCM study has been carried out in a workgroup with representatives from Göteborg Energi as owner and operator of wind turbines of these types, Triventus as maintenance service provider, SKF as both provider of condition-monitoring services and wind turbine component supplier, as well as the WindAM research group at Chalmers. The combination of practical experience and theoretical expertise as it could be realized in this group (and is inherent to the RCAM method) is considered to be of crucial importance for the development of maintenance management and decision support tools for wind turbine operations and maintenance.

The parallel analysis of the two wind turbines V44-600kW and V90-2MW has been chosen to account for the different reliability characteristics of turbines originating from different generations of technology (see e.g. [21, 22]), but also the potentially different applicable preventive maintenance measures. It is important to note that the turbines have been selected for analysis not due to any abnormal occurrence of failures but because of the fact that these are of particular interest to the project partners and, in case of the V44-600kW, because of the available experience with operation and maintenance of this turbine type in the RCM workgroup.

2 Implemented RCM process

The RCM analysis summarized in this article follows the methodology of a study described in [23] which combined statistical analysis and practical experience. In addition, it is based on the guideline given in [12]. The implemented limited-scope RCM analysis has covered the following steps:

(a) system selection and definition
(b) identification of system functions and functional failures
(c) selection of critical items
(d) data collection and analysis
(e) failure modes, effects, and criticality analysis (FMECA) including failure causes and mechanisms of the dominant failure modes
(f) selection of maintenance actions

The determination of maintenance intervals and the comparative analysis of preventive maintenance measures by means of mathematical models are not considered in this paper but are subject of subsequent work.

The level of analysis moves from the system level (whole wind turbine) to the subsystem level (e.g. electrical system, gearbox) for which failure data is available, and further on to selected critical components (e.g. resistor bundle in rotor current control unit, gearbox bearings) of these subsystems. The width of analysis has been limited to the most relevant subsystems of each turbine with respect to failure frequency and resulting downtime as well as their dominant failures. The focus has been on providing an in-depth understanding of the functions, main failure modes, failure consequences, failure causes and the underlying failure mechanisms on the one hand and suitable maintenance measures to prevent these on the other hand. The consequences of failure have been assessed for the four criteria:

1. Safety of personnel
2. Environmental impact (in a wind turbine e.g. discharge of oil or glycol),
3. Production availability (i.e. the impact on electricity generation),
4. Material loss (including primary damage to the component itself, but also secondary damage to other equipment)

3 System description

In the following, the two wind turbine models which are subject of the RCM analysis are described together with their system-level function and functional failure of interest in this context.

3.1 V44-600kW wind turbine

The Vestas V44-600kW was launched in 1996. It is an upwind turbine with three blades and an electrically driven yaw system. Its rotor has a diameter of 44 m and a weight of 8.4 t. The rated rotational speed of this is 28 rpm. A hydraulically actuated pitch system is used for speed control, optimization of power production, for start-up and for stop (aerodynamic braking) of the turbine. Additional breaking functionality is provided by a disc brake located on the high-speed side of the gearbox.

During operation, the main shaft transmits the mechanical power from the rotor to the gearbox, which has either a combined planetary-parallel design or, as in case of the early V44 turbines analysed here, a parallel-shaft design. The gearbox and the generator are connected with a Cardan shaft. The generator is an asynchronous 4-pole generator with integrated electronically controllable resistance of the wound rotor (so-called OptiSlip technology, see Figure 2), which requires neither brushes nor slip rings. The variability of the rotor resistance is provided by the Rotor Current Control unit (RCC) which is bolted to the non-drive end of the generator rotor and thus permanently rotates during wind turbine operation. It consists of a micro-processor unit to which the control signal is optically transmitted, of a power electronics unit and a resistor bundle. As shown in Figure 2, the rotor resistance is varied in the way that the resistor bundle is short-circuited at varying frequency by means of IGBTs in the power electronics unit. This OptiSpeed technology allows the rotational speed of the generator to vary between 1500 rpm (idle) and 1650 rpm.

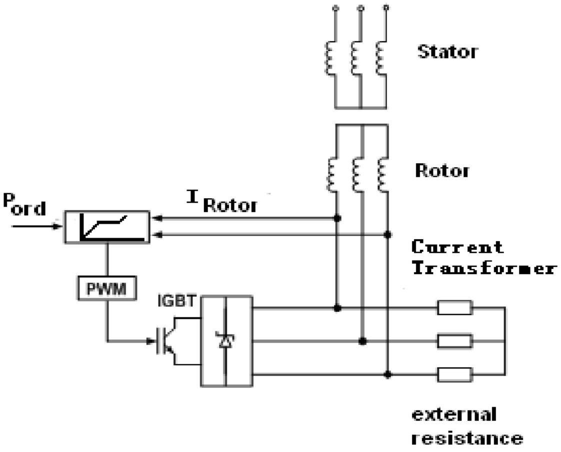

Figure 2: Structure of the wound rotor asynchronous generator with OptiSlip technology [24]

The generator stator is connected to the electric power grid through a thyristor unit. This limits the cut-in current of the asynchronous generator during connection to the grid and smoothly reduces the current to zero during disconnection from the grid. The reactive power required by the generator is partially provided by a capacitor bundle at the bottom of the tower, the power factor correction or phase compensation unit.

The main function of the V44 system, and the only one being of interest in the scope of this study, is the conversion of kinetic wind energy to electric energy which is provided to the electric power grid. More specifically, the system function is to provide up to 600kW electric power at 690V and 50 Hz to the electric power grid, in an operating temperature range of -20…+40°C and at wind speeds of 4-20 m/s.

Failures on the system level which are relevant in this study are both a complete and a partial loss of energy conversion capability of the turbine. The wind turbine system has four operating states (RUN, PAUSE, STOP, EMERGENCY). Only in the operating state RUN, the turbine can be connected to the electric power grid and fulfil the system function defined above.

3.2 V90-2MW wind turbine

Figure 3 shows the structure of the Vestas V90-2MW system. The first turbines of this type were installed in 2004. Like the V44, the V90-2MW is an upwind turbine with three blades and active, electrically driven yaw. Its rotor has a diameter of 90 m and a weight of 38 t. The nominal rotor speed of 14.9 rpm is about half of the rotor speed of the V44. The so-called OptiTip pitch control system with individual pitching capability for each blade continuously adapts the blade angle to the wind conditions and in this way provides optimum power output and noise levels. In addition, it serves for speed control, turbine start-up and stop by aerodynamic braking. Similarly to the V44, an additional disc brake is located on the high-speed shaft.

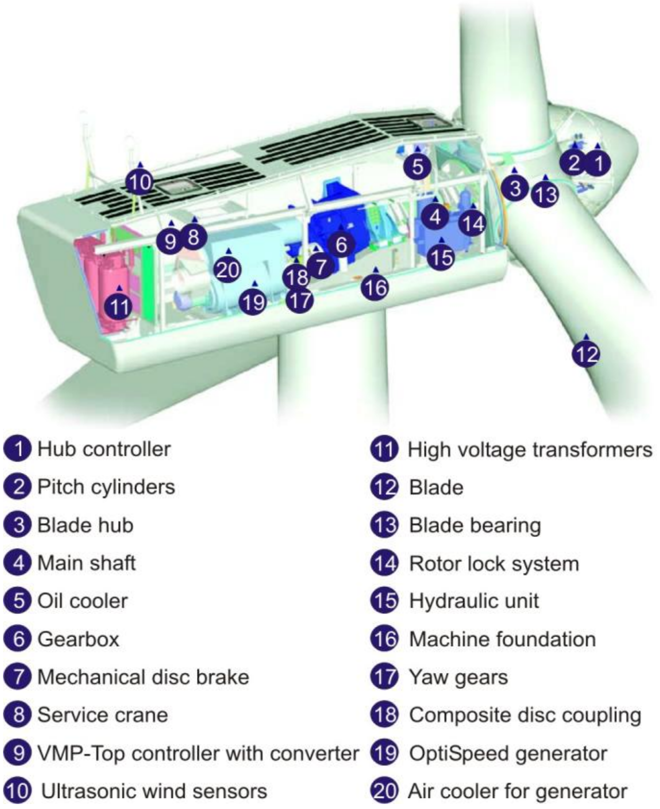

Figure 3: Structure of the V90-2MW system [25]

In contrary to the V44 turbine, all V90-2MW systems apply gearboxes with one planetary and two parallel stages from which the torque is transmitted to the generator through a composite coupling. A major difference to the V44 system is the generator concept: the V90-2MW contains a 4-pole doubly-fed asynchronous generator (DFIG) with wound rotor. A partially rated converter controls the current in the rotor circuit of the generator, which allows control of the reactive power and serves for smooth connection to the electric power grid. In particular, the applied DFIG concept (so-called “OptiSpeed” technology) allows the rotor speed to vary by 30% above and below synchronous speed. The electrical connection between the power converter and generator rotor requires slip rings and carbon brushes. The generator stator is directly connected to the electric power grid. [25-28]

The system function of the V90-2MW is to provide up to 2MW of electric power at 690V and 50Hz to the grid, in a standard operating temperature range of -20…+30°C and at wind speeds of 4-25 m/s. Again in this case, system level failures of interest in this study are (1) the complete loss of energy conversion capability or (2) the partial loss of energy conversion capability of the turbine. As the V44, the V90-2MW wind turbine system has four operating states, among which RUN is the only state allowing connection to the electric power grid. For the RCM analysis of the V90-2MW, it is important to note that the series is not fully consistent, i.e. that small changes in design have been implemented in every year of production [29].

4 Subsystem selection based on statistics and practical experience

In the RCM study, failure statistics of the investigated wind turbines have been used in combination with expert judgement in order to prioritize the wind turbine subsystems for detailed analysis. The failure data used for statistical analysis covers the failures of 32 V44-600kW turbines in the period 1996-2005 which are part of the database [30]. Statistical data analysis for the V90-2MW system has been carried out based on data from [31]. It includes failures of 57 V90-2MW turbines located in Germany, from the period 2004-2008.

In order to include also the expert opinion of the RCM workgroup members in the identification of the most critical subsystems, all group members having professional experience with wind turbine operations and maintenance were asked to fill in questionnaires and in this way provide a subsystem ranking with respect to failure frequency and downtime per failure.

Table 1 summarizes the results of the questionnaire evaluation as well as the statistical failure data analysis. Both the failure frequency and the downtime resulting from a failure are relevant for the criticality assessment of components. Therefore, it was found advantageous to combine these two measures by multiplication, resulting in the average downtime per wind turbine and year related to failures of a specific subsystem (see also [32])

$$t_{lost} = \frac{\sum_{i=1}^{I} d_i}{\sum_{i=1}^{I} X_i \cdot T_i} \qquad (1)$$

with d_i being the downtime due to failures of a subsystem in the time interval i, X_i the number of wind turbines reporting to the database in time interval i, and T_i being the duration of time interval i.

Table 1: Criticality of wind turbine subsystems with respect to failure frequency and downtime, according to expert judgment and statistical data analysis

	V44-600kW			V90-2MW		
	Expert judgment		*Data analysis*	*Expert judgment*		*Data analysis*
	Failure frequency	*Downtime per failure*	*Downtime per year and turbine*	*Failure frequency*	*Downtime per failure*	*Downtime per year and turbine*
1.	Gearbox	Gearbox	Electrical system	Gearbox	Gearbox	Generator incl. converter
2.	Generator	Generator	Generator	Generator	Generator	Rotor
3.	Hydraulic system	Yaw system	Control system	Converter	Converter	Drivetrain incl. gearbox
4.	Rotor	Rotor	Gearbox	Hydraulic system	Rotor	Control and protection system

Based on the results of both the failure data analysis and the questionnaire assessment, the subsystems (a) gearbox, (b) generator, (c) electrical system, (d) hydraulic system and (e) rotor were chosen for in-depth analysis in the RCM study. In spite of the significant contribution of the control system to the average downtime per wind turbine and year, it was decided not to include this system in the RCM analysis because its failures can hardly be influenced by means of preventive maintenance.

5 Results and discussion

To present the comprehensive results obtained during the RCM study would go beyond the scope of this article. The presentation is thus limited to a tabulated compilation of selected analysis results for the three most critical subsystems identified above: the gearbox, the generator and the converter (V90) / rotor current control (V44) as critical parts of the electrical system. Due to the found broad similarity of failure modes, mechanisms and applicable countermeasures for the V44-600kW and the V90-2MW system, the results for the two turbines are presented in only one table for each analysed subsystem.

Table 2 summarizes the results of RCM analysis of the gearbox. Bearings, gearwheels and the lubrication system are identified to be the components with highest relevance for gearbox failure. Failure of shafts in the gearbox is considered to occur only as a secondary damage and has thus not been included in the RCM analysis. Gearbox failure can have severe consequences: in case of complete demolition, parts of the gearbox can constitute a risk for personnel. Oil spill of up to 120l (V44) or 300-400l (V90) of lubrication oil contained in the respective gearboxes can cause environmental impact. Gearbox failure is among the failures resulting in the longest average downtime and thus has a strong impact on production availability, and it can cause severe secondary damage, e.g. in the main bearing or the rotor shaft.

The central results for the generator subsystem are compiled in Table 3. Generator failure usually does not constitute a risk to personnel safety or the environment, but often implies significant loss of production availability and costly down-tower repair. Secondary damage to other subsystems can occur e.g. in case of excessive vibrations from damaged generator bearings or strong heat release.

Table 4 summarizes selected analysis results for the subsystems providing rotor current control: these are the RCC unit in the V44-600kW (being, according to the statistical analysis, the most frequently failing component in the category “Electrical system”, see Table 1) and the partially-rated converter in the V90-2MW respectively. The consequences of RCC failure in the V44 are usually limited to production losses: while failure of the power electronics unit or the micro-processor unit still allows operation at reduced power of 300kW, failure of the resistor unit fully prohibits turbine operation. In case of the V90-2MW system, failure of the converter results in a full loss of the power generation capability.

As the results in Tables 2-4 show, a particularly frequent cause of failure is vibration. Excessive vibration is often a result of bearing damage. Among the variety of proposed preventive measures, those aiming at prevention or early detection of bearing damages are thus considered to be especially cost-effective. In case of the gearbox, early detection of impending bearing failure can e.g. prevent severe secondary damage, enable up-tower repair instead of significantly more expensive removal and external repair; moreover in case of a necessary replacement, the loss of residual value of the gearbox (e.g. due to internal shaft fracture) can be avoided.

Suitable measures to detect impending bearing failure are vibration-based condition monitoring systems (CMS) and temperature measurements. A major difference between vibration and temperature monitoring is that vibration CMS usually provide a pre-warning time (P-F interval) in the range of several weeks to months while this is only in the range of hours to days in case of temperature-based detection.

Table 2: Selected analysis results for the gearbox (statements valid for the V44-600kW only are marked with index “1”, index “2” indicates those limited to the V90-2MW)

Subsystem: Gearbox						
Item	**Function**	**Failure mode**	**Failure cause**	**Failure mechanisms**	**Failure characteristic**	**Proposed task, PM action**
all gearbox components	transmission of torque from the rotor to the generator shaft, providing the desired conversion ratio for speed and torque	loss of torque transmission capability	manufacturing or installation deficiencies	increased friction or inappropriate high cyclic loading which leads to damage	damage accumulating	training of technicians for improved quality in manufacturing, installation, and repair; alignment check; temperature and vibration monitoring (for enhanced planning, secondary damage prev.)
bearings	keep shafts in position while allowing rotary motion at minimal friction	high friction	overloading, often due to design or installation deficiencies	increased friction due to plastic deformations, high temperature → material fatigue	damage accumulating	endoscopy, temperature and vibration monitoring for early damage detection (not preventing bearing damage)
			inappropriate lubrication (insufficient lubr., over-lubrication, wrong lubricant)	increased friction → high temperature → surface damages	damage accumulating	oil analysis; measurement of oil pressure and temperature; online particle counting; follow lubrication scheme
			moisture in oil	corrosion by oxidation; reduction of steel strength possibly due to H2 ingression → surface failure	damage accumulating	filter dryer in gearbox casing to dehumidify air inflow; oil analysis; online moisture detection
gearwheels	transmit mechanical power while converting speed and torque at desired ratio	pitting	overloading	high local stress → surface fatigue, damage to tooth surface → high friction	damage accumulating	alignment check; avoid emergency stops with mechanical brake
			metal particles in lubricant (e.g. consequence of overloading)			oil analysis; online particle counting; particle indication with magnet; inline magnetic filtering
			loading during standstill	false brinelling	damage acc.	avoid loading during standstill
		scuffing	insufficient lubricant film; load exceeding scuffing load capacity of the oil	metal-to-metal contact, welding and tearing of tooth surface → high friction, particle release	random failure	correct oil type; oil analysis to ensure oil quality, particularly additive content; avoid emergency stops with mechanical brake
		tooth breakage	overload; consequence of material removal by pitting or scuffing; fatigue	results in high friction and particle release	damage accumulating	alignment check; measures against pitting and scuffing as above; vibration CMS for early damage detection
lubrication system	supply lubricant to gearwheels and bearings at right temperature and viscosity; filter lubricant; cooling of the gearbox	loss of lubrication, filtering or cooling function	too high oil temperature, mostly due to defect thermostat	insufficient lubricant film thickness (with consequences as above)		control system modification: introduction of warning thresholds for oil temperature instead of present alarm levels
			too low oil temperature, due to failed heating system or insufficient mixing/circulation	too low viscosity → insufficient lubrication		oil temperature measurements, avoid start-up below a threshold value (preventing secondary damage)
			insufficient oil filtration due to blocked inline filter → filter by-passed until replacement	(see consequences of particles in oil)	risk increasing with filter age	additional filter stages (standard: inline filter in V44; coarse inline and fine offline filter in V90); online particle counting; differential pressure measurement over filters; bleeding point for air in filter enclosure
			loss of oil, low oil pressure (e.g. due to leakage at shaft seals or badly installed filters; sudden oil hose rupture)		random failure or increasing failure frequency	visual control at service; pressure measurement^1 (standard in V90-2MW); training of technicians to improve filter installation; filter design for foolproof mounting

Table 3: Selected analysis results for the generator (statements valid for the V44-600kW only are marked with index "1", index "2" indicates those limited to the V90-2MW)

Subsystem: Generator

Item	Function	Failure mode	Failure cause	Failure mechanisms	Failure characteristic	Proposed task, PM action
all generator components	convert shaft to electric power, provide up to 600kW^1/2MW^2 at 690V and 50 Hz to the grid within specified range of rotational speed	no power conversion capability				
stator and rotor windings	lead electric currents in order to provide electric power	short circuit failure	melting of the isolation due to overheating, due to material degradation (aging) of the isolation or due to mechanical impact / vibrations; can cause excessive gearbox loading		increasing failure frequency	temperature measurement in the windings (done already); vibration CMS for early detection of bearing failures and unbalances
		open circuit failure (loss of conduction)	broken windings or failed contacts at connections	fatigue as a consequence of excessive vibrations; material defects in copper conductors	sudden event or accumulating damage	avoid excessive vibrations → vibration CMS; early diagnosis of impending failure by means of thermography or using a motor tester; vibration CMS for detection of electric unbalance
bearings	keep generator rotor shaft in position while allowing rotary motion at minimal friction	high friction	inappropriate lubrication (insufficient lubr., over-lubrication, wrong lubricant)	increased friction → high temperature → surface damages	damage accumulating	follow lubrication scheme; automatic lubrication; temperature and vibration monitoring for early damage detection
			design deficiencies (under-dimensioning)			design change required, preventive measures limited to early damage detection
			bearing currents^1 caused by winding damage in the generator rotor or by ground currents (only V44, hybrid bearings applied in V90-2MW)	formation of sparks → local destruction of lubricant film	damage accumulating	bearing current detection via measurement of high-frequency electromagnetic emissions from sparks; scheduled bearing replacement; temperature measurement, vibration CMS
brushes, slip rings^2 (V90-2MW only)	provide electrical contact to the generator rotor^2	loss of contact; high friction and contact resistance	slip ring damage	carbon dust from wear of brushes causes electric spark-over		solved successfully with suction system for removal of carbon dust; condition-based replacement
			over-worn brushes			monitoring of brush thickness, e.g. by means of an integrated electrical contact or a camera system; condition-based replacement

Table 4: Selected analysis results for the rotor current control / converter subsystem (statements valid for the V44-600kW only are marked with index “1”, index “2” indicates those limited to the V90-2MW)

Subsystem: Rotor Current Control (RCC unit in V44-600kW, converter in V90-2MW)						
Item	**Function**	**Failure mode**	**Failure cause**	**Failure mechanisms**	**Failure characteristic**	**Proposed task, PM action**
all RCC^1 components (V44 only)	control the generated electric power by regulating the rotor current^1	loss of current control capability				
RCC power electronics unit^1		loss of rotor resistance variability	failure of cables or contacts, predominantly due to mechanical impact: loose contacts due to vibration, cable twist		increasing failure frequency	avoid strong vibrations (e.g. due to damages bearings) → vibration CMS
			failure of power electronics components due to overheating	ambient temperature exceeds design operating conditions, e.g. due to failure in nacelle / gearbox cooling system	increasing failure frequency	ensure design operating conditions
			failure of power electronics components due to electrical operating conditions	failure correlates with grid disturbances / frequent transients in the grid	increasing failure frequency	clarify correlation between grid disturbances and failures
RCC micro-proc. unit^1		no target value for current control			seldom failure	
RCC resistor unit^1		open circuit failure (loss of conduction) in rotor circuit	overheating	frequent operation at high slip, failed temperature monitoring	seldom failure	temperature monitoring; at high temperatures, operation at reduced power
			open circuit / contact failure due to mechanical impact	e.g. cracking of welds due to impacts of rotation and vibration	seldom failure	avoid strong vibrations (e.g. due to damages bearings) → vibration CMS
all converter^2 components (V90 only)	feed generator rotor circuit with electric current of desired amplitude and frequency for control of power output to the grid^2	loss of current control capability				
converter micro-proc. unit^2					random failure	software update
converter power electronics unit (IGBT)^2			overheating, e.g. due to failed cooling system; aging; moisture ingression or condensation; mechanical impact e.g. from vibration; electrical impact from grid disturbances		increasing failure frequency	temperature monitoring; avoid strong vibrations (by design or using vibration CMS for early detection)

On V44 turbines, CMS are usually not installed; the “Elida” turbine of Göteborg Energi, equipped with a CMS prototype from SKF since 2001, is an exception in this respect. On V90-2MW turbines, vibration-based CMS are not part of the standard equipment provided by the wind turbine manufacturer, but are in practice installed in virtually all turbines of this type. However, vibration monitoring and vibration-based diagnosis of planetary stages in gearboxes is at present still challenging and an improvement of condition-monitoring technology for this purpose is subject to intensive development activities today.

An interesting finding has been obtained with respect to present practices in wind turbine maintenance: According to the RCM workgroup, experience has shown that the better the schedules and plans for service maintenance are followed, the more reliable a wind turbine works. This apparently trivial statement suggests that the present service intervals of 6 months are appropriate. Moreover, in a variety of cases, a lack or bad execution of service maintenance has been found to lead to low availability and costly secondary damage. This shows that not to perform maintenance in the right way can result in high consequence costs in practice.

A challenge identified in the context of the RCM analysis is the large number of new personnel in wind turbine maintenance with limited experience in this field, being a side-effect of the strong growth of wind turbine installations. Correct installation and de-installation routines as well as a proper alignment of components have a strong impact on the reliability of wind turbines. There is thus a need of enhanced training and education of wind turbine maintenance personnel in this respect.

A fundamental problem revealed during the RCM study is that maintenance decisions are at present usually made with the aim of a short-tem minimization of cost per kWh, not with a focus on long-term minimization of total life cycle cost. A difficulty is perceived in practically justifying the installation of additional equipment for prevention of failures in wind turbines because a quantification of the benefit of such investments is challenging. This issue can be addressed by means of the data-based, quantitative methods for maintenance optimization to which the present work intends to contribute.

However, it must be noted that the broad practical application of quantitative methods in maintenance decision-support tools will require the structured and automated collection of in-depth failure and maintenance data of wind turbines. Thus, further and intensified efforts towards such systematic data collection, as e.g. using the RDS-PP component designation structure combined with the EMS designation structure for maintenance activities (see [33, 34]) as proposed in [22] and [35], are strongly needed in order to tap the full potential of quantitative maintenance optimization for cost-reduction of wind energy.

6 Conclusions

In a workgroup involving a wind turbine owner and operator, a maintenance service provider, a provider of condition-monitoring services and wind turbine component supplier as well as researchers at academia, a limited-scope Reliability-Centred Maintenance (RCM) analysis of the wind turbines Vestas V44-600kW and Vestas V90-2MW has been carried out. The RCM study forms the basis for the development of quantitative models for maintenance strategy selection and optimization within the framework of the Reliability-Centred Asset Maintenance (RCAM) approach.

The analysis has focused on the subsystems which in the past have contributed most to the average downtime of these wind turbine models. For these subsystems, it has identified the most relevant functional failures and their failure causes as well as suitable measures to prevent either the failure itself or to avoid critical secondary damage. Analysis results for the subsystems gearbox, generator and rotor current control (V44-600kW) / converter (V90-2MW) have been presented here. It has been found that a considerable number of preventive measures proposed by the RCM workgroup for the V44-600kW turbine have been implemented in the V90-2MW series. Measures for prevention or early detection of bearing damages are concluded to be particularly effective due to the identified central role of vibration as a failure cause for mechanical failure of a variety of components.

In addition to the analysis of specific wind turbine failures and appropriate preventive measures, comprehensive background information regarding the current maintenance practices has been obtained during the RCM study. Challenges which are at present impeding the operation and maintenance of wind turbines from becoming more cost-effective have been identified and solutions have been proposed. Standardized and automated collection of in-depth failure and maintenance data, enhanced training of maintenance personnel, and the utilisation of quantitative methods for decision support in wind turbine maintenance are considered to be important steps to improve the reliability, availability and profitability of wind turbines.

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