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Reliability of Different Wind Turbine Concepts with Relevance to Offshore Application

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ABSTRACT

This paper investigates the reliability of more than 6000 modern onshore wind turbines and their subassemblies, ranging in size from 300-1800 kW, in Denmark and Germany over 11 years and particularly the changes in reliability of generators, gearboxes and converters in a subset of 650 of these wind turbines in Schleswig Holstein, Germany.

The analysis yields some surprising results about which subassemblies are the most unreliable but stresses that Mean Time to Repair (MTTR) is also important.

The paper then proceeds to consider the failure frequencies of subassemblies in direct and geared drive wind turbines in one German population. This analysis shows that direct drive wind turbines do not necessarily have better reliability than geared drive turbines but do have better potential to improve their reliability with time. Wind turbine generators and converters are both achieving reliabilities considerably below that of other industries but the reliability of these subassemblies is improving with time. The paper concludes by considering the effect of wind turbine concept on reliability and its influence on future wind turbine concepts if they are to achieve the reliability performance needed offshore.

1. INTRODUCTION

The reliability of large modern onshore wind turbines (WT) is improving but in order to face the more inclement conditions encountered offshore, where the wind energy harvest will be more substantial but where access is limited, it is necessary to increase reliability still further.

This paper will consider the reliability, or failure frequency, λ, of WTs rather than the wider issue of availability and Capacity Factor (CF). This is because reliability is fundamental to the WT construction and is potentially calculable, while availability, yearly production and CF depend upon reliability, wind conditions and the consequences of faults, which in turn depend upon turbine location, access logistics and maintenance regime, outside the scope of the wind turbine itself.

The paper carries forward analysis previously made by the authors [1], [2] on data collected from publicly available European databases of WT failures, paying particular attention to the failure frequency and MTTR of the most vital subassemblies in the WT. The foundation of that analysis had been the application of recognised reliability methods on data, collected over a period of 11 years, from Windstats surveys in Denmark and Germany [3], known in this paper as WSDK and WSD respectively.

That analysis has been supplemented by further work on a population of turbines, of known model and concept, installed in Schleswig Holstein in Germany, contained in a survey [4] performed by the Schleswig Holstein LandWirtschaftsKammer, known in this paper as LWK.

These analyses show striking differences between the reliability of selected subassemblies. Some of the results can be related to experience with such subassemblies outside the wind industry.

Considerable interest has also been shown in the industry of late in the differences in cost and performance achieved by different WT architectures, see for example [5], but reliability information was lacking from that study. The analysis in this paper sheds light on these issues and identifies specific reliability behaviours of selected subassemblies, where work could be done to improve overall WT reliability.

2. WT CONSTRUCTION

General Arrangement

As the technology of modern WTs matures the construction has become relatively standardised around the three-bladed,
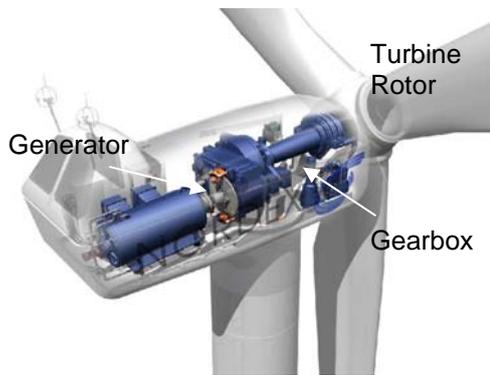
upwind, variable speed concept shown in Fig. 1.

Figure 1 a: Construction of the nacelle of a Geared WT showing the main subassemblies.
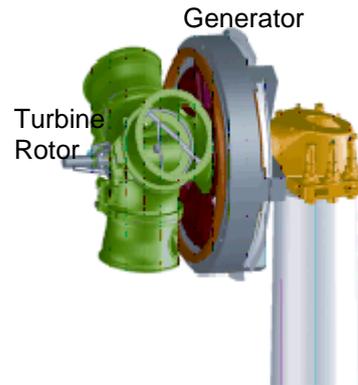

Figure 1b: Construction of the nacelle of a Direct Drive WT showing the main features.

But within this basic concept there are different architectures as follows:

- Geared WTs with a gearbox, a more standardised, high-speed asynchronous generator and partly rated converter, Fig. 1a.
- Direct Drive WTs with no gearbox but a specialised direct drive, low-speed synchronous generator and fully rated converter, Fig. 1b.

The anticipated benefit of the geared concept is that it uses a more standardised, high-speed generator and a partially rated converter, thereby saving cost as shown in [5].

There are also a number of control configurations which need consideration and these are listed in Table 1. The examples in Fig. 1a & b use the last two speed control methods shown in Table 1. This paper will investigate the reliability of a number of these turbine concepts where

a concept means the sum of the WT architecture and power control method.

Subassemblies

In order to understand WT reliability we need to break the WT down into more detail than given in Fig. 1 and this is done using the following nomenclature:

- System, the whole WT;
- Subsystem of the WT, such as:
  - Rotor, consisting of rotor blades, pitch mechanism and rotor hub;
  - or Drive train, consisting of main shaft, main bearing, gearbox, brake, generator and couplings;
- Subassemblies of subsystems, such as the gearbox;
- Components of subassemblies, such as a bearing in a gearbox.

Table 1: Turbine Control Configurations			
Speed Control	**Pitch Control**	**Power Control**	**LWK WT models using this configuration**
Fixed speed/Dual speed	None	Passive stall regulation geared drive train with asynchronous generator	NEG Micon M530 TW600
Fixed speed	Yes, pitch to stall	Active stall regulation geared drive train with asynchronous generator	Vestas V27 Nordex N52/54
Limited variable speed	Yes	Geared drive train with asynchronous generator control using variable rotor resistance	Vestas V39
Variable speed	Yes	Geared drive train with slip ring asynchronous generator control using a partly rated converter	Tacke TW1500, Bonus 1MW/54
Variable speed	Yes	Direct drive with synchronous generator control using a fully rated converter	E40, E66

This paper focuses on the subassemblies recorded in the surveys WSDK, WSD and LWK. The terminology used by the different surveys is slightly inconsistent and it has been necessary to use a unified terminology to clarify understanding.

3. POPULATIONS

In order to fully understand the reliability of WTs it is essential to consider operator experience and the WSD, WSDK and LWK data was collected by such operators. These surveys have some limitations, as follows:

- They gather the number of failures experienced in each turbine and subassembly in the population, in a given period without giving details of the failure modes.
- The periods of data collection differ for each population as follows; WSDK monthly; WSD quarterly; LWK annually. These periods have some effect on the results presented.
- There are other differences between the populations:
  WSDK is a large mixed population decreasing in numbers (2345-851 turbines over the period), with turbines of average age 15 years and mostly stall-regulated configuration. Their technology is consolidated as confirmed by their failure frequency, which is approaching the bottom of the bathtub curve, see Section 4. The failure results of individual turbine models cannot be distinguished in this data.
  WSD is a larger mixed population growing in number (1295-4285 turbines over the period) and includes larger turbines, with an average age of <3 years, including a variety of turbine models with different control configurations but their failure frequency is also approaching the bottom of the bathtub curve, although at a faster rate than WSDK. The failure results of individual turbine models again cannot be distinguished in this data.
  LWK is a smaller segregated population largely static in number (158-643 turbines) and includes larger turbines with an average age of >3 years, including variable speed configurations. The failure frequencies experienced are tending towards the bottom of the bathtub curve and the deterioration phase.

4. PREVIOUS WORK

The failure frequency of repairable systems is modelled by the bathtub curve, that represents three different phases of the life of a population of objects. In turn each phase of the bathtub curve can be modelled by the intensity function of a PLP, as shown in Fig. 2. The material set out in this paper is based on the concept of bathtub curve and its mathematical formulation, the Power Law Process (PLP).
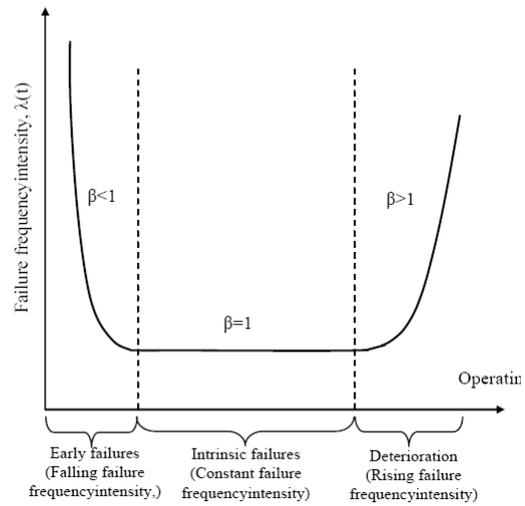

Figure 2: The "Bathtub Curve" for the intensity function showing how the reliability varies throughout the life of repairable machinery.

The authors' previous work [1] & [2] concentrated on understanding the behaviour of WTs and their subassemblies by analysing the average failure frequency. This is equivalent to assuming that failure frequencies were constant, in the bottom part of the bathtub Fig. 2. The PLP is a special case of the Poisson Process with an intensity function:

$$\lambda(t) = \rho \beta e^{-\beta t}$$

β determines the trend of the curve and is called shape parameter. ρ is a scale factor which has units of the reciprocal of time. For $\beta < 1$ or $\beta > 1$ the curve shows respectively a downward or an upward trend. When $\beta = 1$ the intensity function of the PLP is identically constant $\lambda = \rho$, and the process represents the bottom of the bathtub curve in Fig. 2, called the intrinsic failures phase. λ has units of failures per unit time.

The previous work taken from WSD, WSDK and other data, [1], showed the overall trend in WT failure frequencies with time since the days of the "California Wind Rush", see Fig. 3a. That Fig. also shows the measured constant failure frequencies of other power generation sources, largely extracted from IEEE Reliability Survey data sources. This shows that WT reliability is improving and becoming better than some other power generation sources, notably diesel generator sets. However, this graph needs to be treated with caution for the following reasons:

- The WT data is taken from mixed and changing populations of WTs and the averaging, implicit in the failure frequencies, will tend to underestimate the failure frequency of newer, larger, more complex WTs.
- The other power generation source failure frequency data came from historic surveys of limited size, which cannot represent the inherent reliability improvement also present in those sources.

- The data does not show the relative reliabilities of different WT subassemblies, which is essential if we are to understand what is controlling the reliability of WTs being developed and installed in the future.

The latter point can be elicited from the WSD, WSDK and LWK data as shown in Fig. 3b, where constant failure frequencies of 12 major subassemblies of turbines in those surveys, identified by a common terminology, over a period of 11 years for more than 7000 turbines, are plotted.

Fig. 3b reveals some interesting information:

- The overall failure frequencies in Danish turbines are lower than German turbines, as seen in Fig. 3a. This was attributed in [1] to the greater age and smaller size of the Danish turbines resulting in a higher overall reliability.
- The failure frequencies of subassemblies in the WSD and LWK surveys are remarkably similar even though they do not include the same WTs.
- Fig. 3b clearly shows those areas of the turbine which need more attention in terms of design and or maintenance and some of the results are surprising, for example:
  Rotor subassembly, which includes the rotor hub, has a dominant failure frequency.
  Electrical system and converter subassemblies also have dominant failure frequencies.
  Gearboxes, generators and hydraulics, anecdotally considered to be the "bête noires" of WTs, have significant but not dominant failure frequencies.

Similar results have been reported from Sweden [7] and have been extracted from a different survey (WMEP) in Germany [8].

Fig. 3b considers failure frequency only and does not consider MTTR. It is possible from the LWK data to determine the downtime or MTTR due to failures in different subassemblies and this is shown in Fig. 3c, in the same subassembly order as Fig. 3b, where the effects of grid, generator, gearbox, air brake and main shaft failures are more apparent and in particular the dominance of gearbox downtime.

Therefore it is MTTR which is the main reason for the industry's focus on the gearbox. Similar results have also been obtained in Sweden [7].

5. RESULTS & DISCUSSION

Comparison Previous Analysis

The authors used LWK data in [9] to draw reliability conclusions between different WT concepts and control configurations. This paper will now expand this work by considering the average failure frequencies of individual subassemblies in order to understand which are most at risk.

The next analysis will repeat that approach for the turbine subassemblies of identified turbine concepts, but first in Fig. 4 is shown the average failure rates for turbine models in the LWK survey averaged over the 11 year period of the survey. Larger turbines have a lower reliability, direct drive turbines appear to have a lower reliability but more about that later.

The differences highlighted here are consistent with the observations made in Section 3. Both the WSD and WSDK populations are volatile, due to the variability and age of turbine concepts, whereas the LWK population has a higher consistency, due to being an installed fleet that remained relatively unchanged, in terms of technology, throughout the survey period.

The conclusions of [1] were that the gearbox was not necessarily the most failure prone subassembly and that converter and electrical system components of the WT are less reliable. Similar data, collected from the LWK survey, displayed in Fig 3b, show a similar result. In fact this comparison suggests that the two German populations, WSD and LWK, have more in common with one another than with the WSDK data. This is to be expected as Section 3 made clear that Danish data comes from a population of smaller, older turbines that include relatively few variable speed drive machines, whereas the two German populations include larger turbines with variable speed. Furthermore this consistency proves the validity of the two German surveys. The results of Fig 3b suggest that the following subassemblies require reliability attention:

- Electrical system
- Rotor (ie Blades & Hub)
- Converter (ie Electrical Control, Electronics, Inverter)
- Generator
- Hydraulics
- Gearbox

Data on failure rates for some subassemblies used outside the wind industry is available [6] and this is shown on Fig 3b as follows:

| Subassembly	Failure rate per year
Gearbox	0.155
Hydraulic system	0.040
Mechanical brake	0.030
Generator	0.050

Improve Reliability by Concept

One simple approach to improve reliability, taken by Enercon, has been to remove the gearbox and use a direct drive configuration. Enercon has also adopted an all-electric approach avoiding the use of hydraulics for pitch or yaw control.

- From Fig 4 direct drive WTs do not necessarily have better reliability than indirect drive WTs. In Fig. 4 the direct drive E40 has a higher failure frequency than its indirect drive partners

of the same size, whereas the direct drive E66 has a lower failure frequency than its partners, although the E66 data is rather limited in number of WTs.
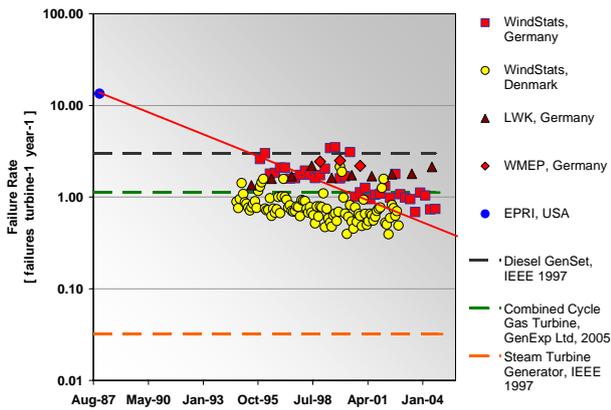
a) Summary of WT failure frequencies from various sources over 15 years and >10000 turbines [1]
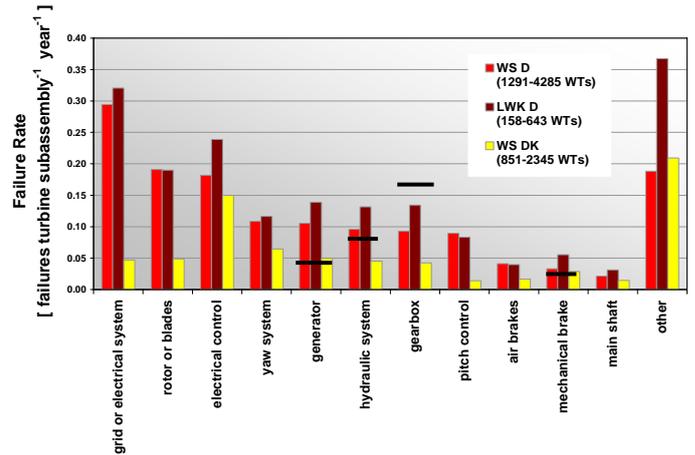
b) Distribution of failure frequencies between subassemblies in WTs from the WSD, WSDK and LWK surveys, averaged over 11 years and >7000 turbines. Industrial failure rates superposed in black
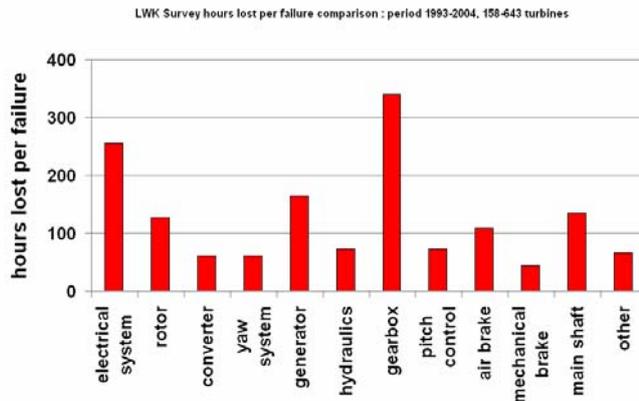
c) Distribution of downtime between subassemblies in WTs from LWK
Figure 3: Results from previous work assuming a constant failure frequency and the HPP model.
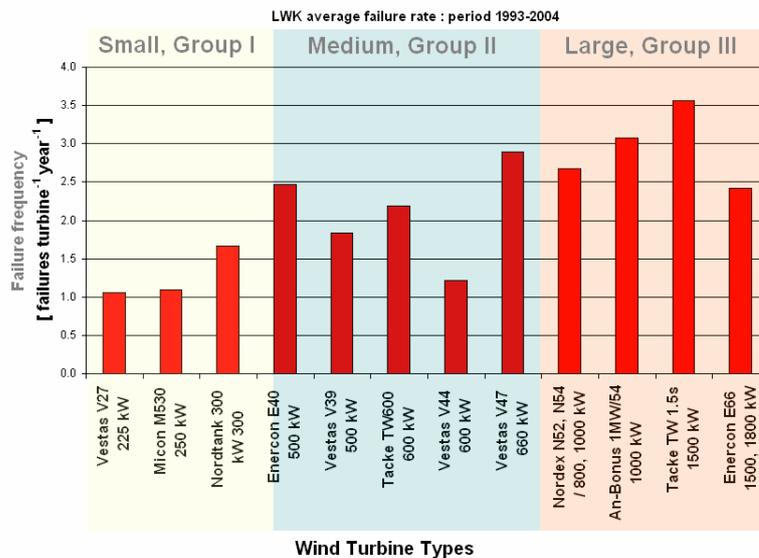

Figure 4: Distribution of failure frequencies between different turbine models, sorted by turbine size

- From Fig. 5 the failure frequencies of gearboxes in geared WTs are higher than the failure frequencies of converters in variable speed, geared WTs and the aggregate failure frequencies of generators and converters in direct drive WTs are greater than the failure frequency of gearboxes, generators and converters in indirect drive WTs [9].
- Therefore the price paid by direct drive WTs for the reduction of failure frequency by the elimination of the gearbox is a substantial increase in failure frequency of electrical-related subassemblies.
- From Fig 4 it can be seen that the downtime or MTTR of electronic subassemblies is lower than the downtime of gearboxes, which depends not only on the basic design of the subassembly but also on the maintenance strategy. These results suggest that an all-electric direct drive WT may ultimately have an intrinsically higher availability than an indirect drive WT.

Taking up the comparison between direct and indirect drive WTs, raised by Polinder et al [5], this paper shows that:
- From Fig. 5 the failure frequency of direct drive generators higher than that of the geared generators and the following explanation is offered. The direct drive machines studied in this paper are wound-rotor, synchronous generators with a large number of pole pairs, incorporating a large number of individual rotor and stator coils. Whereas the indirect drive machines are 4 or 6 switchable pole, high-slip, induction generators or 4 or 6 pole double-fed, induction generators, with far fewer individual coils. It is suggested that the disparity in failure frequencies is due to:
  o The much larger number of coils used in the direct drive machine. The failure frequency could be improved by replacing the field coils by permanent magnets, but
    this would introduce other, reactive control issues.
  o The larger diameter of the direct drive generator making it more difficult to seal the windings from the environment, exposing the insulation to damage due to the presence of humidity or other contaminants in the air.
  o Insufficient standardization in the manufacture of large direct drive machines, as a consequence of smaller production runs, compared to the more common doubly fed induction generator.

From these results, [6] and consideration of direct drive or geared concept WTs the following arise:
- The reliability of WT generators is worse than that achieved by generators in other industries, during the initial phases of operation.
- The reliability of WT converters is considerably worse throughout their operation than that achieved by converters in other industries.
- The reliability of WT gearboxes are seen to be that of a mature technology, comparable with those obtained by gearboxes in other industries. Therefore substantial improvements in the designed reliability of gearboxes are unlikely in the future without radical redesign.
- From the above improvements in generator and converter design with respect to reliability performance will be crucial to improving the reliability of both direct drive and geared concept WTs.

Compare Control Configurations

Fig. 6, extracted from Fig. 5, shows the relationship between failure frequencies of blades, pitch mechanism, gearbox and generator as turbine concepts and control configurations change as shown in the third column of Table 1.

With fixed speed, stall-regulated turbines the failures appear concentrated in the blades and gearbox, but with the introduction of variable speed, pitch-regulated machines pitch mechanism failures appear, as expected, but the gearbox failure frequencies reduce.

The reduction in blade faults is even more noticeable with the larger direct drive turbine.

In other words the technological advance of variable speed and pitch has not only conferred energy extraction and noise reduction improvements but also, when well-designed, has conferred an overall improvement, with time, in reliability.

6. CONCLUSIONS

The paper has investigated the reliability of more than 6000 WTs in Denmark and Germany, ranging in size from 300-1800 kW, over 11 years and particularly the reliability of subassemblies in up to 650 WTs in Schleswig Holstein in Germany. The results of the paper are supported by other surveys in Sweden and Germany. The paper has demonstrated the following from this data:
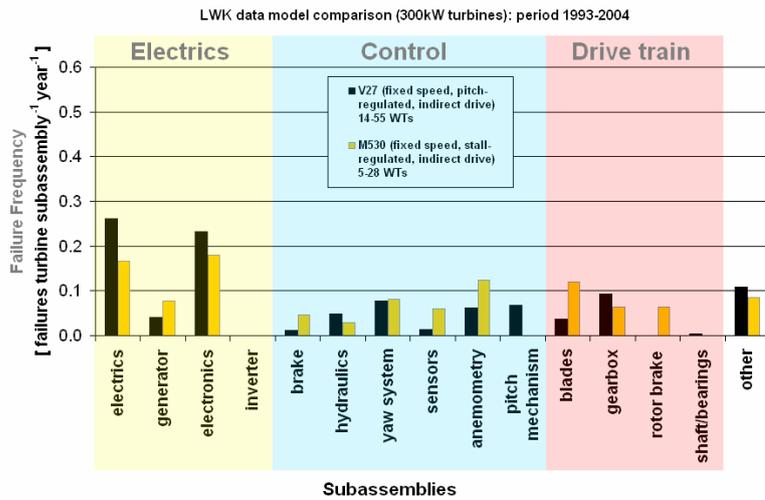
a) Group I 300 kW
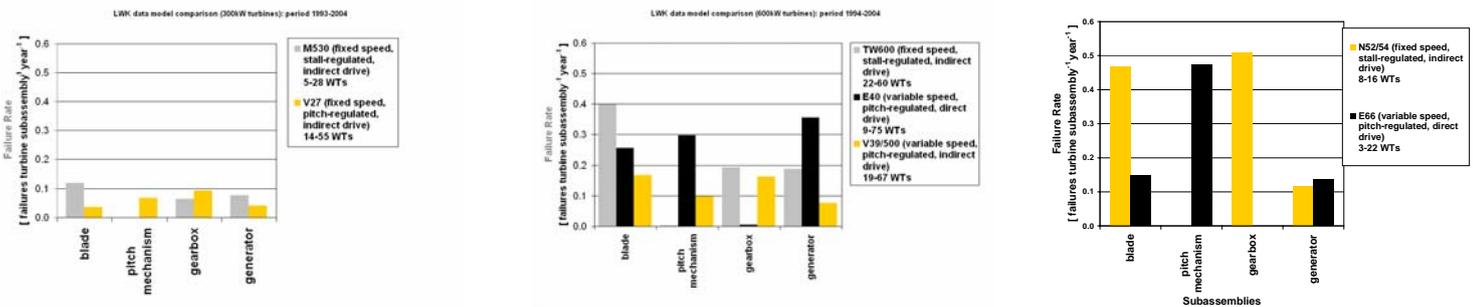**fixed speed, geared turbines with pitch-regulated or stall-regulated control.**
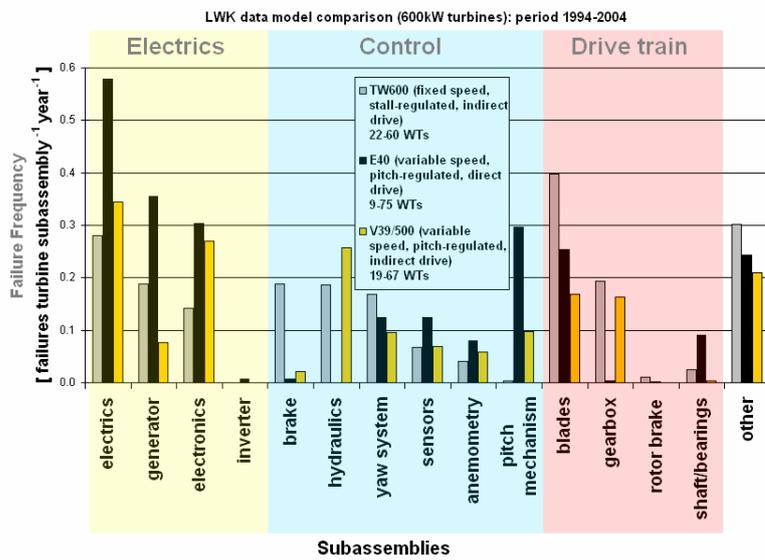
b) Group II 600 kW
fixed speed, stall-regulated or limited variable speed pitch-regulated, geared turbines or variable speed direct drive, pitch-regulated, turbines.
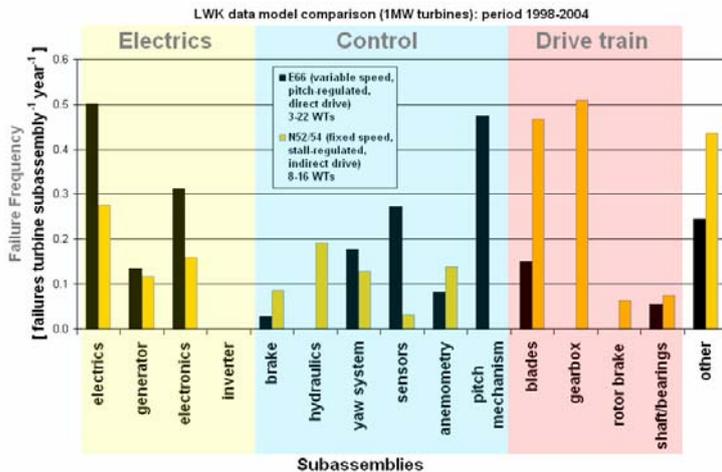
c) Group III 1 MW
geared, fixed speed , stall-regulated, turbines or direct drive, pitch-regulated variable speed turbines.

Figure 5: Distribution of failure frequencies between subassemblies in 3 different size ranges of WTs of different concepts and different control configurations, taken from the LWK survey, averaged over 11 years and >200 turbines

a) Group I 300 kW
fixed speed, geared turbines with pitch-regulated or stall-regulated control.

b) Group II 600 kW
Fixed speed, geared, stall-regulated, or limited variable speed pitch-regulated turbines or variable speed direct drive pitch regulated turbines.

c) Group III 1 MW
Variable speed geared, pitch-regulated, turbines or variable speed direct drive, pitch- speed turbines.

Figure 6: Distribution of failure frequencies focussing solely on the blades, pitch mechanism, gearbox and generator

- That, in the WTs surveyed, the subassemblies with the highest failure frequencies are, in descending order of significance:
  - Electrical system
  - Rotor (ie Blades & Hub)
  - Converter (ie Electrical Control, Electronics, Inverter)
  - Generator
  - Hydraulics
  - Gearbox
- Larger WTs have a lower reliability than smaller WTs.
- Technological advances in WT variable-speed and pitch-control have conferred reliability improvements on wind turbines with time.
- WT direct drive and geared generators exhibit higher failure frequencies than generators in other industries, during the initial phases of operation.
- The failure frequency of direct drive generators is generally higher than that of geared generators. This disparity may be due to the much larger number of coils used in the direct drive machine, the larger diameter of the machine and the fact that it is not a standard machine produced in large numbers. The failure frequency of the direct drive generator could be improved by replacing the field coils by permanent magnets.
- WT direct and indirect drive converters exhibit higher failure frequencies throughout their operation than converters in other industries. Direct drive WTs are not necessarily more reliable than geared WTs.
- Aggregate failure frequencies of generators and converters in direct drive WTs are greater than the aggregate failure frequency of gearboxes, generators and converters in geared

WTs. The price paid by direct drive WTs for the reduction of failure frequency by the elimination of a gearbox is a substantial increase in the failure frequency of electrical-related subassemblies.

- However, the MTTR of electrical-related subassemblies is lower than the MTTR of gearboxes. This suggests that an all-electric, direct drive WT may ultimately have an intrinsically higher availability than an indirect drive WT.

7. ACKNOWLEDGEMENTS

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