Design for Reliability

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Abstract
In many cases future offshore projects will be not only larger than any existing projects, but also located further from the nearest harbour facilities and at greater water depths. As a result the technical and commercial risks related to reliability will be dramatically increased relative to the projects that form the experience base of today. The paper presents the ARM (Availability, Reliability, Maintainability) model developed by Siemens Wind Power. The ARM model is used to quantify the risks and to highlight areas of design modifications required to minimise risks. Background data from existing offshore wind farms are presented. The methodology and conclusions of the ARM model are shown, and using the Siemens 3.6 MW wind turbine as example the implementation of the conclusions in real life is demonstrated.

Introduction

Offshore wind energy has the potential for becoming a significant source of electricity in Europe, and considerable efforts on research, studies, technology developments, planning and demonstration are paving the way for the implementation. Nevertheless, the offshore application of wind turbines still provides an unprecedented challenge to the wind industry.

Several simultaneous developments increase the technical and commercial risks relative to the project experience base of today. Some of these developments are

- The increased size of the wind farm projects
- The limited knowledge of the environment and the external conditions (wind, wave, ice, humidity etc.) in true offshore locations
- The move towards greater water depths for new projects
- The larger distances to nearest harbour facilities
- The problems of access during severe weather conditions
- The likely emergence of new foundation concepts in the search of more cost effective solution, with their inherenet uncertainties
- The use of the largest and most recent wind turbines as the costing structure of the foundations and grid connections favour larger units

In short, the combination of new technologies, limited operational experience, long travelling time and difficult access creates a strong concern for lost production and costly maintenance. Hence, the need for focus on reliability and maintainability in the turbine design cannot be underestimated. Reliability analysis with the key words Availability, Reliability and Maintainability (ARM) therefore deserves increased attention for offshore wind farm projects.

In the following the ARM model developed by Siemens Wind Power is presented. The ARM model is used to quantify the risks and to highlight areas of design modifications required to minimise risks. Background data from existing offshore wind farms are presented. The methodology and conclusions of the

ARM model are shown, and using the Siemens 3.6 MW wind turbine described in [1] as example the implementation of the conclusions in real life is demonstrated.

ARM Model Definitions

The purpose of an ARM model is to assist in the determination of the probability of a wind turbine failure and the time necessary to return the turbine to an operational state. The probability can be determined both in terms of time, production and repair costs. Hence the ARM model can be used to demonstrate that relevant faults and errors have been taken into account, also in relation to site-specific access conditions, and to select priorities for accelerated maturing of the wind turbine type by identifying reliability focus points.

A comprehensive ARM model must take account of the following parameters:

- The design at major component level (e.g. blades, pitch system, main bearings, gearbox, generator, cooling system)
- The maintenance strategy (e.g. times to maintain and times to repair)
- The logistics and spares strategy (e.g. travel times for available resources and lead times for unavailable resources, where resources might include spares, personnel and vessels)
- The impact of the weather on access to turbine tower and the ability to effect a repair in those weather conditions

The basic definitions follow from international standards, e.g. [2] and [3]. Most standards operate with a distinction between time and energy based factors, i.e.

Time reliability	=	Reliability factor
Time availability	=	Availability factor
Energy reliability	=	Equivalent reliability factor
Energy availability	=	Equivalent availability factor

The reliability and the availability factors are defined as

$$RF = 1 - \frac{FOH}{PH}; \quad AF = 1 - \frac{FOH + POH}{PH} \tag{1}$$

In which FOH is the forced or unplanned outage hours, POH is the planned outage hours and PH is the period hours. Note that the difference in the outage hours.

The reliability factor can also be expressed in terms of the terms MTBF = Mean Time Between Failures (forced outage) and MTTR = Mean Time To Repair. The availability factor requires two additional terms, namely the MTBM = Mean Time Between Maintenance (planned outage) and MDT = Mean Down Time for maintenance. Hence

$$RF = 1 - \frac{MTTR}{MTBF + MTTR}; \quad AF = 1 - \frac{MTTR + MDT}{MTBF + MTTR + MTBM + MDT} \tag{2}$$

In using these definitions for offshore wind turbines and for assessing the financial consequences the following special features must be taken into account:

- Wind turbines are unmanned production units.
- The classical principle of wind turbine control and monitoring is to ensure that the wind turbine is always in a safe state – this is not automatically the same as ensuring that the operating time is maximised.

- The classical principle of redundancy generally aims at ensuring proper function of safety system – shaft speed monitoring as example
- Technicians will not be available on the spot to implement manual overrides
- A significant proportion of availability loss is due to errors that require no repair work
- Reduction of availability due to forced outages is normally always considerably more important than reduction due to planned outages, which can be carried out at low winds with little production loss
- The weather may not allow access or sufficient repair time, i.e. an insufficient weather window

Note that for offshore applications only limited valid onshore experience is available to determine MTBF for the most recent competitive wind turbines. Also, time to detect and evaluate failure or error and to account for a restricted weather window shall be added to the MTTR determined from onshore applications.

Reliability Model

The reliability of a product or component constitutes an important aspect of product quality. Of particular interest is the quantification of a product's reliability, so that one can derive estimates of the product's expected useful life. For example, suppose you are flying a small single engine aircraft. It would be very convenient information (more strong words might be considered here) to know what the probability of engine failure is at different stages of the engine's "life" (e.g., after 500 hours of operation, 1000 hours of operation, etc.). Given a good estimate of the engine's reliability, and the confidence limits of this estimate, one can then make a rational decision about when to swap or overhaul the engine.

A useful general distribution for describing failure time data is the Weibull distribution. This distribution turns out to be suitable not only for the determination of wind speed distributions (for which it is widely known in the wind industry) but also for modelling a wide variety of different data sets, such as the life times of gears, electronic components, relays, ball bearings, or even some businesses.

The Weibull distribution is generally calculated with the expression

$$f(x)=\frac{a}{c}\left(\frac{x-\theta}{a}\right)^{c-1}\exp\left\{-\left(\frac{x-\theta}{a}\right)^{c}\right\};\ \theta \le x;\ a>0;\ c>0 \qquad (3)$$

where

a is the scale parameter of the distribution
c is the shape parameter of the distribution
θ is the location parameter of the distribution

It is generally accepted that for most machines (components, devices) the probability of failure during a given time increment can best be described in terms of the "bathtub" curve: Very early during the life of a machine, the rate of failure is relatively high (so-called Infant Mortality Failures); after all components settle, and the electronic parts are burned in, the failure rate is relatively constant and low (so-called Random Failures). Then, after some time of operation, the failure rate again begins to increase (so-called Wear-out Failures), until all components or devices will have failed.

For example, new automobiles often suffer several small failures right after they were purchased. Once these have been "ironed out," a (hopefully) long relatively trouble-free period of operation will follow. Then, as the car reaches a particular age, it becomes more prone to breakdowns, until finally, after 20 years and 250000 miles, practically all cars will have failed. A typical bathtub failure rate function is shown below.

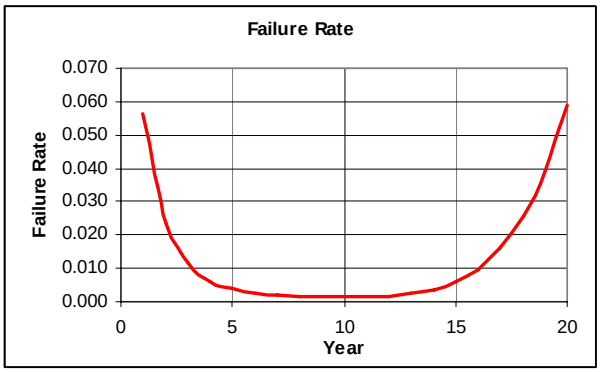

Fig. 1: Bathtub curve

It turns out that the Weibull distribution is flexible enough for modelling the key stages of this typical bathtub-shaped failure rate function. This is done by using one Weibull function for the Infant Mortality phase, another for the Random phase, and a third for the Wear-out phase.

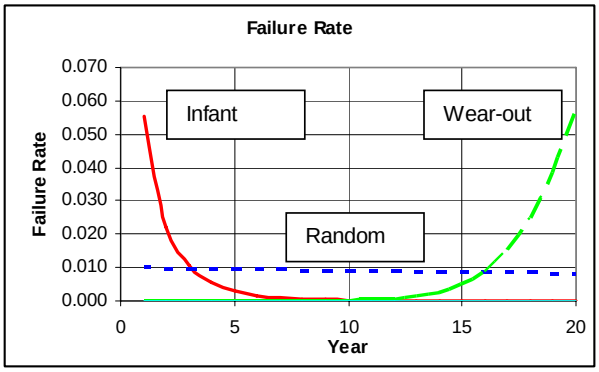

Fig. 2: Elements of bathtub curve

The different shapes are the result of different selections of the shape parameter c.

The early Infant Mortality phase of the bathtub can be approximated by a Weibull hazard function with shape parameter c<1; the constant Random phase of the bathtub can be modelled with a shape parameter c=1, and the final Wear-out phase of the bathtub with c>1. In the example above the values of c are 0.8, 1 and 10, respectively.

Experience shows that wind turbines sometimes experience serial failures that do not emerge as true teething troubles (Infant Mortality) but rather emerge as premature wear-out. The reason for this is that due to the rapid product development the main components of wind turbines are generally at an early stage of maturity, at least for this application. Consequently, for wind turbines it is reasonable to introduce a fourth contributor to the calculation of the failure rate. We have decided to call this contributor the Premature Serial Failure or PSF phase.

Figure 3 shows the PSF phase and the contribution to the total bathtub curve. The PSF is always modelled with c>1.

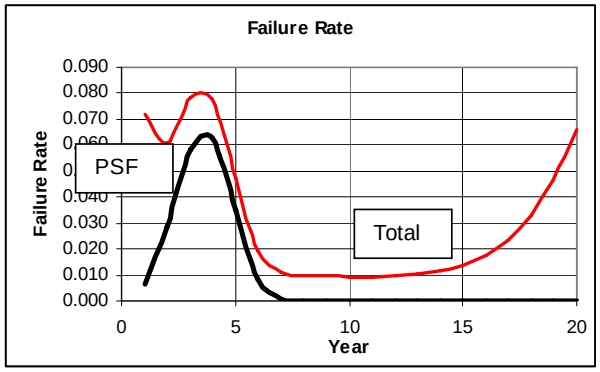

Fig. 3: Premature Serial Failure Elements of bathtub curve

In principle a stringent Weibull analysis assumes that a component can fail only once. This does not represent real life, however. A component that was installed as a replacement for an original component due to Infant Mortality or Premature Serial Failure will still have a finite lifetime and will be described by the Wear-out curve. Obviously the starting point in time will be different than for the original component, but in practice this has little influence on the Wear-out calculations, provided the any significant rate of Wear-out only occurs significantly later than replacements due to Infant Mortality or Premature Serial Failure.

Consequently, in our analysis we have selected the approach that failures are additive and that the aggregate number of failures over a certain period of time (typically the project lifetime) is the sum of Infant Mortality Failures, Random Failures, Wear-out Failures and Premature Serial Failures, and that each of these failure types can be determined independently.

Determination of the Failure Rate Parameters

Ideally the failure rate parameters should be determined on the basis of observations for the specific component types. This is not really possible for competitive wind turbine types; however, since the experience basis with the specific components is not sufficient for this exercise. In many cases wind turbines will be marketed in significant numbers long before any main component failures have been experienced at all. Consequently, the failure rate parameters are determined on the basis of general experiences, both with the precursors of the relevant turbine type and with the component types in general industrial applications.

The failure rate for a specific year n is calculated with the equation

$$\gamma = \eta \left[\exp\left(-\left(\frac{n-1}{a} \right)^c \right) - \exp\left(-\left(\frac{n}{a} \right)^c \right) \right] \tag{4}$$

where

- γ is the failure rate per turbine per year
- η is the total number of components affected by the failure type.
- a is the scale parameter of the distribution. The scale parameter is equal to the characteristic lifetime, i.e. the year at which the aggregate failure rate reaches (1-1/e) = 63 %.
- c is the shape parameter of the distribution. By experience c can reasonably take the values 0.5 for Infant Mortality Failures, 1.0 for Random Failures, 3.0 for Wear-out Failures and 3.5 for Premature Serial Failures.

The challenge of the analysis is to select proper values for η for Infant Mortality Failures and Premature Serial Failures, and proper values of a for all failure types. Note the fundamental difference between the

use of equation (4) for Infant Mortality Failures and Premature Serial Failures and for Random Failures and Wear-out Failures. Assuming a single component, the value of η is selected in the range $0 \leq \eta \leq 1$ for Infant Mortality Failures and Premature Serial Failures to represent that not all components may be affected by these failure types. For Random Failures and Wear-out Failures η is 1, because ultimately all components will be affected.

Eventually, these values of η are multiplied with the number of components of the specific type that is installed on the turbine. For example, η is multiplied with 1 for the gearbox (because there is only one gearbox) and with 3 for the blades (because the turbine has three blades). It should be noted that for Infant Mortality Failures and Premature Serial Failures all components will in many cases be affected if failures of these types occur. Consequently, the value of R should be interpreted as the product of the probability that failures of this type will occur, and the number of components affected if it does occur.

The failure rate γ is the reciprocal of MTBF (Mean Time Between failure), and the reliability R(t), measured as the probability for failure free operation during the time interval t, is related to γ and MTBF by

$$R(t) = \exp(-\gamma t) = \exp(-t/MTBF) \tag{5}$$

Having determined the Weibull hazard functions for the four error types, Infant Mortality Failures, Random Failures, Wear-out Failures and Premature Serial Failures for all major components, the time dependent failure rate for each major component is calculated as the sum of error type failure rates. With estimates of MTTR, production loss and cost of repair for each component, MDT and MTBM, the expected cost of repair and maintenance, reliability factor and availability factor can be determined for each major component and in total.

ARM procedure

From the discussion above it follows that the implementation of the ARM model is performed in 5 steps:

1. *Determine consequence of failure for relevant error types and component failures*	In general, all error types, and all components down to a level, where the component is unlikely to affect availability or can be analysed as a part of a larger composite component, need to be included. For each error type or component the consequences are determined with respect to energy output (100% output, 0% output or de-rating) and cost of repair.
2. *Determine MTBF and MTTR for each relevant error and component failure*	MTBF (or the failure rate) must be interpreted broadly and include not only actual failures but also errors that do not constitute a physical failure. Traditionally MTBF is determined on the basis of generic databases, supplier experience or sub-supplier information. For offshore wind turbines the tools are more limited, for the most competitive wind turbines experience is limited, and generic databases or sub-supplier information do not exist or cannot be relied on. Also, serial failures are difficult to predict and may cause large deviation in MTBF.
3. *Calculate reliability expected cost from repairs*	The reliability of major components and in total are determined, using fault tree analysis where complexity, inter-dependence and cross-relations makes it relevant. Monte-Carlo simulations may be used to combine probability functions. From the reliability, consequences and MTTR, production loss and expected cost of repair can be predicted.
4. *Calculate availability*	Availability is determined from the availability by by taking into account scheduled maintenance; see (1) and (2).

Designing for Reliability

The 3.6 MW machine is the first Siemens turbine exceeding the 100 m line. The turbine has a rotor diameter of 107 m. and a hub height of 80 - 120 m. The prototype hub height is 90 m. The 3.6 MW turbine is a three-bladed upwind machine with pitch regulation and variable rotor speed. The turbine is equipped with B52 blades made of fibreglass-reinforced epoxy in the IntegralBlade® manufacturing process.

From the start the 3.6 MW turbine has been designed for reliable offshore application and easy maintainability. The special features include various design considerations

Climate	– Arrangements generally according to principles having shown their worth from Vindeby onwards
	– Corrosion, outside – surface protection to C5M in splash and spray zone
	– Corrosion, inside – "closed room system", with climate control (dehumidifiers, salt filters) and cooling via heat exchangers. Need for hatch opening reduced to a minimum.
	– Operational conditions generally more benign offshore due to low turbulence
Reliability	– The blade is manufactured in a single operation, using a closed process invented by Siemens Wind Power, with no glue joints between spars and shells, no weak points, no easy access for water or lightning
	– Blade design details have been thoroughly tested with follow-up by material coupon test setup for every blade
	– Hydraulic pitch system with independent pitching of all three blades and a mechanical locking system with the blade in stop position
	– Main shaft with two spherical roller bearings to reduce loading on the gearbox
Maintenance	– Bed frame where main components can be lowered through the frame
	– A gear box with two planetary stages and one helical stage which can be dismantled in situ and a mechanical brake with two calipers
	– An Induction generator without slip rings, thermal rating class F, used for class B and an internal air circulation, cooled with air-air heat exchanger
Access	– Helicopter access platform on nacelle for access at severe sea states

An overview of the machine is presented in Figure 4 below.

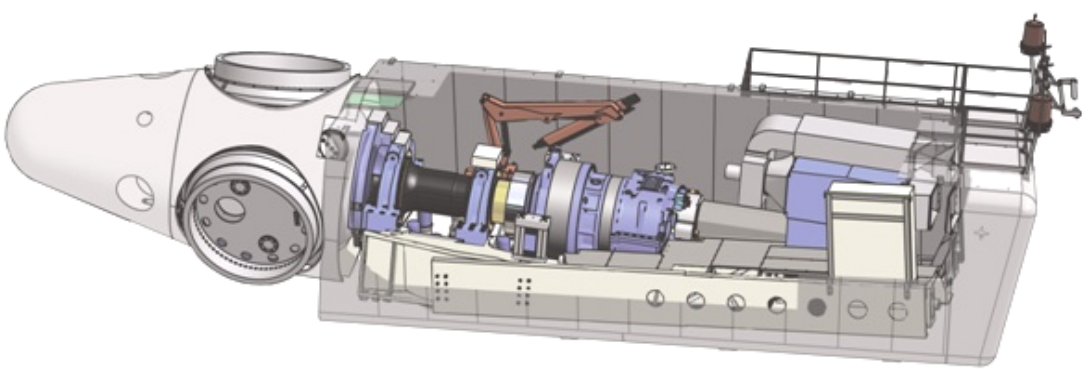

Figure 4: Nacelle arrangement of the Siemens 3.6 MW turbine.

Some important data and weights are shown in table 1 below.

Main data		**Main weights**	
Rotor diameter:	107 m	Blade:	16 t
Main shaft diameter:	1,06 m	Main shaft:	15 t
Nacelle + hub length:	20 m	Gearbox:	37 t
Nacelle width:	4,2 m	Generator:	10 t
Nacelle height:	4,1 m	Rotor complete:	95 t
		Nacelle complete:	125 t

Table 1: Key data of the Siemens 3.6 MW turbine.

In addition to the turbine design other reliability issues need to be considered regarding project infrastructure in order to optimise the maintainability. Such issues include:

- Maintenance strategy (local base or central service unit)
- Logistics and spares strategy (normal spares at local base, strategic spares immediately available etc.)
- Access and travelling time (access conditions, boat availability, distance and travelling speed)

Results

The most difficult and critical parameters to determine in the ARM model are MTBF and MTTR. In order to provide qualified and quantified estimates for MTBF and MTTR for the Siemens wind turbines programme, an ongoing ACE (Avaliability, Component, Error) tracking project was initiated in 2004. In the project ACE tracking data are collected from projects in Denmark and UK on a 24 h basis by the Service Department. Additional support is given by the Service Manager, Country Managers and Service Engineers. The projects comprise existing offshore projects in Denmark using recent wind turbine types (Nysted and Samsø with 82 2.3 MW turbines) and 201 turbines in UK over a 5 year period of continuous operation.

In general, the results are proprietary, but examples of results from the initial project period are shown below. Fig. 5 shows the accumulated outage hours from fault identified by error code from the first 14 months of operation (in total 100 years of operation) of Danish offshore wind farms.

Fig. 5: ACE Tracking Data – Hours at various error codes

Similar data are collected from the UK onshore wind farms from which the data in Figure 6 for MTTR, again identified by error code, are obtained.

These statistics form the basis for the Siemens ARM model, which with time become more and more firmly based. Some preliminary results can be mentioned from the ACE Tracking project, namely that for both the offshore and the onshore wind turbines, error types that can be remotely reset cause a 0.1% avail-

ability loss. However, due to the travelling time and limited access for offshore wind turbine error types requiring technician visit for reset but no physical repair works cause as much as a 1.1% availability loss.

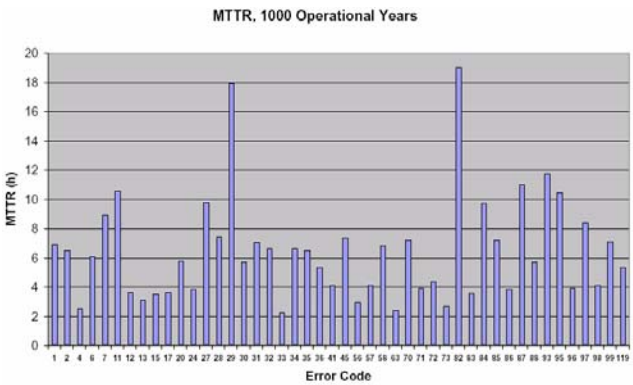

Fig. 6: ACE Tracking Data – Mean Time to Repair at various error codes

In order to illustrate the model, we will divide the turbine in the reliability critical major components: blades, pitch-bearing, main bearings, gearbox, generator, converter, yaw-ring and transformer, and take a closer look on how a poor transformer design may affect the reliability and costs.

Let us assume that Weibull hazard functions for the four error types, Infant Mortality Failures, Random Failures, Wear-out Failures and Premature Serial Failures are given by the purely fictitious parameter values in Table 2.

Error type	Components affected in %	Weibull a-parameter	Weibull c-parameter
Infant Mortality Failures	10	1	0,8
Random Failures	100	100	1
Wear-out Failures	100	30	3
Premature Serial Failures	30	4	3,5

Table 2. Assumed hazard function parameter values.

The resulting failure rates for each error type as well as the total obtained by adding the individual failure rates assuming independent failure events are shown in Figure 7.

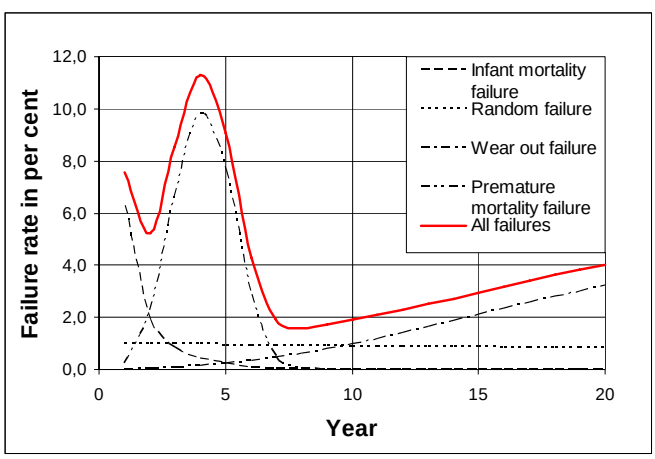

Fig. 7: Example failure rates

Assuming that the repair in case of a transformer error involves a replacement and requires 4 working days, a vessel mobilisation period of 7 days and a probability of obtained a daily weather window of sufficient duration of 60%, the Mean Time To Repair MTTR becomes 14 days. The resulting reliability factor is shown below in Figure 8 together with the reliability factor omitting the premature serial failure.

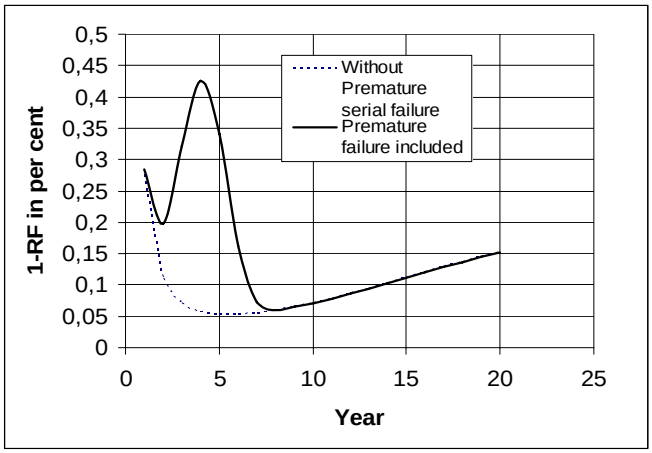

Fig. 8: Example reliability factors

The assumed characteristics of the Premature Serial failure has a significant effect and cause a reduction of the reliability factor from 0,16% to 0,10%. The weather window effect is also significant, a weather window probability of 25% results in a reliability factor of 0,26%, while a 100% weather window probability results in a reliability factor of 0,13%.

The numbers quoted in this example are an order of magnitude smaller than the availability loss of 1.1 % observed for offshore wind turbines from minor error types requiring a technician to visit for inspection and reset but no physical repair works. This illustrates the general experience that the primary contributor to reliability and availability losses is not major failures of important components but rather the much more frequent smaller and irritating errors from sensors faults, noisy signals etc. However, the economic impact of, in particular serial, failures of major components can be considerable.

Concluding remarks

The background for Siemens ARM (Availability, Reliability, Maintainability) model has been presented, and the use has been illustrated. The model is operational, and it is being used to demonstrate and quantify risks and costs due to availability and reliability issues in turbine and wind farm development. Efforts are ongoing to improve the statistical basis for the model, and the ARM provides an important tool in Siemens Wind Powers efforts to design for reliability.

References

[1] Steffen Frydendal Poulsen, Peder Enevoldsen, Henrik Stiesdal, *Crossing The 100 M. Line – Challenges And Experiences,* Proc. AWEA Wind Power 2005, Denver Colorado, May 15-18, 2005.
[2] ISO 3977-9: 1999(E), Gas Turbines – Procurement – Part 9: Reliability, availability, maintainability and safety.
[3] ANSI/IEEE Std 762-1987(R2002), IEEE Standard Definitions for Use in reporting Electric Generating Unit Reliability, Availability and Productivity.

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