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**Project UpWind**

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“Integrated Wind Turbine Design”

# Work Package 9: Electrical grid
## Deliverable D9.1
# Survey of reliability of large offshore wind farms
## Part 1: Reliability of state-of-the-art wind farms

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**Abstract:**

This report identifies the main factors, which have an impact on the reliability of offshore wind farms. The survey is based on experience derived from offshore projects carried out in Denmark.

Since the number of offshore wind farms is still relatively small, the statistical information and the basis of quantitative assessment are limited. For this reason this report deals with the various factors having an impact on the reliability as to the quantity.

Subsequently, the report takes into consideration the reliability data, which can be derived from operational experience and from various studies.

The conclusion of this survey in relation to the overall power-system reliability is that the main focus has been on system security, eg on solving the stability issues, whereas the possibilities of contributing to power system adequacy, which can improve the reliability, must be investigated.

As to the current state of offshore installations, the conclusion can be made in relation to the first offshore wind farms that it is necessary to increase our focus on the following aspects: design, procurement, quality, risk assessments and quality assurance. New standards or practices regarding risk assessment and quality assurance of offshore wind-farm installations are required, and existing IEC standards may not be sufficient.

Specific attention at wind turbine transformers, generators and power electronics as well as other electronic equipment in wind turbines is required.

The experience with the wind-farm grid infrastructure indicates that the common practice of employing the simplest radial system may be the best solution.

Quantification of reliability parameters is still uncertain due to the few installations and the short operational experience.

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| STATUS, CONFIDENTIALITY AND ACCESSIBILITY | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Status | | | | Confidentiality | | | | Accessibility | |
| S0 | Approved/Released | X | | R0 | General public | X | | Private web site | |
| S1 | Reviewed | | | R1 | Restricted to project members | | | Public web site | X |
| S2 | Pending for review | | | R2 | Restricted to European. Commission | | | Paper copy | |
| S3 | Draft for commends | | | R3 | Restricted to WP members + PL | | | | |
| S4 | Under preparation | | | R4 | Restricted to Task members +WPL+PL | | | | |

**PL:** *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

# 1. Background and objectives

The overall objective of UPWIND work package no. 9 (WP9) is to investigate the requirements for wind turbine design as to the reliability of wind farms in power systems and to study possible solutions in relation to reliability improvement. This work is important particularly in connection with large offshore wind farms as failure of future very large wind farms may have a significant impact on the power balance in the power system. In addition to this, offshore wind farms are normally more difficult to access than onshore wind farms.

The reliability of the power production from a wind farm depends on the wind turbine; the collecting grid of the wind farm, including transformers, the power grid. Also the wind farm monitoring system can have an impact. However, critical situations are where the complete wind farm trips. The impact of the grid is most important as grid abnormalities normally affect all the wind turbines in a large wind farm simultaneously. The consequences of grid abnormalities like voltage dips, outages and unbalance, depend on the ‘ride-through’ capability of the wind turbines. Finally, extreme wind conditions are important if all wind turbines are affected, that is if cut-out wind speed is reached, or when the wind speed drops after a front passage.

The work package will investigate operational and statistical aspects of wind farm reliability. Investigating grid code requirements, extreme wind conditions and specific wind-farm control options in order to comply with these requirements are included in the operational aspects. The statistical aspects will include the development of a database and the statistical modelling of the reliability of wind energy.

The first task of WP9 is to investigate the state-of-the-art offshore wind farms in terms of reliability. The task has been divided into two sub-tasks:

D9.1 Identification of main factors with an impact on the reliability of wind farms

D9.2 Reliability parameters and statistical reliability model for electrical components of wind farms (ECN).

This report aims to identify the main factors, which have an impact on the reliability of offshore wind farms. The survey is based on operational experience in relation to electrical aspects:

- Design and construction
- Reliability during operation
- Protection
- System earthing
- Grid abnormalities.

Since the number of offshore wind farms is still relatively small, the statistical information and the basis of a quantitative assessment are limited.

Section 3 deals with the various factors, which have an impact on the reliability as regards the quality.

Section 4 deals with the reliability data, which can be derived from operational experience and from various studies.

## 2. Introduction

In the recent twenty years, many countries have developed an interest in wind generation and some of them have already moved their attention from onshore to offshore locations. The main reasons for that may be found in the improved wind conditions of offshore sites, eg North Sea locations, and in the congestion of onshore spaces due to the huge amount of installed wind turbines, eg in Denmark and Germany.

After some years of technology testing (approximately during the period from 1991 to 2001), the first offshore wind farm has been put into operation in 2002 in Denmark: Horns Rev is built in the North Sea close to the Danish west coast. This wind farm comprises 80 wind turbines and has a total capacity of 160 MW. After this, many other projects have been planned and some of them are already fully operating, or they will soon be commissioned. Some of the projects, which are already in service or whose installation have been approved appears from the below Table I.

**Table I: Some built or planned offshore wind farms (WF)**

| Ref | Name | Country | Commissioning date | WF Size [MW] | Webpage |
|---|---|---|---|---|---|
| 1 | Horns Rev | DK | 2002 | 160 | http://www.hornsrev.dk/ |
| 2 | Nysted | DK | 2003 | 165.5 | http://uk.nystedhavmoellepark.dk |
| 3 | Samsø | DK | 2003 | 23 | http://www.samsohavvind.dk/ |
| 4 | Arklow Bank I | IRE | 2003 | 25 | http://www.airtricity.com/ireland/wind_farms/offshore/operating/arklow_bank |
| 5 | North Hoyle | UK | 2003 | 60 | http://www.natwindpower.co.uk/northhoyle/ |
| 6 | Scroby Sands | UK | 2004 | 60 | http://www.eon-uk.com/481.aspx |
| 7 | Kentish Flat | UK | 2005 | 90 | http://www.kentishflats.co.uk/index.dsp?area=1374 |
| 8 | Barrow | UK | 2006 | 90 | http://www.bowind.co.uk/index.htm |
| 9 | Egmond | NED | 2007 | 108 | http://www.noordzeewind.nl/ |
| 10 | Burbo | UK | 2007 | 90 | http://www.burbo.info/ |
| 11 | Q7-WP | NED | 2008 | 120 | http://www.q7wind.nl |
| 12 | Gunfleet Sands | UK | 2009 | 108+64 | http://www.gunfleetsands.co.uk/ |
| 13 | Horns Rev 2 | DK | 2009 | 215 | |
| 13 | Thornton Bank | BEL | 2008-2010 | 216-300 | http://www.c-power.be |
| 14 | Butendiek | GER | 2009 | 240 | http://www.butendiek.de/ |

At present, many other projects are under primary evaluation, especially in UK, and an overview of them can be found in the following references [1-4].

Most of the installed projects, cf Table I, have a maximum capacity of 160MW. This is mainly due to economical and technological reasons, eg Horns Rev, or to regulation limitations, ie the United Kingdom, where a fixed number of installable wind turbines per wind farm could not be exceeded for environmental reasons. However major wind farms have been planned for future installations as it appears from Table I.

The wind turbine technology used for offshore installations usually tends to adopt wind turbines with a large rated capacity in order to profit of the advantageous wind speed conditions. Sizes vary from 2 to 3.6MW per turbine since that is the technology currently available in the market. However, larger turbines are being developed, eg 4.5 to 7MW, and it may be assumed that future projects will use these new solutions. As it appears from Table II, it is possible to observe a number of typical wind turbine features chosen for offshore installations.

**Table II: Wind turbine technology used in various offshore wind farms**

| | WF Size [MW] | Wind Turbine | | | | | |
|---|---|---|---|---|---|---|---|
| | | Nr. | Size [MW] | Manufac-turer | Type | Rotor Diameter [m] | Hub Height [m] |
| Horns Rev | 160 | 80 | 2 | Vestas | V80 – 2MW | 80 | 70 |
| Nysted | 165,5 | 72 | 2.3 | Bonus | Bonus 2.3 | 82 | 69 |
| Samsø | 23 | 10 | 2.3 | Bonus | Bonus 2.3 | 82 | - |
| Arklow Bank I | 25 | 7 | 3.6 | GE | GE 3.6MW | 104 | 73.5 |
| North Hoyle | 60 | 30 | 2 | Vestas | V80 – 2MW | 78 | 67 |
| Scroby Sands | 60 | 30 | 2 | Vestas | V80 – 2MW | 80 | 70 |
| Kentish Flat | 90 | 30 | 3 | Vestas | V90 – 3MW | 90 | 70 |
| Barrow | 90 | 30 | 3 | Vestas | V90 – 3MW | 90 | 75 |
| Egmond | 108 | 36 | 3 | Vestas | V90 – 3MW | - | 70 |
| Burbo | 90 | 25 | 3.6 | Siemens | Siemens 3.6 | 107 | 83.5 |
| Q7-WP | 120 | 60 | 2 | Vestas | V80 – 2MW | 80 | 59 |
| Gunfleet Sands | 108 | 30 | 3.6 | - | 3.6MW | 110 | 80 |
| Horns Rev II | 215 | 95 | 2.3 | - | 2.3 MW | 82 | - |
| Thornton Bank | 216-300 | 60 | 3.6-5 | Repower | 5M-5MW | 126 | 95 |
| Butendiek | 240 | 80 | 3 | Vestas | V90 – 3MW | - | - |

In Table III, some characteristics of wind park installations are described. The distance between the wind turbines is usually proportional to the rotor diameter (5-8 times), whereas the choice of the distance between the turbine rows is based on an attempt to reduce the wake effects in the park. Internal grids are operating at 33 to 36kV; and the existence of an offshore substation where the voltage level is stepped up before the generated energy is transmitted to shore depends on the size of the wind farm, its distance from the shore and the voltage level of the point of common coupling (PCC) located on shore. For wind farm sizes above 100MW, the use of offshore step-up transformers can be reasonable in order to reduce transmission losses. However, the choice of this solution must depend on the actual requirements in each case.

When choosing an installation of an offshore substation this will have an impact on the number of connectors to shore – the higher the transmission-voltage level is, the lower the number of cables.

## Table III: Internal grid, connection to shore and other information

| | Water depth [m] | Distance between WT [m] | Distance between rows [m] | Area WF [km$^2$] | Offshore substation | | Connection to shore | | Investment Cost [Euro] |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Existence | Size | Distance [km] | Nr cable | |
| Horns Rev | 6-14 | 560 | - | 20 | YES | 36/150 | 14-20 | 1 | 270 millions |
| Nysted | 6-9.5 | 480 | 800 | 24 | YES | - | 10 | - | 270 millions |
| Samsø | - | - | - | - | NO | - | 3,5 | - | 32,3 millions |
| Arklow Bank I | 2-5 | - | - | - | NO | - | 7-12 | - | - |
| North Hoyle | 12 | 350 | - | 10 | NO | - | 6.5-8 | 2 | 113 millions |
| Scroby Sands | 5-10 | - | - | - | NO | - | 2,3 | 3 | 75 millions |
| Kentish Flat | 5 | 700 | - | 10 | NO | - | 10 | 3 | 105 millions |
| Barrow | 15-20 | 500 | - | 10 | YES | 33/132 | 7,5 | 1 | 145 millions |
| Egmond | 16-22 | - | - | 30 | NO | - | 10-18 | 3 | >200 millions |
| Burbo | 1-8 | 530-720 | - | 10 | NO | - | 10 | 3 | - |
| Q7-WP | 20-25 | 550 | - | | YES | | >23 | | 270 millions |
| Gunfleet Sands | - | - | - | - | YES | - | 7 | - | - |
| Horns Rev II | - | - | - | - | YES | - | 42 | 1 | - |
| Thornton Bank | - | - | - | - | YES | 36/150 | 27-30 | 2 | >500 millions |
| Butendiek | 20 | - | - | - | - | - | 34 | - | 400 millions |

# 3. Factors with an impact on the reliability

The reliability of wind farms can be considered from two aspects:

- The overall system reliability, ie from the Transmission System Operator's (TSO's) point of view.

- The availability of the individual wind farm, ie from the owner's point of view focusing on maximum energy yield and maximum revenue from the installation. This is considered in relation to:

    - wind turbine electrical design
    - grid connection infrastructure
    - offshore cable installations
    - offshore substation
    - wind farm internal-medium voltage system
    - protection
    - grid events.

## 3.1 Overall power system reliability

In this context the impact of wind farms on the reliability can be considered from the following two aspects:

- The overall system reliability in terms of system adequacy, ie considering the availability of sufficient capacity and existence of sufficient transfer facilities to cover the load requirement under various system constraints.

- The overall system reliability in terms of system security, ie the system ability to respond to dynamic and transient disturbances.

These aspects must be clearly distinguished from the reliability of the wind farm as a generating plant, considering availability and aiming at optimising costs as well as revenue for the owner of the wind farm.

**System adequacy and capacity**

As to system adequacy, it is widely recognised in Europe that due to the wind energy intermittent nature, wind generation plants cannot replace conventional energy generation plants. Wind energy generation plants are considered to be energy replacements rather than capacity replacements. It is customary practice to base the transmission system planning on deterministic methods considering the worst cases of wind coinciding unfavourably with the load variation, ie no wind in high-peak hours or maximum wind in low-peak hours.

In the USA and Canada a lot of efforts have been invested in evaluating the capacity credit of wind generation. Historically, it can be seen that wind generation has reduced the requirement for conventional capacity in operation. However, it is still widely recognised that wind power hardly qualifies as capacity reserves at all. Even if a probabilistic planning approach is used, it is still debatable whether the capacity value is really useful in practice. Although the capacity credit may seem to provide a useful measure, it is only useful as an indicator of overall contribution; but it is imperfect as a useful reliability index for either customers or energy suppliers – particularly in connection with intermittent sources like wind.

For this reason, the adequacy analyses of wind power have mainly been related to the cost effective wind farm design, ie optimisation of the installation costs and owner's revenue, rather than the contribution (positive or negative) to the power system reliability.

This also implies that the availability of the wind farms have not really been of any concern to the transmission system operator. Consequently, grid codes do not include any specific requirements for or incentives of improving the wind farm availability or capacity value.

However, as the size of and capacity factor of offshore wind farms increase, it becomes even more important to assess the impact, which these have on the entire system reliability.

**System security**
The system security issues have been most important to the Transmission System Operators associated to integration of large offshore wind farms or to a general high penetration of wind power in the system. Much effort have been invested in developing the requirements and methods rendering it possible for wind turbines to withstand critical system events, which eventually could lead to dynamic, transient or voltage instability of the system.

As result of TSO requirements, the wind turbine technology have matured, so that the state-of-art wind turbines and wind farm facilities used for offshore installations can fulfil the TSO requirements related to system security. These requirements are generally realised in the grid codes by defining voltage sag profiles, which wind turbines must ride through.

The important issue of verifying the performance of wind turbines still need attention, even though a massive development has been seen within modelling, simulation and also verification by testing since the construction of the first offshore wind farms.

The impact on wind farm reliability is discussed in section 3.8.

## 3.2 The electrical design of wind turbines

Offshore wind turbines do not basically vary from wind turbines on land.

The electrical aspects of wind turbine generator systems are regulated by the design standards of the IEC 61400-series. Electrical installations should comply with the EU Machinery Directive, electrical regulations adapted in EN 60204-1 and EN 60204-11 Safety of Machinery- electrical equipment of machines. Furthermore, applicable IEC standards for the following components and subsystems must be observed:

- generators
- transformers
- power electronics
- controls
- electrical installations
- auxiliary systems
- back-up power supply
- earthing and lightning protection.

Concerning the experience gained from plants in operation, it must at first be highlighted that the first offshore wind farms experienced several problems with the electrical equipment, which clearly could be categorised as built-in weak points or simply inadequate designs. The fact that simple systems and equipment experience new impacts in relation to eg climate, vibrations, intermittent operations, when placed off shore, turned out to be a more important issue than first envisaged.

In addition to that, the fact that offshore wind farms include a large number of identical units, and the fact that repair of even simple technical defects may take a disproportionately long time must be taken into consideration.

Based on the above-mentioned aspects, the experience of eg DONG Energy from the first offshore wind farms, is the need for an increased focus on design, procurement, quality, risk assessment and quality assurance. New standards or practices in relation to risk assessments and quality assurance useful for offshore wind-farm installations are required. Applicable IEC standards may not be sufficient.

**Generators**

Until now, wind turbine generators have primarily employed low-voltage generators. Experience from offshore installations is limited to squirrel-cage induction generators and doubly-fed induction generators (DFIG).

Relevant issues:

- Thermal loading
- Leak current through bearings
- Slip ring systems.

The experience from present offshore wind farms has not indicated any major thermal problems with generators. Occasional tripping due to high temperature has been observed. This will result in a controlled stop and an automatic restart when the generator temperature has decreased. However, this is a minor issue with little impact on the availability.

Especially in connection with doubly-fed induction generators bearing problems have been observed. For Horns Rev this was a major issue during the first two years of operation. Retrofit modifications seem, however, to have solved the problem.

Regarding DFIG systems, it is also well known fact that the slip rings are weak points requiring regular maintenance. Vattenfall reports that for Horns Rev, semi-annual maintenance is required, whereas for Kentish Flats this has been extended to annual maintenance.

**Wind turbine transformers**

The wind turbine transformer transforming the generated voltage (until now commonly low voltage) to a medium voltage level (commonly 33-36kV), has appeared to be a critical item.

More or less all transformers have been replaced in the wind farms at Middelgrund and Horns Rev. Also a number of transformers have failed at Samsø. The majority of these problems are related to faults in manufacturing or in some cases operating error.

After replacements and retrofit modifications, serious transformer failures are significantly reduced approaching to non-existing.

Relevant issues with an impact on lifetime and reliability:

- Thermal loading
- Overvoltage, eg from switching or earth faults
- Mechanical problems (vibrations)
- Environment (pollution with salt)

Thermal problems have been observed repeatedly in some installations – particular with dry type transformers tightly rated or insufficiently ventilated. This will force the wind turbine to Thermal problems have not been reported for Horns Rev.

Some concerns also remains in relation to the very intermittent loading of wind turbine transformers and the consequences regarding lifetime. A Danish working group under the Danish Standard Association, involving manufacturers and owners, is investigating the impact on transformers and other electrical equipment in wind turbines.

Transient overvoltage was to some extend a contributory factor to transformer damage initially experienced. For this reason, the level and nature of transients have been recognised as important factors in relation to the lifetime of transformer insulation. The fact that the internal power system is made completely with cables in a regular network configuration may be important in this context [18].

At Horns Rev where the wind turbine transformers are installed in the nacelle, Vattenfall reports that mechanical problems occur regularly. These problems are related to the fastening of transformers or connections, which cannot withstand the vibrations in the nacelle.

**Electronic equipment**
All wind turbine types used for offshore wind farms include primary power electronic equipment:

- Active stall – electronic reactive power control
- DFIG – rotor side converters
- Full size converters.

Present experience from offshore applications is related to the first two types.

Interestingly, experience from these projects shows that power electronics and control electronics in general turn out to have failure rates, considerably higher than expected.

As for the power electronics, the development in higher rating for smaller size is remarkable. Often the recently developed compact water-cooled IGBT modules are employed in wind turbine converter equipment, but generally they appear to have failure rates significantly higher than the values specified by the IGBT manufacturer. The IGBT modules have repeatedly been reported as weak links.

These IGBT failures necessitate access to the wind turbines to allow for replacement of the module. Apparently the IGBT failures tend to occur at wind turbine start-up after having been stopped. This could indicate moisture condensation or spills from the cooling system as plausible reasons in some cases.

At Horns Rev, Vattenfall reports that cooling of electronic (control) cubicles is a major problem. This is due to a combination of factors like a high temperature in the nacelle, high design temperature for the electronics and compact design of cubicles. Temperature monitoring of the circuit boards will force the wind turbine to stop for a cooling period of approximately 15 minutes, and subsequently the turbine will restart. In some worst-case periods, this has had a major impact on wind turbine availability.

Based on the above-mentioned specific offshore problems, experience shows that simple, conservative and well-tried solutions should be preferred.

**Earthing and lightning protection**
Depending on the site location, experience shows that the number of lightning strokes affecting offshore wind turbines may be as high as 3-4 times larger (Nysted) than is the case with wind turbines on land. Due to this increased exposure an increased risk of damage exists. Consequently a new standard for practices and testing is being developed.

After retrofit modification of lightning protection, there have not been any reports on lightning damage at Horns Rev.

## 3.3 Grid connection infrastructure

Various concepts have been applied to the division between the wind-farm internal power system and the transmission grid. In general, the necessary transmission system from the offshore location to the transmission grid is part of the wind farm. In Denmark the transmission system, including offshore substations, are built, owned and operated by the Transmission System operator (the TSO).

In terms of reliability this has an impact on the wind farm reliability and availability as a generating unit. However, in terms of the overall power system reliability the ownership boundaries are irrelevant. Eventually, the divided ownership may lead to different optimisation criteria and different reimbursement schemes for lost generation, etc, which may have an impact on reliability.

Issues to be considered in relation to grid connection are:

- Internal cable system
- The offshore substation (if present)
- Connectors to shore
- Protection.

Regarding the configuration of the internal grid, it must be noted that the wind turbine positions first of all are chosen in order to optimise the wind source. The internal grid layout is consequently determined in order to find a balance among transmission losses, reliability issues and economical aspects. Based on the available projects listed in the tables, it can be noted that almost all installations are based on cluster/string configuration without redundancy. As examples of this, some layouts are shown in the following figures (Figure 1-3).

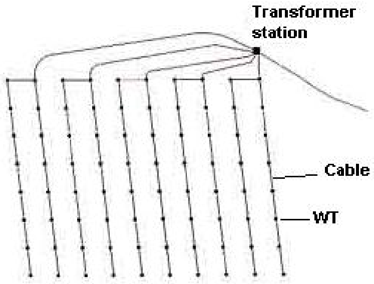

**Figure 1: Horns Rev layout**

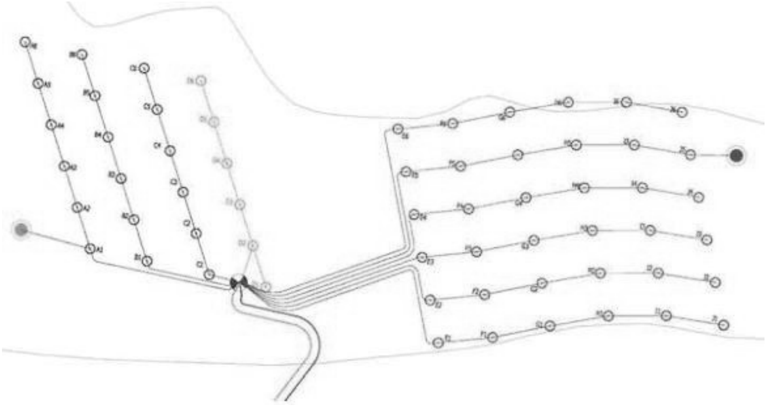

**Figure 2: Thornton Bank layout**

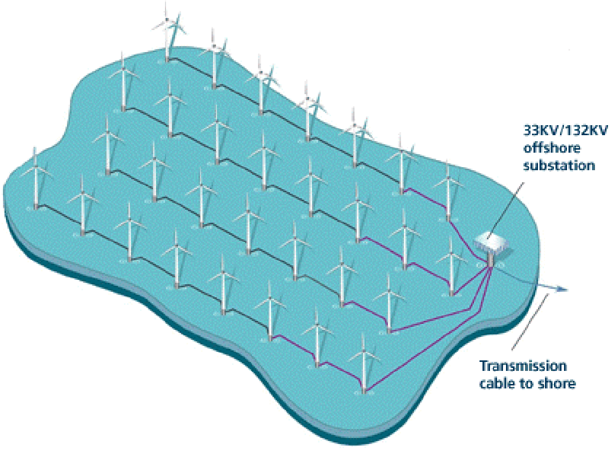

**Figure 3: Barrow layout**

A unique exception to the standard layout is represented by the North Hoyle wind farm where a redundant cabling system is installed (Figure 4). The choice of the configuration seems to allow the connection to shore to transmit the generated energy even if a failure occurs in one of the internal grid cables. (However, it is not known if problems related to component overload may occur in the system in case of component failure).

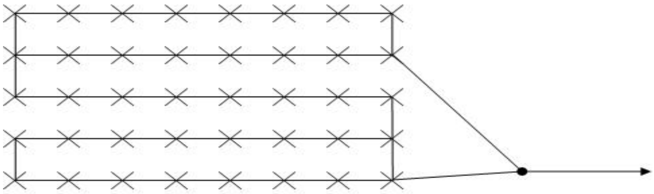

**Figure 4: North Hoyle layout**

For most major wind farms the connectors to shore are at transmission level.

The choice of the number of connectors to shore depends on the chosen transmission configuration. If a step-up transformer is used, then one cable is usually chosen for the transmission (also if, for large farms, the number may increase), whereas for medium-voltage transmission level, one cable per cluster is usually utilized (ie the right hand part of Thornton Bank wind farm, assuming that each row represents a cluster, or the North Hoyle system, considering the system divided into two clusters).

The investment cost of the wind farm is usually proportional to the size of the wind farm: investment costs vary from 1170€/kW (Barrow) to 2250€/kW (North Hoyle), and they can be assumed as site-specific.

## 3.4 Offshore cable installations

The most common practice has been to operate the internal cable networks as pure radial feeders and install a single transmission connection to shore.

It is costly to provide offshore redundant connections. Assessments until now shows that break-even with probable value of improved reliability cannot be met. However, operational experience in relation to offshore transmission installations is sparse.

Experience on submarine cable installations before the construction of offshore wind farms was primarily derived from transmission systems and especially from HVDC links. In relation to these systems, cable damage due to trawling or dragged anchors was a known fact. However, it should be considered that these cables are normally laid on deep water, and that these cables are not always embedded. So the failure rates of HVDC links may not necessarily be applicable I relation to offshore wind farms.

If damage during construction or failures during installation or commissioning are disregarded, the offshore wind farms presently in operation will not have experienced many cable failures. The only known case of post commissioning cable damage is an anchor damage to a cable in the Arklow Bank wind farm.

For DONG Energy's and Vattenfall's portfolios of offshore wind farms, an assessment of the total cable lengths and the number of years of operation without failures see Table 2, indicate that failure rates could be significantly reduced compared to what was expected in previously assessed generic values, eg based on experience from high-voltage DC-links.

| **Internal Grid** | | | | | |
|---|---|---|---|---|---|
| | **km** | **comm. year** | **years** | **km × year** | **1/(km × year)** |
| Tunø Knob | 8 | 1995 | 11 | 88 | |
| Middelgrunden | 9 | 2000 | 6 | 54 | |
| Horns Rev | 60 | 2002 | 4 | 240 | |
| Nysted | 48 | 2003 | 3 | 144 | |
| Kentish | 20 | 2005 | 1 | 20 | |
| **Total** | | | | **546** | **0.002** |
| **Connector to shore** | | | | | |
| | **km** | **comm. year** | **years** | **km × year** | **1/(km × year)** |
| Horns Rev | 22 | 2002 | 4 | 88 | |
| Nysted | 11.5 | 2003 | 3 | 34,5 | |
| Kentish | 30 | 2005 | 1 | 30 | |
| **Total** | | | | **152.5** | **0.007** |

**Table 4: Operational experience of internal grids of existing wind farms**

This reduced probability of failures can be justified by the following elements:

- Cables are buried. It has been normal practice in wind farms to use cables embedded in seabed – for internal cables as a minimum 1 meter, for transmission 1-3 metres. In areas close to the coast 5 metres.
- Wind farms are located in shallow waters.
- Cables between wind turbines are easily identified by fishing/ship traffic.

This seems to indicate that cable failures are not a major issue, and consequently the practice of single connections is validated. However, more operational experience is required in order to draw any decisive conclusion on this matter.

One issue related to the MV cables is at the entry to the wind turbines through the J-tubes. At Horns Rev it is reported that the scour protection is sinking, and there is a risk that this eventually will lay the cables bare and consequently expose them to damage. A major concern is that the bedding will be displaced leaving the cable in a free span and exposed to the risk of being damaged by sharp rocks or stones.

In areas where seabed movements are common, this risk of laying cables bare or in free span will increase the risk of failure. In any case intensified maintenance of scour protection and cable routes (survey and embedding) may be necessary.

## 3.5 Offshore substation

The use of offshore high-voltage substations was not known before offshore wind farms were constructed. The very fist installations were at Horns Rev and Nysted. Obviously, one of the significant aspects related to reliability is the environmental conditions, which can be rough especially in the North Sea.

High-voltage switchgear is totally enclosed gas-insulated switchgear, which means that main circuits are not exposed to any atmospheric impact.

**Wind farm transformer employing tap changer and automatic voltage control**

Until now, no major problems related to excessive wear and failure of tap changers have been experienced. New requirements for wind farm voltage-control may increase this.

One transformer failure has been experienced at Horns Rev. This was an oil leakage at a bushing. This was caused by corrosion, ie it can be categorised as a result of the harsh environment in the North Sea.

## 3.6 Wind farm internal medium-voltage system

A radial structure is normally used in the wind farm power-collection grid and the protection applied is made as a distribution feeder. The design, which has been widely used for onshore wind farms for more than a decade, has in principle been transferred to the offshore installations. The only difference is the voltage level increase and the power of each feeder.

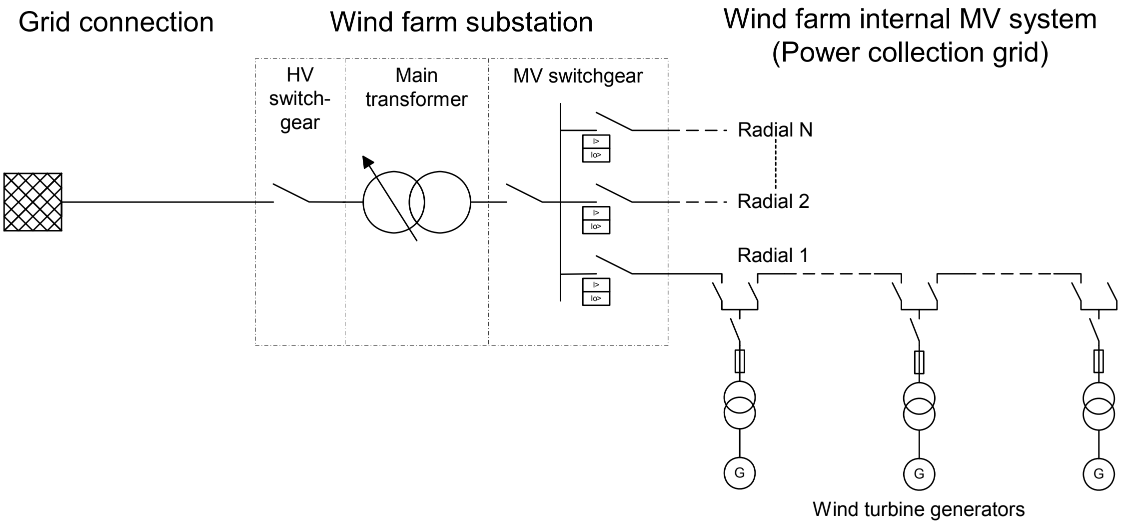

**Figure 4.** Principle for medium voltage system I wind farms. The switch configuration in offshore wind turbines is often simplified.

Here obviously the protection and switching possibilities of the feeders are important.

Normal practice is to install protection against phase overcurrent and single phase to ground faults in the starting point of the feeder. Faults inside the wind turbines will be tripped selectively by either the low-voltage protection or the protection (fuse or circuit breaker) on the primary side of the wind turbine transformer. However, a fault in cable or in termination will trip the complete feeder.

Some installations include arc detection in the transformer compartment of the wind turbines, which will disconnect the complete radial. The benefit of this is that transformer faults are disconnected almost instantaneously and before developing into multi-phase faults damage – thus limiting damage.

Regarding switching possibilities, various approaches have been taken: In the simplest cases, the transformer switches can only be operated locally. In case of transformer faults it may take some time before a radial can be energised.

Faults in wind turbines transformer have occurred after commissioning in the wind farms at Horns Rev, Nysted, Middelgrund and Samsø.

According to experience from eg Nysted in worst case a radial was out of operation for a couple of days due to a failure in a transformer, which coincided with unfavourable weather.

After the replacement of transformers at Horns Rev, no incidents of increased outage time caused by the switch topology have been reported.

In recent wind farms with major wind turbines where transformer protection is provided by means of circuit breakers, remote control is or can be applied. However, reconnecting a radial after a short circuit has occurred without proper visual inspection is risky and would normally not be performed. Consequently, benefit in terms of an increased availability may be limited.

Short circuits within the zone of the transformer are not really a big issue in terms of reliability and outage time. From the owner’s perspective, the capitalised costs relating to lost power generation would hardly balance the extra costs for additional switches.

Experience also shows that:

- in case of short circuits, it not advisable to reconnect a feeder before visual inspection and fault tracing has been performed.
- complicated switching procedures for re-supply, which must be performed seldom during the lifetime of the wind farm, involve the risk of human errors.

Another important subject in relation to the MV network design is the system earthing. The well-known practice of operating MV distribution networks with an isolated neutral has been applied in eg Nysted. Horns Rev is now impedance earthed. The advantage of an isolated neutral is the reduced earth fault level and consequently the reduced damage in case of faults. Experience and studies [18] indicate that the risk of overvoltage and component failures should be considered.

## 3.7 Protection

The protection system design for a wind farm should allow for the following two objectives in relation to fault conditions:

- Compliance with the requirements for normal network operation and network support during and after fault occurrence.
- Securing the wind farm against damage caused by network faults.

For these reasons, wind farms must be designed with protection for overfrequencies and underfrequencies, for overvoltages and undervoltages, overcurrent protections, efficient protections of the generator transformer and backup protections (ie overcurrent generator protection, voltage-controlled generator overcurrent protection or generator distance protection). Sundry requirements have been established by various grid operators, and a wide comparison between these aspects is presented in [6].

The ‘grid protection’ employing under- and overvoltage as well as under- and overfrequency is applied in the control equipment for each wind turbine. The internal power system, which constitutes the grid connection, is designed as a more or less standard distribution and transmission system – only the direction of power flow is different – and the electrical design end protection schemes are developed accordingly.

## 3.8 Grid events

Grid events and their interference with the protection of wind turbines and wind farms have an impact on the reliability during operation

In this context, an important issue is the capability of the wind turbines to ride through faults in the external transmission grid. Fault ride-through requirements have been applicable to offshore wind farms from the very beginning starting with Horns Rev, and grid code requirements have developed into also utilising the capability of wind turbines to support the grid during disturbances.

The most common grid faults are single-phase faults, and the majority of these are temporary faults as illustrated in the Nordel statistics listed below. Fast reclosing is normally performed in transmission for single-phase faults, but is more seldom for three-phase faults.

| | km OH-lines 400-132kV | No of faults/100km | Lightning and other nature | Single phase faults | Temporary single phase faults |
|---|---|---|---|---|---|
| Denmark | 4320 | 0.87 | 76% | 57% | 50% |
| DK-FI-S | 51795 | 1.67 | 70% | 63% | 57% |
| Nordel total | 72420 | 1.48 | 74% | 58% | 51% |

**Table 5: Nordel statistics 1995-2005**

Not all grid codes include requirements for fault ride-through in case of single-phase faults to ground with successive reclosing; however among others the Danish Grid Code from Energinet.dk does.

Studies have indicated that even remote single-phase faults may reduce the positive sequence voltage in the wind turbines and eventually force the wind turbines into a fault ride-through state. Here an aspect of concern is the impact on the wind turbines entering into a fault ride-through sequence, such as the mechanical stress, stress on gear system and tower vibrations.

The operational experience from present applications does not indicate the number of times that the wind turbines actually experience grid faults and (successfully) go through a fault ride-through sequence and what the possible impact is. However, more focus is put on investigating and understanding the impact on the gear system in case of grid faults.

Statistical information is not available from the present Danish wind farms with fault ride-through capability due to the simple fact that the events have not been recorded if the fault ride through is successful. Only low-voltage conditions causing wind turbine trips (correct or unintended) have been recorded.

# 4. Reliability data

When focusing on wind farm reliability, the ability of the wind farm to supply energy during the intended period of time and under the intended operating conditions must be taken into consideration. In relation to that, a wind farm must allow for two main aspects regarding its reliability: variability and randomness of the wind speed and the availability of its components.

## 4.1 Capacity factor

The first of the above-mentioned aspects is relevant as it provides a lower capacity factor of the wind farm than the one of a conventional power plant. In general, the capacity factor can be defined as the ratio of the electrical energy, which is produced by a generating unit for a certain period of time compared with the amount of electrical energy, which can be produced at continuous full power operation during the same period ([2]). In the case of a conventional unit (ie a thermal power plant), this value is usually higher than 95%, whereas due to the wind speed variability in relation to a wind farm the equivalent value may vary from 25% (ie very low wind-speed conditions) to 40% (ie very high wind-speed conditions) ([2]). Furthermore, the production is dispersed over a period of time and is thus not possible to control. Consequently, a wind farm cannot be considered a standard generation unit from a system adequacy point of view. Also as regards the design and control of wind farms, new challenges must be met.

## 4.2 Equipment failure rates and repair times

The second of the above-mentioned aspects having an impact on the reliability of an offshore wind farm – and in general on the reliability of all sorts of generation units – is the set of possible component failures in the system. This is usually investigated by measuring the availability of the generation unit. The availability can be found eg by recording the failure history of a unit equivalent to the one being investigated. Based on these recordings it is usually possible to provide statistical information on the component like failure rate or Mean Time to Repair (MTTR) of the component. However, in order to obtain a reasonable level of accuracy, it is necessary to measure the failure history for a period of time long enough to provide the necessary amount of information. As previously mentioned, the main problem is that the first large offshore wind farm was not commissioned until 2002; thus it is still too early to trust any statistical information based on any of the offshore wind farms in operation at present. This also means that it is not possible to obtain any relevant and reliable data in relation to the calculation of the reliability.

### 4.2.1 Experience

Experience derived from offshore wind farms in operation shows that the availability mainly depends on the wind turbines themselves.

Unavailability due to faults occurring outside the wind turbines, including faults in the internal electrical system and faults in the public grid, normally accounts for less than 1%.

**The availability of wind turbines**

In general, detailed statistical data from wind farms in operation are not available to the public due to both the owner’s and the wind turbine supplier’s commercial interests.

In this connection, it is also important to note that the guaranteed overall availability of the wind turbines generally are agreed between the owner and supplier and are specified in the contract. The contract also defines how the availability is calculated from the recorded down time. This ‘contractual availability’ would basically exclude all down time, which cannot be ascribed to the supplier like stops performed by the owner, stops due to low or extreme wind speed. Also extended repair time due to weather conditions or other kinds of force majeure may also be excluded from the ‘contractual availability’.

Consequently, wind farm suppliers and wind farm owners calculate the availability in a similar way, and statistical information is not available or applicable for reliability analysis.

In addition to that, experience derived from many of the existing wind farms shows that various retrofit installations and replacement works have had a major impact on the overall availability during the initial years of operation; and this will not necessarily be reflected in the availability statistics.

Bearing these limitations in mind, the existing offshore wind turbines generally meet an availability of 95-97%. Public information on various projects is sparse. However, information on some of the offshore wind farms is listed below:

| **Wind Farm** | **Wind turbine availability** | **Total wind farm availability** | **Source** |
|---|---|---|---|
| Horns Rev | 96-96,5% | 95% | Vattenfall |
| Nysted | ≥ 97% | ≥ 96% | DONG Energy<br>(2003-2005) |
| Kentish Flats | ≤ 95% |  | Vattenfall |
| Middelgrund | 98.5% | 96% | Middelgrunden.dk<br>(2002-2004) |
| North Hoyle |  | 84% *) | Dti.gov.uk<br>Annual Report 2004 |
| Scroby Sands |  | 84.2 % *) | Dti.gov.uk<br>Annual Report 2005 |

*) Initial operation

**Table 6: Information on availability of some wind farm projects**

The electrical faults account for a marginal part of the unavailability. However, no detailed information is available, which can quantify the failures discussed in the qualitative review in section 3.2.

The review in section 3.2 clearly indicates that failure rates for electronics and converter equipment must be reviewed.

**Grid connection and grid faults**

In general, only a limited amount of statistical information is available in relation to the faults in the internal power system as described above in section 3.

As mentioned in section 3.4, cable failures seem to be less frequent that expected according to theory (see section 4.4 below) and experience in other sectors (e.g. transmission systems).

As mentioned in section 3.8 grid faults cannot be quantified. However, experience does not indicate any significant contribution to the unavailability.

### 4.2.2 Other sources

It is possible to find a number of studies where information on land based installations is transposed to offshore installation. The two different installation types are not equivalent even if some correlations can be found to some extent.

Relevant studies on the topic have been performed by the DOWEC project [3], the Energy research Centre of the Netherlands [4], ISET [5] and reference [6]. ISET has collected data on on-land wind turbine failures from 1989 in the programme ‘250 MW Wind’. Data on failures distinguish between causes of failures, relevant components and operational age issues. These data may be used as a database for deducting reliability figures for components in offshore installations.

In [3] and [6], future evolutions and necessary improvements in relation to offshore installations are considered, and some figures for wind farm component availability are obtained.

Reference [6] lists some of the aspects affecting component failure rates and repair time in offshore environment like:

- impact of marine environment on failure rate (humidity and salt fog, water intrusion and wave impact, marine traffic, moving sea bottom, icebergs, etc) with the necessity of verifying electrical components in accordance with marine standard test procedures;

- impact of electrical environment on failure rate (lightning-induced failures and overvoltages, transient overvoltages caused by switching surge actions);

- impact on repair time (increased time consumption in connection with inspection access, transport, type of transport and weather conditions).

## 4.3 Repair times in offshore environments

Furthermore, evaluation of MTTR depends on the position of the component: submarine component, eg cables, have a large variation in MTTR (from 10 days in summer up to three months in winter), whereas other components, eg breakers, may be repaired between 4 (summer) and 10 days (winter).

Based on these considerations, average values may be utilised for reliability analysis.

## 4.4 Available data

Regarding offshore wind turbine availability, a more detailed analysis has been performed by the DOWEC project. Data on failures have been collected from on-land installation databases, and based on these data the following list of main components has been prepared:

- shaft and bearings
- brake
- generator
- parking brake
- electric
- blade
- yaw system
- blade tips
- pitch mechanism
- gearbox
- inverter
- control

The DOWEC project gives an indication of individual failure rates and a total failure rate of 2.20 to 2.31 failures per year. Then the components, which may be improved in offshore installations with an increase of price, have been listed (eg it is assumed in [9] that generators will reduce their failure rate by 50% due to enhanced cooling and greasing systems. Similarly improvements are given for other components) and new failure rates have been assessed. Six different wind turbine concepts have been defined in [7] and based on the assumed failure rates, values of 0.99 to 1.55 failures per year have been detected.

Based on [7], two other reports ([10-11]) analyse repair time issues and failure rates. In relation to these, various configurations (improvements of deployment of crew and equipment, reduction of failure rate and redundancy, fault tolerant operation, improvement of accessibility) have been analysed in order to obtain the best compromise between costs and failure/repair issues. Depending on the chosen policy, the average downtime per turbine per year varies from 220 to1095h/y according to the assumed configuration [11].

As an example from the references, some of the proposed data are shown in Table 7.

These figures are anyway just indicative, and various assumptions can provide different results.

| | | **Failure rate** | **MTTR** |
|---|---|---|---|
| **Wind Turbine** | | 0.99-1.55 1/y | 220-1095h |
| Cables | Internal Grid | 0.015 1/(y × km) | 1440h |
| | Tower cable | 0.015 1/(y × km) | 240h |
| | Connector to shore | 0.0094-0.015 1/(y × km) | 1440h |
| Equipment | Platform breaker | 0.025 1/y | 72h |
| | MV breaker | 0.025 1/y | 240h |
| | MW switch | 0.025 1/y | 240h |
| | LV contactor | 0.0667 1/y | 240h |
| | Nacelle transformer | 0.0131 1/y | 240h |

**Table 7:** Figures for reliability issues in relation to various wind farm components

# 5. Conclusions

The influence of large offshore wind farms in power system operation and planning has assumed higher relevance in the past years. This survey has analysed the various aspects of relevance for offshore wind farms.

In relation the overall power system reliability, the conclusion of this survey is that the main focus is put on system security, eg concentrating on solving the stability issues. The possibilities of contributing to power system adequacy are still debatable, and the possible solutions to improving the reliability must be investigated.

As for the present state of offshore installations, the survey analyses in detail the main characteristics of the components (eg wind turbines, internal distribution grid, connectors to shore, protections) from the reliability point of view. Based on the provided considerations, it can be concluded that experience derived from the first offshore wind farms show a need for an increased focus on design, procurement, quality, risk assessments and quality assurance. Also new standards or practices for risk assessments and quality assurance of offshore wind farm installations are required, and existing IEC standards may not be sufficient.

Specific attention must be drawn to wind turbine generators and transformers as well as to the power electronics and other electronic equipment in the wind turbines.

Experience derived from the wind-farm grid infrastructure indicates that the common practice of employing the simplest radial system is the best solution.

Furthermore, quantification of reliability parameters is still uncertain due to the few installations and the short operational experience.

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