Grid Connection and Remote Control for the Horns Rev 150 MW Offshore Wind Farm in Denmark

Peter Christiansen, Senior Eng., B.Sc., Elec.Eng.[1], Knud K. Jørgensen, Senior Eng., M.Sc., Elec.Eng.[1]
and Aksel Gruelund Sørensen, M.Sc., Elec. Eng.[2]
[1] Tech-wise A/S, Kraftværksvej 53, DK-7000 Fredericia.
E-mail: pc@techwise.dk and kkj@techwise.dk, Phone: +45 7923 3333, Fax: +45 7556 4477
[2] Eltra, Fjordvej 1-11, DK-7000 Fredericia.
E-mail: aks@eltra.dk, Phone: 7622 4000, Fax: +45 7924 5180

ABSTRACT

The paper shortly presents the background of the Danish 750 MW offshore wind power demonstration programme and the programme itself. The prospects are concentrations of up to 1800 MW of wind power in a geographically confined area besides 1500 MW of on-shore turbines and other future offshore wind farms. This raises the need for new requirements to the wind turbines, as this form of renewable energy changes status from a marginal producer with no or little impact on the overall electricity network, to a major contributor in the electricity supply system. The paper presents the grid connection scheme for the first wind farm in the programme and describes the specifications for connection of wind farms to the transmission network drawn up by the two companies responsible for the Danish transmission network (the Transmission System Operators – TSOs). The paper finally touches on the subjects of remote monitoring, control and communication, as these issues will be of considerable importance in offshore wind farms where the access conditions are considerably more difficult than for the on-shore wind farms known today.

KEYWORDS

Offshore, Grid Connection, Power Control, Reactive Power Control, Harmonics, Stability, Dynamic Stability, Monitoring, Communication, Remote Control.

INTRODUCTION

Since the start of the modern development of wind turbines for electricity production, offshore siting of wind farms has held the promise of vastly increasing the viable wind resources without the obvious disadvantages of large-scale on-shore wind farms with regard to visual impact and noise. The energy plan of the Danish Government “Energy 21” calls for an installed wind power capacity of 5500 MW by 2030 - 4000 MW offshore and the rest on-shore. As the density of wind turbines in the on-shore areas has almost reached the limit and almost 2500 MW on-shore turbines were installed by the end of 2000, utilisation of the offshore resources is the only way to fulfil the goals set up in “Energy 21". A feasibility study finished in 1995 and followed by an “Offshore Wind Farm Plan of Action” in 1997 has identified sites for up to 8000 MW of offshore wind farms in the Danish coastal waters. The feasibility study concluded that the wind energy technology and wind turbine size have matured to a point where large scale offshore demonstration wind farms are a technical and economic possibility. On this background, the utility groups Elsam/Eltra and Elkraft, serving the western and eastern parts of Denmark respectively, were asked by the Government in early 1998 to construct five offshore wind farms - each with a rated power of 150 MW - in the period from 2002 to 2008 and to operate them for a 20-year period.

According to the present plans, the first five offshore wind farms, the potential installed capacity (in water depths below 10 m) at the sites and the commissioning year for the first 150 MW sections are (Figure 1):

Name	Year	Potential
Horns Rev	2002	700 MW
Rødsand	2003	600 MW
Læsø	2004	1800 MW
Gedser Rev	2005	200 MW
Omø Stålgrunde	2008	300 MW

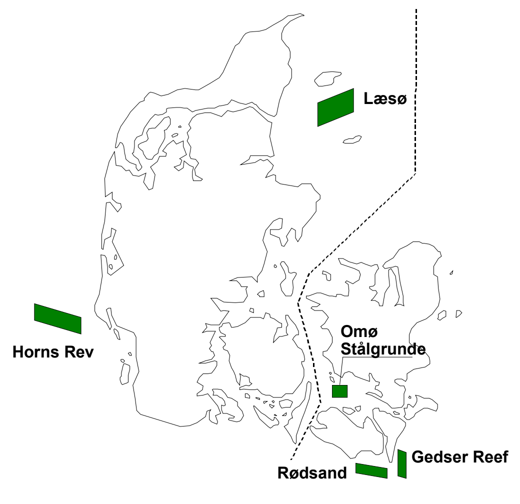

Figure 1. Major offshore wind farm sites in Denmark

The paper concentrates on the Horns Rev Wind Farm to be built by the power producer Elsam A/S. It outlines the electrical requirements as laid down by Eltra - the TSO in the western part of Denmark - in the “Specifications for Connecting Wind Farms to the Transmission Grid”, the grid connection and the communication system to be installed. It finally touches on the subject on advanced machine condition monitoring.

THE WIND TURBINES

The wind turbines for Horns Rev Wind farm were chosen after competitive bidding according to EU-rules among five pre-qualified wind turbine manufacturers. The successful manufacturer was Vestas Scandinavian Wind Technology A/S and the wind turbine is the new V80 / 2MW with opti-speed technology, i.e. a variable speed (9 to 20.7 rpm) pitch controlled turbine with a wound rotor induction generator and power electronics in the rotor circuit. The 80 turbines has a rated power of 2 MW each and the total rated power of the wind farmn is thus 160 MW. The turbines will be placed on monopile foundations driven 22 m into the sandy bottom of the reef and have a hub height of 70 m above MSL (Mean Sea Level).

GRID CONNECTION

During the initial investigations a number of different schemes for connecting the wind farm to the grid were investigated. The technical solutions ranged from 400 kV over 150 kV for multiple wind farms and HVDC (based on voltage source converters) to one 150 kV cable for the first wind farm alone. The solution finally chosen was one 150 kV cable but with space reserved on the offshore transformer station for an additional 150 kV circuit breaker intended for a cross connection to a possible future second section with its own 150 kV cable. The distance to the shore is 18 km and the principal layout is shown in the single line diagram in Figure 2.

The geometry of the wind farm is simple, 10 rows with 8 turbines each in an almost rectangular pattern with 560 m between the turbines and one radial connection to the transformer station for every other row. The cables in the wind farm are 400, 150 or 95 mm^2 (depending on load) XLPE-Cu, operated at 34 kV nominal voltage. To be able to separate a faulty row, the first turbine in each of the 5 rows, where the cables to the transformer station are terminated, is equipped with motor operated disconnectors which can be operated from land.
The transformer station is a three-legged steel structure with all the necessary equipment, including an emergency diesel generator. The weather in the North Sea is very rough, and it is likely that the electricity

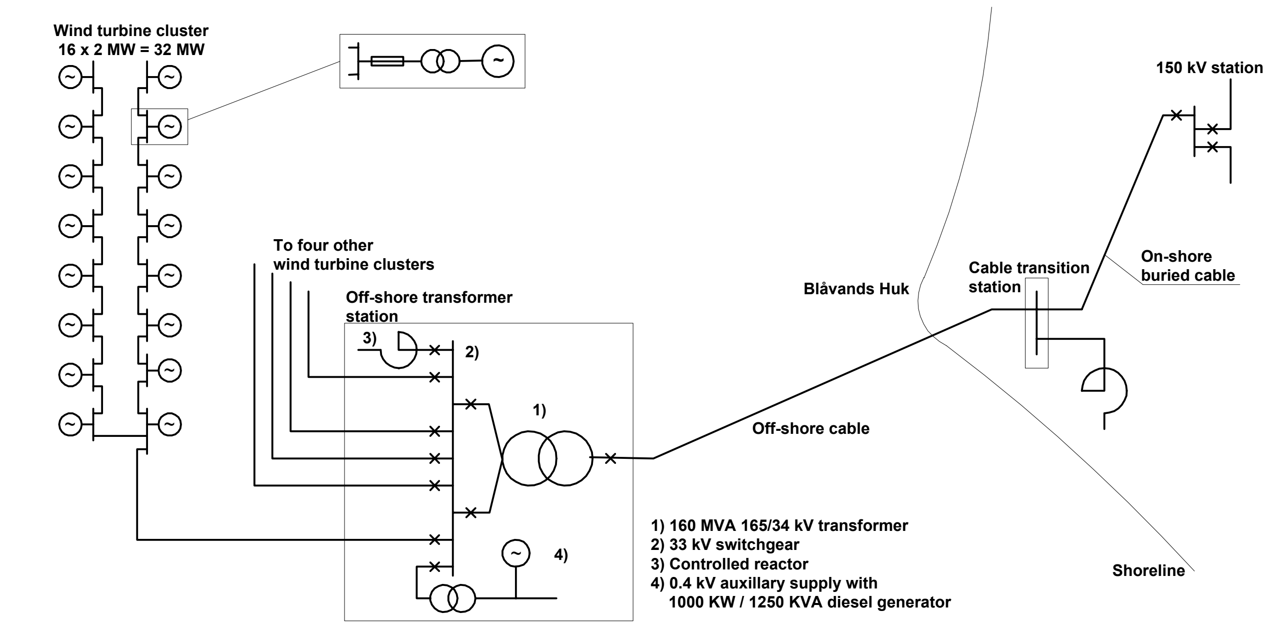

Figure 2. Horns Rev single-line diagram

supply to the wind farm can be cut for prolonged periods at a time in case of cable faults. The diesel generator cannot supply the station and the wind turbines with enough power to keep all essential equipment (climate conditioning, control and safety systems, yawing system etc.) operating during such periods. However when wind is available, one or more of the turbines can be operated together with the diesel generator as a wind-diesel system supplying the needed power. To reduce the generator size there is further a controllable reactor to balance the capacitive production of the 34 kV cables in the wind farm.

The submarine cable to shore – 21 km long – is a three-conductor 630 mm^2 cable with copper conductors and dry extruded insulation (XLPE). The outer diameter is 190 mm and it weighs 70 kg per/m. The onshore cable – length 34 km – consists of three single-conductor XLPE-Al cables with a cross section of 1200 mm^2 each installed in a close trefoil formation. The total length of the cable connection is 55 km.

The normal operating voltage is 165 to 169 kV. The capacitive generation in the cable is considerable, and a reactor of 80 Mvar will be installed in the connection point between the submarine cable and the onshore cable. In addition to this connectable reactive power will be installed in the transmission grid.

SPECIFICATIONS FOR CONNECTING WIND FARMS TO THE TRANSMISSION NETWORK

The conditions for connecting wind farms to the transmission grid, elaborated by the transmission system operator - Eltra - differ in significant respects from the conditions used up to now for connection to the medium-voltage distribution grid in Denmark. The possibility of a concentration of wind energy of up to 1800 MW in a geographically limited area has a severe impact on the transmission grid, and the marginal considerations applied up to now are consequently being replaced by more rigorous requirements. The specifications deal with the technical requirements to the wind farm such as power and power control, frequency, voltage including reactive power compensation and stability during faults in the transmission system. The requirements are described in the following in a degree of detail in respect of their novelty to the wind turbine manufacturers, operators and utilities.

Power and Power Control

According to the specifications the wind farm must be able to participate in control tasks on an equal level with conventional power plants, constrained only by the limitations imposed at any time by the existing wind conditions. The requirements can be summarised as follows.

During periods with reduced transmission capacity in the grid, e.g. due to service on lines and or components in the transmission grid the wind farm must be able to operate at reduced power levels with all turbines running. The production – measured as a 1-min average values – must not exceed the power setpoint or the rated power, whichever applies, of the wind farm with more than 5% of the rated power of the wind farm.

The wind farm must, if necessary, be able to participate in the area balance control (secondary control). In this mode the power setpoint will be generated by the transmission system control and sent to the wind farm through the SCADA-system (Supervisory Control And Data Acquisition system) on a regular basis. The updating interval to the wind turbines will be in the order of 1 s.

Large and fast variations in the power production can be caused by passing weather fronts and thunderstorms. While there are no counter-measures against sudden drops in the wind speed, the wind farm must be able to impose a positive dP/dt (rate of change of power) limitation in such situations. The rate setpoint can be set through the SCADA-system to the wind farm main controller, which will update the power setpoint to the turbines approximately once a second.

The frequency control (or primary control) affects the whole of the UCTE grid and is carried out on a proportional basis by the UCTE participants. Large and fast frequency deviations may occur if smaller areas are isolated from the grid, and in such situations the wind farms must be able to participate in frequency control. This control mode should be implemented directly in the wind turbines with adjustable droop, deadband and offset for both control directions. The control speed required is high. The maximum power rate of change should correspond to a reduction in production from 100% of rated power to below 20% in 5 s under the worst operating conditions.

Frequencies

The requirements to the wind farm regarding operation at frequencies deviating from the rated (50 Hz) are as follows:

Underfrequency:	Below 47.0 Hz:	Disconnection compulsory after 0.3 s
	Below 47.5 Hz:	Disconnection allowed after 10 s
	Between 47.5 and 48.0 Hz:	At least 5 min. operating time required.
	Between 48.0 and 49.0 Hz:	At least 25 min. operating time required.
	Between 49.0 and 50.0 Hz:	Unlimited operating time required.
Overfrequencies:	Between 50.0 and 50.3 Hz:	Unlimited operating time required.
	Between 50.3 and 51.0 Hz:	At least 1 minute’s operating time required
	Above 53.0 Hz:	Disconnection compulsory after 0.3 s

Voltages and Reactive Power Control

The specifications mention the operating range of voltage at the land-based 150 kV station during normal operation. It is worth mentioning that for some periods the area is subjected to severe salt storms and the grid is operated at voltages down to 122 kV in such situations (the normal operating voltage is 165-169 kV). The adjustment range of the automatic tap changer on the transformer on the offshore station is thus 122-170 kV.

The basic requirement to reactive power compensation is that the wind farm is reactive power neutral at the 34 kV terminals of the offshore transformer with a tolerance of ± 10% of the rated active power of the wind farm, i.e. ± 16 Mvar. The wind turbines can both produce and absorb significant amounts of reactive power. The reactive power is continuously adjustable, and apart from being reactive power neutral on the 34 kV side the wind farm will be able to perform voltage control on the 165 kV side of the transformer and constant production or absorption on the 34 kV side.

The assessment of the wind farm’s impact on the voltage quality is further based on requirements to rapid voltage changes, flicker, telephone interference, harmonics and interference to telecommunucations.

Stability

The stability requirement is new to wind farms. Up to now an accepted method of coping with short interruptions in the voltage has been to shut down the wind turbines immediately and restart them when the voltage has returned to normal after a period of time - the methods have, however, varied. The new requirement is that the wind farm must be able to withstand a three-phase fault in the grid without attempting to reclose and a two phase fault with an unsuccessfull attempt to reclose.

To illustrate the first case a wind farm consisting of 6 x 2 MW pitch controlled machines – based on the old Tjæreborg Wind Turbine - has been modelled in DigSILENT, a modern power system stability and load flow computational tool, and two cases simulated. The single line diagram of the model system is seen in figure 3, and the results in figures 4 through 7.

In Figure 3 the point of common coupling is station S1/B1 and a three-phase short circuit is simulated on one of the two parallel lines leading to the next station in the grid (stationS2/B1). The wind turbines are fixed speed pitch control machines, and the power controller remains in operation during the whole simulation. All figures refer to the turbine at the farthest end of the radial connecting them.

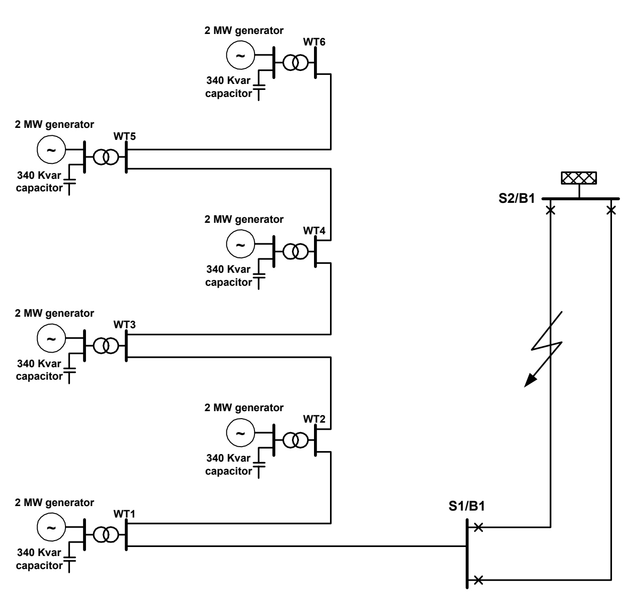

Figure 3. Model wind farm for stability analysis

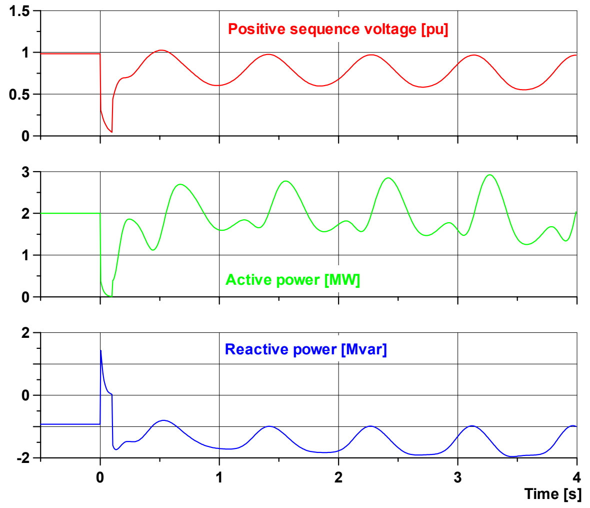

Figure 4. Voltage, active and reactive power without acceleration limiter

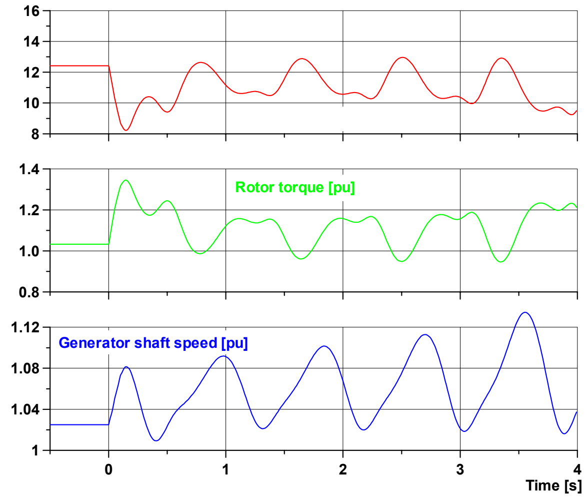

Figure 5. Pitch angle, rotor torque and generator speed without acceleration limiter

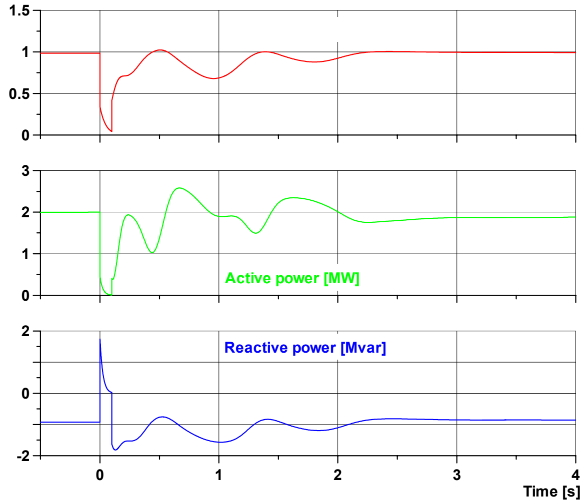

Figure 6. Voltage, active and reactive power with acceleration limiter

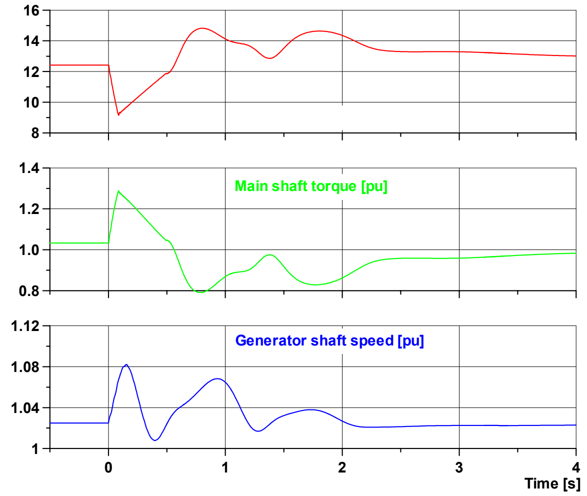

Figure 7. Pitch angle, rotor torque and generator speed with acceleration limiter

Immediately after the fault (at 0 s) the voltage at wind turbine drops to a very low value (0.3 pu) and remains below this value until the fault is cleared after 0.1 s. The voltage, active and reactive power are seen in Figure 4. In the period with no voltage, the electrical power is also close to zero and the power controller tries to counteract this by turning the blades towards 0 degrees (Figure 5). When the voltage returns the driving torque is so high that the drive train goes into an uncontrolled oscillation and overspeeds as shown in the bottom curve in figure 5. The system is unstable.

With a slightly modified turbine, where the control system is enhanced with an acceleration limiter turning the blades with maximum speed towards positive angles when a rotor acceleration above a set limit is detected, the same short circuit is simulated again. When the sign of the acceleration changes to negative, the power controller is engaged again. The results are seen in Figures 6 and 7. Note the rapid change in pitch angle from 9 to 12 degrees after the acceleration limiter cuts in at around 0.08 s (Figure 7). As can be seen in figure 15 the overspeed is limited to 8 % and the situation stabilises after 2 to 3 s. The wind turbine is dynamically stable during this fault.

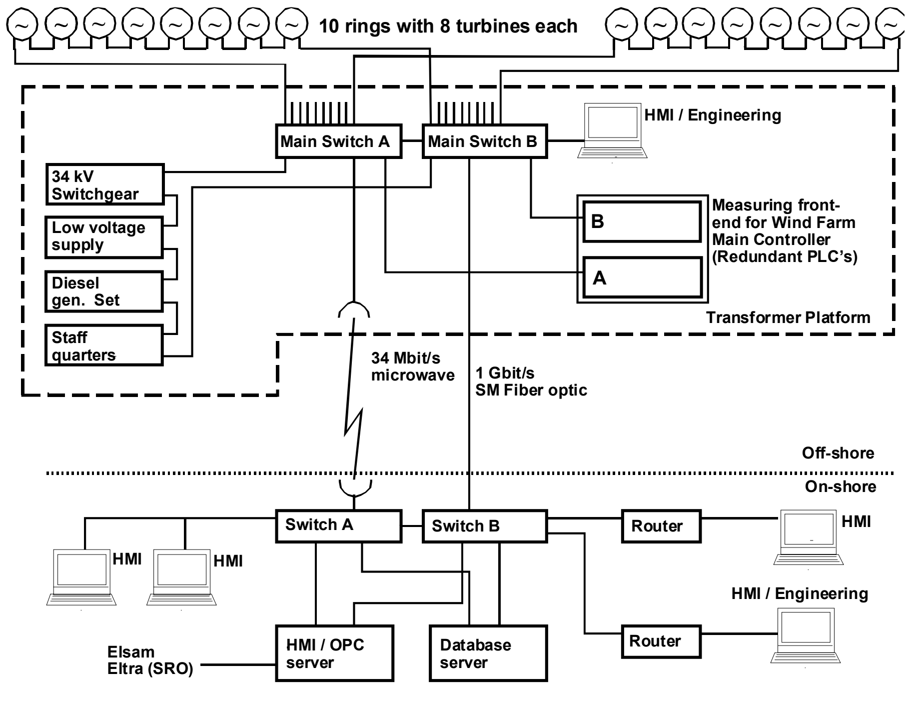

Figure 8. SCADA communication scheme

If the period with low voltage prevails for 2 to 10 s further measures may be applied. A continued fast reduction of the power input to the rotor combined with an increase in the reactive production. This intervention should take place in a few seconds. If the voltage is below 70% after 10 s, the wind farm must disconnect. Similar simulations can be carried out for other types of faults and generators and at different distances from the wind farm.

The manufacturer of the wind turbines is required to supply models, with sufficient details to perform such simulations during the tender evaluation and later, models based on measurements for the wind farm's final stability assessment. One of the wind turbines in the wind farm and the transformer station will be equipped with fast fault recorders to monitor the actual performance of the wind farm and turbines during real faults.

COMMUNICATION AND MONITORING

The costs of operating and maintaining wind farms of this scale are a major contributor to the total energy cost. Over the technical lifetime of an offshore wind farm, the total O&M costs are expected to equal or exceed the initial investment in the wind turbines themselves, and a Supervisory Control And Data Collection System (SCADA-system) that can contribute to minimise the O&M costs is imperative. In the following the the monitoring and communication system are addressed.

Monitoring

The wind farm at Horns Rev presents a new set of problems not previously encountered – particularly the access problem due to weather conditions. For long periods of the year access by boat will be impossible, and to mitigate this the wind turbines will be equipped with a platform on top of the nacelle for helicopter hoisting operations. This is intented to be the prime way of access for service visits throughout the year. Only operations requiring lifting and transporting of heavy components will be seaborne. The costs associated with visits make it necessary to be able to recognise and diagnose faulty components in advance in order to bring the required spare parts along at the first possible visit.

The techniques used for monitoring of the turbines are the same as those applied to other types of technical equipment where conditioned-based maintenance is applied. Routine possibilities in the regular control system is statistics on e.g. operating speeds, actuation times, wear, pump operating times, number of actuations and power demand to name a few of them. With a wind farm consisting of 80 identical wind turbines the possibilities of pin-pointing deviations at an early stage in the development of a fault are indeed present. Regular and unscheduled service and maintenance will be administrated by the central maintenance management system of Elsam - MP5 - which has access to the database on operations in the SCADA system. Each turbine will produce around 1 Gbyte of data per year.

The recent focus on gearbox bearings, gears (tooth mesh quality) and generator bearings highlights the need for advanced systems for monitoring of bearings and tooth mesh quality. Recent developments in sensor technology, such as the micro-machined accelerometer for automotive use, have made advanced vibration monitoring devices using advanced signal processing techniques - combined with trend monitoring of selected parameters - possible at reasonable prices. Dedicated commercial systems are available today from independent vendors making this type of monitoring a must in the large offshore wind turbines.

Data logging capabilities and the use of cyclic buffers collecting fast sampled data on many channels for post event analysis of faults will facilitate analysis of faults and events prior to sending service personel to the turbines.

Communication

Speed, reliability, reasonable costs and the possibility of fulfilling future, not yet known reguirements, point towards a fibre-based intranet solution based on the TCP/IP protocol, a protocol which is gaining increasing importance in industrial control and monitoring environments. The configuration of the communication and SCADA system is shown in Figure 8. The system configuration selected is based on the requirement that all functions common to more than one wind turbine should be redundant, whereas functions touching one wind turbine only need not be. The system is based on a 100 MB network with optic fibres in the cables. The stretch from the transformer station to the first on-shore routers is redundant (a 1 Gb fibre link and 34 a Mb radio link) as are the switches on the transformer station. The system in the wind farm itself is configured as 10 rings with 8 wind turbines in each ring. The switches in each turbine has routing capability and the system will detect a fault and recover in less than a minute after a fault occurs. The optic fibres will be integrated with the medium voltage cables and the fibres will be patched in the bottom of each turbine (Figure 9).

Each fibre ring is made up of two fibres operating in full duplex. The four fibres thus needed in each turbine is taken from the patchboard in the bottom of the tower to a switch in the nacelle where different devices, each with its own IP address, can be connected to the system. One device is of course the control system of the wind turbine. Each turbine will be equipped with a Thin Client able to access a documentation server from where all drawings, repair procedures and template reports can be uploaded, viewed and filled in. Others types of equipment could be dedicated measuring systems (load measurements), digital cameras, internet telephones for communication and many others.

The control functions outlined above will be realised as a “Wind Farm Main Controller” in one of the servers in the SCADA system based on data from the individual turbines and measured summed data from the transformer station. The signals to the wind turbines will be distributed from the WFMC to the individual turbines.

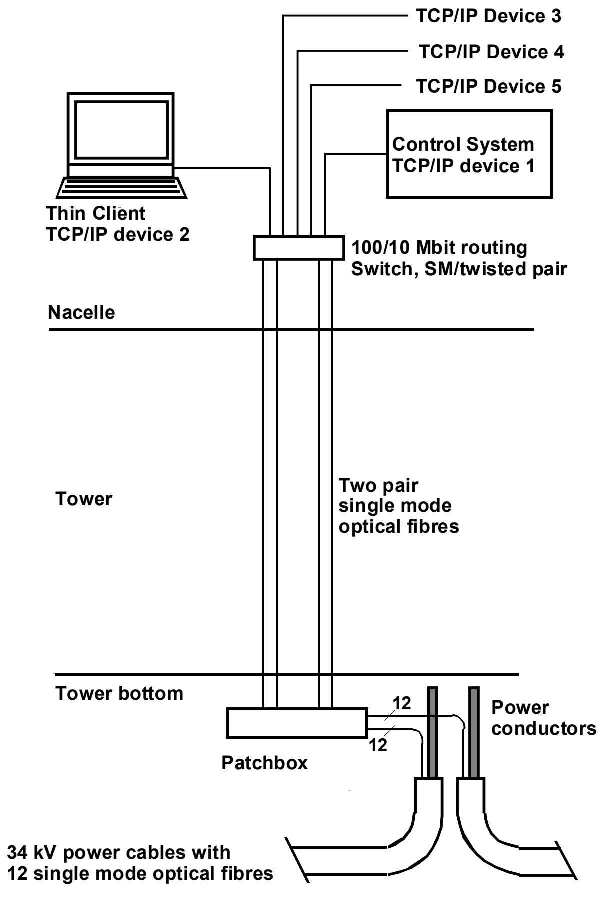

Figure 9. Communication scheme in wind turbines