Electrical Systems for Offshore Wind Farms

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Synopsis

Offshore wind farms are different from onshore wind farms in many respects and so the usual ways of thinking about the electrical aspects may not be appropriate. Clearly costs will be higher than on land. However, reliability and availability are also much more important, because faults may be more frequent and could take much longer to locate and repair. Unlike onshore public transmission and distribution networks, the relatively low capacity factors are likely to make full redundancy uneconomic. The restricted space and high cost of support structures offshore conflict with the need for additional switchgear to isolate faulty equipment. Within the offshore wind farm, the regular array may produce electrical system configurations different from the radial system typical of onshore wind farms. The wind farm monitoring or SCADA system also needs to be reconsidered.

1. INTRODUCTION

The purpose of this paper is to review the requirements and options for wind farm electrical systems offshore. Control and SCADA systems are also addressed. The principal differences offshore are:

- larger arrays of larger machines;
- longer times to repair faults;
- less frequent scheduled maintenance;
- further to network connection points;
- more aggressive environment;
- less space available for equipment;
- possibly a regular array with more freedom to choose cable routes.

2. ELECTRICAL SYSTEM WITHIN THE ARRAY

It is useful to treat the electrical system within the array separately from the connection to shore.

2.1 Voltage levels

Onshore practice is to step up the generator voltage directly to the voltage of the network point, if possible, via a dedicated turbine transformer. Presently the highest voltage used to interconnect the turbines is in the region of 33 kV, i.e. within the range conventionally defined as Medium Voltage (MV). It appears likely that this limit will also apply within offshore arrays, because switchgear and transformer cost and size increase rapidly above this level. Alternatively, turbines could generate directly at MV, but no turbine manufacturer has yet shown serious interest in this possibility. The argument often quoted against MV generation is that MV switchgear would be required, which is otherwise unnecessary onshore. However, MV switchgear is necessary offshore for other reasons, so this argument is less valid.

2.2 Cable damage

Submarine cables can fail in service. Depending on the location, the consequences could be severe: to obtain a suitable repair vessel and wait for suitable weather could take several months in winter. Cable failure data are presented in (1). Data for many different types of cable are listed, but it is difficult to extract conclusions specifically relevant to this application. A global figure of 0.32 failures per year per 100 km is given. As the data in (1) are now relatively old (1950-1980), it is likely that this figure is now an overestimate.

The other important conclusion from (1) is that 53% of all failures in service are due to ships' anchors and fishing gear. Depending on the seabed conditions and the likely shipping traffic, burial of the cable can give a high level of protection.

However, for interconnections within offshore arrays, it seems clear that an alternative approach to cable failure should be adopted. The distances between turbines will be a few hundred metres, say 1 km maximum. It will be obvious to shipping that care is required, and depending on national legislation it may be possible to prevent shipping entering the array. Burial is therefore not justified, and in the event of a failure the cable is abandoned and a new section laid. Unless the turbine spacing is very irregular, a spare cable of the correct length can be kept at the shore depot. The replacement section can be laid from a barge, removing the need for special vessels. The same applies to initial installation.

2.3 Configuration

In onshore wind farms, the electrical system configuration is usually decided by the turbine and substation positions, and the site track routes. Offshore, there is more freedom, and at first sight it is not clear how to choose from the wide range of possible options. Every situation will be different, but a logical approach to the problem is as follows:

2.3.1 No redundancy

Assuming no redundancy in the electrical system is required, it becomes clear that a 'radial' arrangement is best (Figure 1). The maximum number of turbines on each radial feeder is determined by the maximum rating of the cable (for example, 20 turbines of 1.5 MW) but, if the array dimensions allow, several shorter feeders with the same total length will result in reduced electrical losses, and less lost production in the event of cable failure.

In an irregular array a 'tree' structure may be justified at some points to reduce total cable length, but there is a limit on the number of cables that can be brought in to a single turbine support structure.

The radial feeders are brought to 'connection points' on the side of the array closest to the cable landfall. The number of turbines connected to each point is determined by the capacity of the connections to shore: see Section 3.

2.3.2 Redundancy within the array

Figure 2 shows an obvious possible addition to the radial arrangement. This provides redundancy in the event of a failure at some point on a radial feeder. Probabilistic analysis techniques were used to establish the value of this link, in terms of lost production avoided. The technique developed allows all relevant parameters to be adjusted, but the results presented here are based on the following:

- cable failure rates of 0.32 and 0.1 faults per year per 100 km;
- turbine separation of 500 m;
- cable faults occurring in April to September are repaired instantly;
- cable faults occurring in October to March are repaired in April;
- twenty 1.5 MW turbines arranged as in Figure 2;
- winter wind speed distribution derived from 10 coastal sites in the European Wind Atlas;
- cable rating of 235A.

The lost production saved over a 20 year period is presented in Table 1. Clearly in this case the additional production (equivalent in the most favourable case to only 0.026% of ideal production) will not justify the additional capital cost of providing redundancy. However under other assumptions and configurations the answer could be different. It is believed that analyses such as this will become standard practice for offshore design.

Clearly for each site there will be a further stage of analysis, to determine optimum cable size or sizes to reduce electrical losses to the economic optimum. In principle this is no different to the onshore case.

2.4 Switchgear and protection

Devices are required to isolate faulty equipment while leaving as much of the healthy equipment connected as possible. However, switchgear is expensive and bulky. A sensible starting point is shown in Figure 3. The circuit breakers protect against faults in the transformer and in the cable to the next turbine, and can be operated from the shore via the SCADA system. There will also be manually operated equipment to isolate and earth the cables and transformer as necessary. Gas-insulated switchgear (GIS) is suitable for this application, and is available from several manufacturers with demonstrated performance on offshore installations.

If liquid-filled transformers are to be used (see Section 5), then there may be some benefit in providing in-tank fuses to protect the transformer, as on land-based wind farms. However it is likely that if the fuses fail the transformer should be replaced, as opening the tank to replace fuses offshore is likely to cause further problems.

For relatively short feeders it may be adequate to provide only one circuit breaker in the turbine at the “shore” end of each feeder.

2.5 Electrical system design

GH have analysed representative offshore wind farms using a power-systems analysis package. Although there are differences from onshore wind farms, conventional design approaches are suitable, and adequate control of voltage and reactive power is achievable.

Achieving a satisfactory earth system will be easier than onshore. In addition, there is no need to limit step and touch potentials around the foundation.

3. CONNECTION TO SHORE

The optimum arrangement for transmission of the array output to shore is highly project specific. All existing offshore wind farms are connected to shore at the voltage used within the wind farm (generally 10 kV). The proposed large wind farms in the ELKRAFT area, each 100 x 1.5 MW, are planned to connect to shore at 132 kV, the voltage of the onshore network (3). Larger arrays further offshore could use higher voltages. It is possible to produce useful general conclusions by defining two cases: with offshore substations, and without.

3.1 No offshore substation

The offshore array is split into several sub-arrays such as in Figure 1, each connected to shore by its own MV cable. The size of each sub-array is determined primarily by the rating of the largest feasible MV submarine cable, typically 30 MW to 35 MW. There is no additional equipment offshore: each shore cable is protected by switchgear at the shore end. For all but small arrays, there will be a transformer station onshore to step up to the network voltage.

3.2 Offshore substations

Offshore substations require a support structure, transformer, and switchgear. Other studies have assumed that the equipment can be fitted within a turbine support structure, but this is unlikely (5). The cost, in very approximate terms, will be similar to a complete offshore turbine (depending on whether the need for transformers onshore is removed). They will present installation difficulties. Previous studies assumed they would serve a useful purpose as stores and workshops, but this now seems unlikely. There will be technical challenges in designing and maintaining high-voltage equipment offshore: the offshore oil and gas industry experience stops at 13.8 kV. However, for large arrays long distances offshore, the use of higher voltages will undoubtedly be justified by reduced cable cost and losses.

Each substation will have several sub-arrays connected to it. Almost certainly each substation will have a separate connection to shore. The voltage of the connection to shore may well be determined by the voltage at the network connection point. Beyond this, no general conclusions can be drawn.

Options for locating substations on the seabed have been considered, based on developments in subsea oil and gas production. However the power and voltage levels will be much higher, and major technical development will be required. Damage from shipping is also a danger.

The substations could also hold converter stations to allow DC connection to shore. This option is currently too expensive except for large wind farms several tens of kilometres out. Costs and performance will undoubtedly improve.

3.3 Value of redundancy

Failure of a cable to shore is a significant risk. In most cases, these cables will be buried. A network design tool has been developed which determines the best locations to provide redundancy via additional cable links, and calculates the value.

Consider Figure 4, a wind farm of three sub-arrays as in Figure 1. Redundancy is provided by two short links. The figure shows MV connections to shore, but exactly the same calculations apply if three high-voltage connections with offshore substations were provided instead. In the event of failure of one shore connection, the additional links allow the system to be reconfigured. Note that the capacity of the links is no greater than the other cables in the system.

For the following inputs:

- 0.1 cable failures/year/100 km;
- 10 km to shore;
- 3 months to repair a cable failure;
- sub-arrays of 20 x 1.5 MW turbines;
- value of energy 5p/kWh;
- 20-year analysis period;

the design tool calculates the value of the links, in avoided lost production, to be £363,000 (7 m/s annual mean) or £570,000 (10 m/s annual mean). This is certainly more than the additional capital costs, so the links are justified. It is clear that redundancy of this type is much better value than providing an additional connection to shore.

The design tool identified the optimum location for the additional links, as shown in Figure 4. When presented with constraints, such as a maximum of three cables entering each turbine, alternative solutions are selected (which in this case reduced the savings due to the links by approximately 25%).

4. SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA)

4.1 Communications medium

The SCADA system for wind farm monitoring and control will require a communications network between the wind turbines in the wind farm, and back to the shore. Candidate media for this are:

- Copper twisted pair (RS485)
- Fibre Optic - multi mode
- Fibre Optic - single mode
- Radio telemetry

Copper twisted pair (RS485)

Twisted pair copper cable using RS485 drivers is the conventional medium for communications. Equipment and cable is cheap, robust and readily available. Installation is straightforward and requires no special tools. Pairs can be provided within submarine power cables.
The RS-485 specification states a maximum distance of 1200m at 4Mbits/s. In practice the distance achievable depends on the data rate and many manufacturers of drivers quote distances of 2500m at rates of 9600 b/s.

The disadvantages of copper connections is that there is no inherent isolation between the machines and that the drivers are susceptible to transient voltages.

Fibre Optic

Fibre optic cables offer high bandwidth communication over long distances. They also have the advantage of galvanic isolation and immunity to electrical noise. Two types of cable are available, single mode and multi mode. Single mode cable is slightly cheaper and has lower losses but requires laser based drivers. Multi mode fibre optic cable is slightly more expensive but can be used with cheaper, LED based drivers. Again, cores can be provided within submarine power cables.

The bandwidth and distance achievable with laser based drivers and single mode cable is greater than that with LED drivers and multi mode cable. The actual bandwidth achievable depends on the drivers used, more expensive drivers giving higher bandwidth. For single mode cable, data rates of up to 2 Gb/s are available over distances of up to 100 km. With multi mode cables, data rates of up to 100 Mb/s are achievable over distances of up to 6 km.

The disadvantages of fibre optic cable are that it is less robust than copper and that it needs special tooling for making connections.

Radio telemetry

Radio telemetry is attractive as it requires no interconnections. The unlicensed radio technology uses FM in the 400-500 MHz range (depending on local regulations) and works on line of sight. The distance achievable depends on the power of the transmitter, the data rate and whether directional aerials are used.

At a data rate of 9600 b/s, point to point distances of up to 1 km are achievable. At lower data rates of 1200 b/s distances of up to 10 km are achievable.

Licensed radios can be operated at higher powers and distances of approximately 30 km could be achieved.

Radio communications can be affected by sea state and weather conditions.

4.2 Voice communications

Primary voice communications will be separate to the SCADA communications system as communications would be required between support vessels and maintenance crews, probably using maritime radio.

It may be possible to use the SCADA communications network for voice communications but it would not be a requirement.

4.3 Video

Broadcast quality colour video can be sent down a single fibre optic cable. Video cameras on selected turbines are attractive because they can allow a good estimate of the sea state to be made before despatching maintenance crews by boat. Cameras may also help to detect unauthorised vessels fishing, or anchored where they could damage submarine cables.

4.4 Communications topology

Due to the high cost of laying cables, it is sensible to use the same cable routes for SCADA communications as for the power distribution.

It is concluded that optical fibres within the power cables are the best option for the link to shore. Once this is decided, optical fibres are the sensible choice within the wind farm. The only exceptions are for arrays located close to shore and where video is not required, or if the desired communications route is different from the power cable route. In these cases, a radio link to shore could be considered. Communications between turbines could use optical fibre or copper.

4.5 SCADA system design

The SCADA system is conceptually separate to the machines and their controllers. Unless there is a regulatory requirement that requires the machines to stop if there was a loss of communications, the machines should be allowed to run independently of the SCADA system status.

Although the SCADA system needs to be reliable, there is no obvious benefit in making it any more reliable than the power distribution network, if it utilises communications cables within the power cables.

Conceptually the SCADA system is identical to the onshore case, but will be extended to allow control and monitoring of medium-voltage switchgear and transformers in each turbine.

5. TURBINE ELECTRICAL SYSTEMS

5.1 Regulations

The IEE Offshore Regulations (2) give a useful summary of applicable legislation for UK waters. Particularly important is the legislation implementing the Safety of Life at Sea (SOLAS) Convention 1974 (and 1978 Protocol). Other coastal states have similar legislation. Clearly the recommendations protecting against hazards from flammable gases are not relevant, but other recommendations in (2) provide useful guidance for design. For example:

- the control system must survive the operation of a hand-held marine radio inside the structure;
- cable terminations made on site should be separated from other terminations;
- guidance on selection of cable materials is included.

The Germanischer Lloyd offshore regulations (4) also provide some guidance, and are very similar to the regulations for onshore wind turbines. The requirements for earthing do not appear strictly relevant to offshore turbines.

5.2 Reliability

Reliability can be achieved in several ways. It is considered that the most effective route in this case is attention to design details, rather than duplication of major items, or a new design philosophy. It seems sensible to design for extended periods (several weeks or more in winter) without any power available. Therefore solutions relying on continuous heating or dehumidification are not satisfactory.

There is one area where a change of philosophy may be useful. There is more justification in offshore wind turbines for raising alarms (i.e. warning the operator of an unusual condition). This allows maintenance to be scheduled more effectively, and may permit the operator to take action (temporarily reduce rated power, for example) to allow the turbine to run without damage until the fault can be investigated.

5.3 Controller design

In the past, a large amount of machine down time for land based turbines has been attributed to control system faults and sensor faults.

Control systems consist of large numbers of small components from different suppliers and large numbers of interconnections. The reliability is only as good as the worst of these components and interconnections. There is no inherent reason why the control system should not be very reliable but it comes down to detailed design. External sensors such as anemometry in particular will see a much harsher environment and should be designed accordingly.

Indications are that the control systems of recent machines are much more reliable. In the first quarter of 1998, only 6.9 percent of reported turbine downtime in Germany was attributed to sensors and the control system.

Other possible solutions to improve reliability would be to introduce redundancy. Polling/voting systems are not really applicable as they are intended to increase confidence in signals for safety reasons. A sensor fault would still require a shutdown, and attendance by a maintenance crew.

However duplicate sensors could be considered. The controller could be manually switched from one sensor to another via the SCADA system if a fault was suspected. This is only justified if it is not possible to improve the sensor reliability in other ways.

For fail safe inputs, the controller could monitor both sensor signals automatically and assume that the input was in the fault condition only if both signals indicated this. If the inputs differed for more than a given time, it could be assumed that one of the sensors had failed.

5.4 Turbine battery banks

Battery banks are common in marine environments, but require special accommodation and regular maintenance. It is therefore worth considering whether they are necessary for this application. For controller memory and emergency lighting, conventional arrangements are satisfactory.

A few turbines on the edge of the array will require navigation lighting with battery capacity of a few days. In the event of electrical outages of more than a few days, the regulations appear to permit temporary light-buoys to be deployed. Provision for these must be made in costings.

In the event of a cable or transformer failure, it may be desirable to remotely operate switchgear within the turbines, via the SCADA system, to reconfigure the network to allow healthy turbines to operate. With careful design of the electrical system, it is possible to ensure in most circumstances that power is available to operate switchgear when required.

The conclusion is that careful attention to design can remove the need for battery banks, except for those few turbines where navigation lighting is required.

5.5 Transformers

The IEE offshore regulations (2) forbid oil-filled transformers, because of the risk of fire. Other liquid-filled transformers must have a bund to prevent discharges to sea. The GL rules (4) prefer dry-type transformers, but do not forbid oil-filled units. Offshore wind farms built to date have used both liquid and dry-type cast-resin transformers.

It is expected that cast-resin transformers will predominate in offshore wind farms. They are commonly used indoors on offshore platforms. Although the weight is similar, cast-resin transformers are typically narrower than liquid-filled, and so design for removal is simpler. No-load losses may be higher, but this is outweighed by the ease of integration into the tower. With careful design, ventilation through the tower wall may not be necessary.

5.6 Cable entry

The point where the submarine cables enter the structure needs careful design, because this can determine the cable rating. The solution adopted depends on the type of support structure, and the wave and ice loads.

6. CONCLUSIONS

There are several respects in which offshore electrical and control systems differ from onshore practice. Access difficulties are a major consideration: the harder access becomes, the more thought must be given to the design of the electrical and control system. Techniques are available to evaluate the benefits of providing redundancy within the electrical system. The optimum solutions will be site-specific.

ACKNOWLEDGEMENTS

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Table 1: Production saved over 20 years by redundancy within wind farm electrical system

Cable failure rate [failures per year per 100 km]	Annual mean wind speed (hub height, Rayleigh distribution) [m/s]			
	7	8	9	10
0.32	320 MWh	460 MWh	590 MWh	695 MWh
0.10	101 MWh	143 MWh	184 MWh	218 MWh

FIGURES

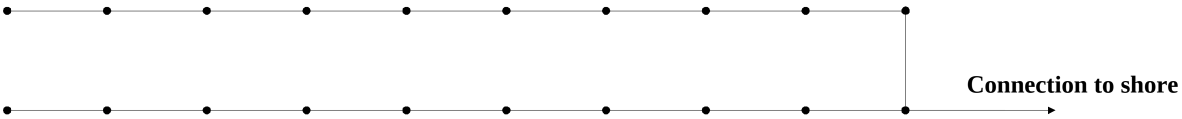

Figure 1: Radial cable arrangement (regular array, no redundancy)

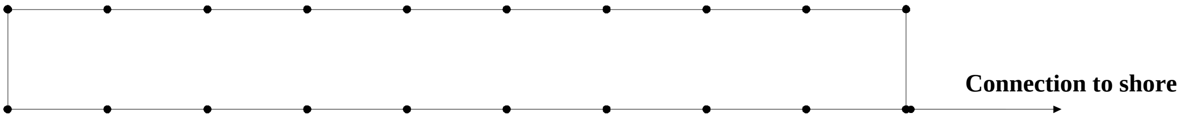

Figure 2: Radial cable arrangement (regular array, with redundancy)

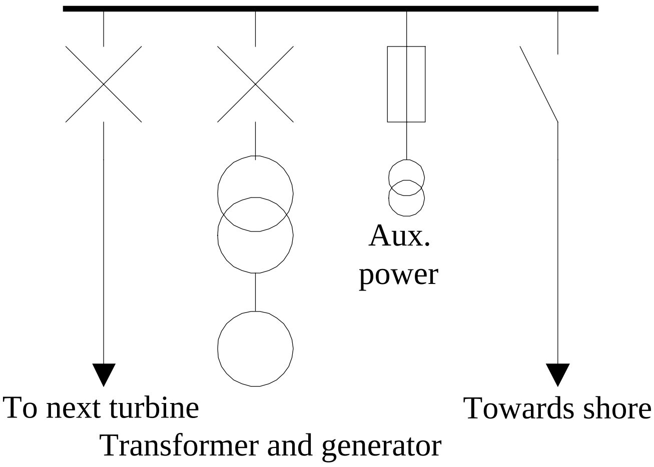

Figure 3: 'Comprehensive' switchgear arrangement in each turbine

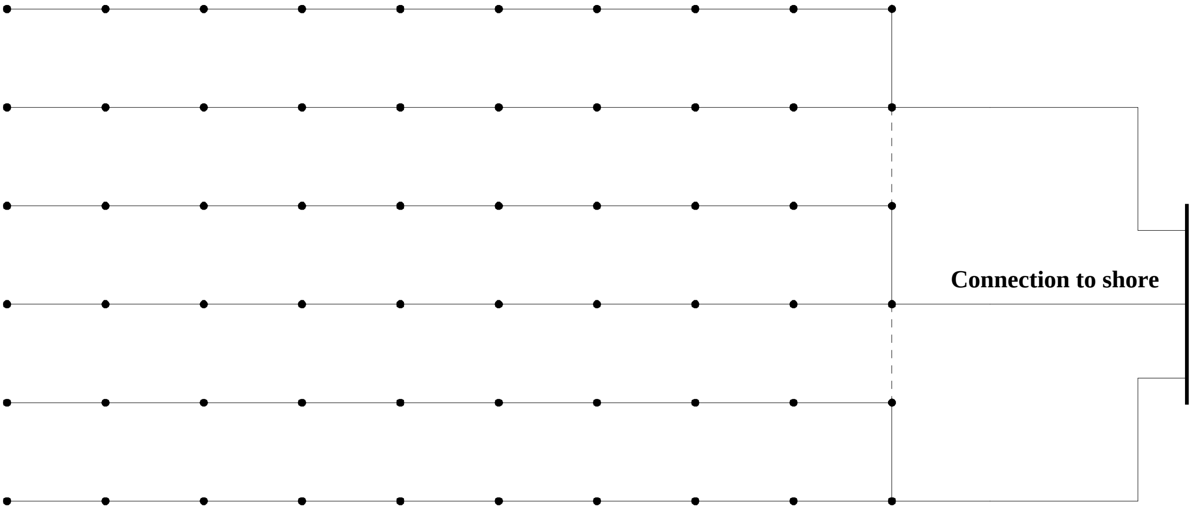

Figure 4: Value of redundancy in connection to shore (additional connections shown dashed)