OPTIMISING THE DESIGN OF OFFSHORE WIND FARM COLLECTION NETWORKS

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ABSTRACT

Wind turbines have reached a stage of maturity such that their use in offshore applications is becoming common. A principal objective of the offshore wind farm developer is to implement the wind farm to give the lowest cost of energy over the lifetime of the project, thus ensuring the greatest return on investment. Economic performance of the turbines is paramount, but the performance of the electrical infrastructure can comprise a significant portion of total project costs, typically 10-20%.

This paper reviews the principles of offshore wind farm collection system economics and outlines methods to optimise the turbine layout, location of offshore substations and the sizing and design of the wind farm collection network. It considers the economic impact of cable size selection and the potential benefits for using multiple offshore substations, with a view to minimising lifetime ownership costs of the scheme without compromising or operational technical requirements.

INTRODUCTION

Designing the electrical collection and transmission system for an offshore wind farm poses unique problems to the electrical engineer. Conventional utility design practice focuses on the need to deliver reliable supplies and duplication of circuits is frequently required, leading to low levels of equipment utilisation.

In common with virtually all renewable power sources, offshore wind incurs the majority of its costs at the project inception, without on-going fuel costs over the life of the scheme. Additionally, discount rates applied to the economic study of offshore wind projects are commonly higher than those applied to conventional generation schemes. Therefore the lifetime financial health of a project is most strongly influenced by the development costs. These include all preliminary studies and licensing, wind turbine supply and erection, offshore and onshore civil engineering and the electrical collection and grid connection infrastructure.

There is, therefore a strong imperative to minimise up-front costs, but in order to understand the lifetime financial costs, it is necessary to consider the cost of ownership, as well as the up-front cost of the electrical infrastructure. In this context cost of ownership generally relates to the cost of losses since the operations and maintenance costs associated with the electrical collection infrastructure are normally small.

OFFSHORE WIND FARM LAYOUT

The area available for an offshore wind farm is determined by the regulatory authorities of the project country and in the UK this is the Crown Estate. Most offshore wind farms to date have had simple geometric boundaries and have adopted a straightforward rectangular or rhomboid grid. Figure 1 shows a layout suitable to accommodate 108 turbines.

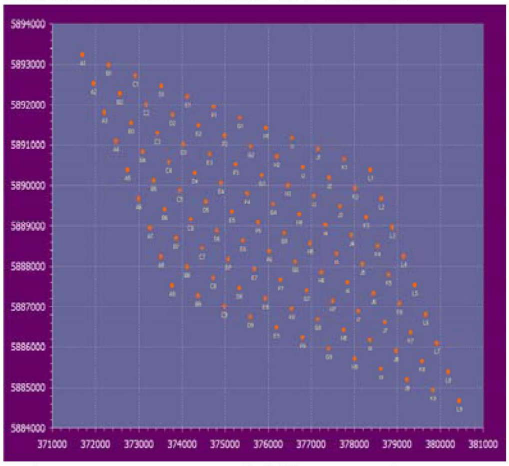

Figure 1 – Layout of Offshore Wind Farm

COLLECTION SYSTEM ARCHITECTURE

Within each turbine there is a step-up transformer to increase the generated voltage of 690V-3.3kV to the collection system voltage. A 33kV radial collection system is commonly used, although some designs have limited interconnection to form rings allowing partial redundancy. Above 36kV it becomes uneconomic to accommodate switchgear and transformers in each turbine tower, so 33-36kV is widely used for collection schemes. Figure 2 illustrates a typical radial collection scheme, this time for a 30 turbine project.

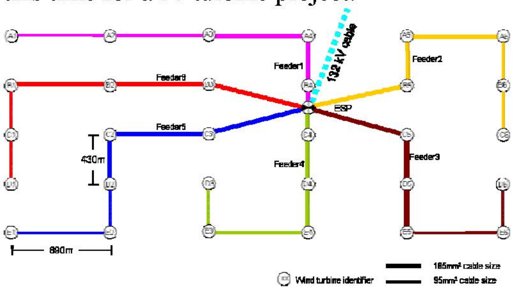

Figure 2 – Radial 33kV Collection System

For onward transmission to the shore, the voltage is again stepped up to a higher level, typically 132kV for UK applications. Higher voltages than this (such as 275kV or 400kV) have not been used to date and are unlikely to be used within the timescale of UK Round 2 offshore developments[1]. This is principally because:

a) three-core cable designs are not available at the highest system voltages, necessitating the use of three single core cables, potentially tripling subsea cable laying costs
b) management of cable charging currents becomes more difficult at higher voltages, limiting current capacity available for exporting power and possibly requiring intermediate compensation platforms
c) developers are typically looking for proven, low risk solutions. XLPE cables are well established and reliable at 132kV, but there is considerably less experience of their use at voltages approaching 400kV.

The 132/33kV transformers are accommodated on a structure similar to an offshore oil platform and the number and location of these can be optimised.

OPTIMUM LOCATION OF TRANSFORMER PLATFORM

Location of the transformer platform strongly influences the layout and extent (and hence capital cost and losses) of the 33kV collection system. SKM have developed a streamlined technique to assess and optimise the location of the transformer platform. The principal objective of the optimisation process is to minimise the total 33kV cable used to connect the turbines to the transformer platform(s).
The optimum location for the transformer platforms is based upon minimising the sum of the distances between the transformer platforms and any associated wind turbines. To simplify analysis, transformer platforms are assumed to be located immediately adjacent to a wind turbine. In practice the expectation would be that a platform would be located midway between wind turbines in order to minimise interference with air flow.

An example is given below to illustrate the principle of optimum transformer platform location. For practical reasons, cable layouts within offshore wind farms by and large follow the regular geometric pattern of the farm layout and this is assumed in this analysis. In the case of two transformer platforms, the distance from each wind turbine to its nearest transformer platform has been used in the evaluation. The evaluation process is computationally intensive and calculates the distances from all wind turbines to all unique combination pairs of transformer locations to select the optimum.

The calculation of distances in the algorithm assumes that each wind turbine will be connected to the transformer platform by dedicated feeders. However, in practice a number of wind turbines will share a cable circuit and hence the overall distance of cable that will be associated with such connections will be significantly reduced, on a simplistic basis by the number of wind turbines associated with each circuit. The distances found in the calculation have to be corrected to take into account the number of wind turbines connected to each feeder cable from each transformer platform for the one and two transformer platform scenarios.

The following drawing indicates the effect on the ratio between connection and circuit distances of a circuit being sharing by a number of wind turbines. It illustrates the process followed to correct the distances obtained from the basic calculation to give a more practical evaluation of distance when multiple turbines share a feeder.

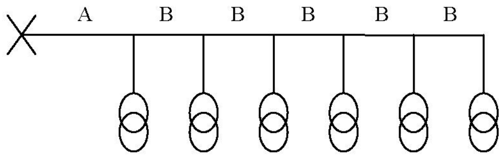

Figure 3 – Radial 33kV String

Based on the above, the total connection distance would be as follows:

-for the first turbine	A
-for the 2nd turbine	A +B
-for the 3rd turbine	A + 2B
-for the 4th turbine	A + 3B
-for the 5th turbine	A + 4B, and
-for the 6th turbine	A + 5B

This gives an overall connection distance of 6A + 15B. In contrast the actual cable route distance would be A + 5B. Assuming A and B to be equal, the ratio between the summed connection distances and actual length of circuit will be 21/6 = 3.5. However, if A were to be three times B, corresponding to a large area wind farm with the need for an extended "end connection" circuit, then the ratio will increase to 33/8 = 4.1.

Using this method on the system introduced in Figure 1, the optimum location of the transformer platforms was found. This is illustrated in Figure 4, with the central area showing the most favourable locations for a single platform, with the two smaller areas indicating the optimum locations for each of a pair of transformer platforms.

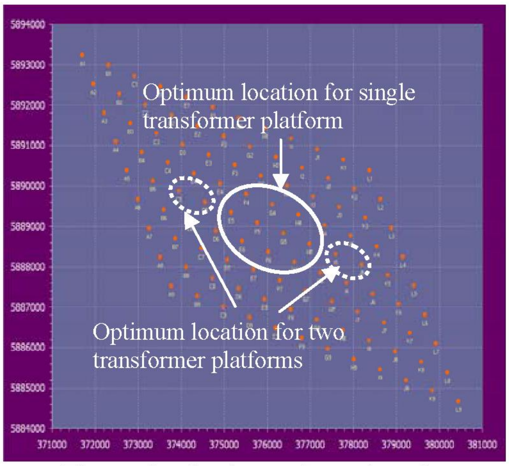

Figure 4 – Optimum Locations for Transformer Platforms

ECONOMIC BASIS OF EQUIPMENT SIZING

In order to provide an acceptable return on investment, the electrical system of an offshore wind farm must have the lowest possible total lifecycle cost in order to achieve its maximum economic potential. Each design choice has an effect on the project financial performance, affecting capital costs, taxes, insurance, energy revenue, maintenance costs, and government subsidies.

Walling and Ruddy [2] introduce a method to simplify the evaluation of different design proposals to determine an optimal solution based on the specific economic circumstances of a particular wind farm. The method considers the differentiating factors that can lead to the selection of one electrical design over another. To do this is breaks the operating costs of each option into three components:

1) Fixed losses, which do not vary with wind farm output. These are primarily transformer excitation losses.
2) Variable load losses, which vary according to the square of output. These are ohmic losses in cables and transformers.
3) Energy not generated due to a constraint imposed by electrical system unavailability (for example, a cable failure).

As an example of the use of this comparison technique, analysis can be performed to determine the economic cable size for a given load current. Lowest first cost is obtained by selecting the smallest cable which, after accounting for appropriate derating factors, is capable of carrying the required current without overheating. Increasing the cable size above this minimum will inevitably increase the first cost. However, a larger cable will also have a lower resistance and hence real power loss for a given load. Total lifetime ownership costs are the sum of the installed first cost and the operating costs (principally losses in this example) over the chosen analysis period.

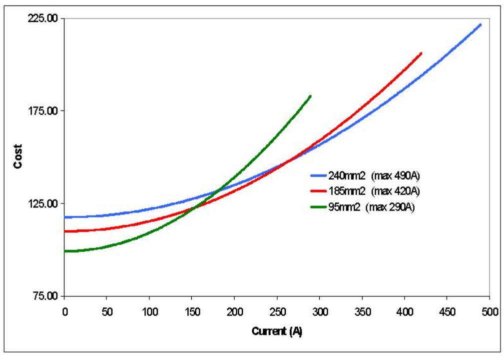

Figure 5 – Lifetime Cost of 33kV Cables

Figure 5 shows a comparison of lifetime costs for 33kV cables of the type used in an offshore wind farm collection system. Salient points are:

1) Installed cost is higher for larger cable, but losses are lower.
2) At the upper end of a cable's capacity, a much larger cable can offer a lower lifetime cost.
3) Loss calculation must take account of operating regime and load factor.

PRACTICAL ILLUSTRATION OF CABLE SIZE OPTIMISATION

A hypothetical 150MW offshore wind farm requires 20km of 132kV cable to connect to the grid. A technical assessment has determined that, after derating factors have been applied, the smallest cable that is capable of safely carrying the wind farm output is $630mm^2$. The developer is seeking an optimal economic design over the lifetime of the project and is willing to consider using larger cables.

The prevailing cost of lost generation, including Renewable Obligation Certificates is taken as 6p/kWh. After allowing for the expected load duration characteristic of the wind farm's output, the annual cost of losses for each cable size under consideration is:

Cable Size	Annual Loss Value	Installed Cost
$630mm^2$	£176k	£5.6M
$800mm^2$	£137k	£5.9M
$1000mm^2$	£109k	£6.3M
$1200mm^2$	£94k	£6.8M

Table 1 – 132kV Cable Costs and Losses

From this it is possible to calculate the lifetime ownership costs of the range of cables considered, assuming a discount rate of 6%, and this is illustrated in Figure 6.

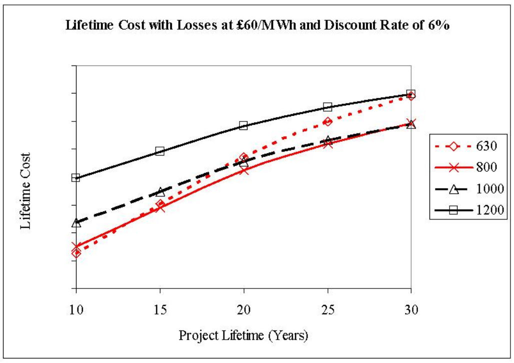

Figure 6 – Comparison of 132kV Cable Lifetime Costs

Unsurprisingly, the analysis confirms that for short project lives, the lifetime costs are heavily dominated by the first cost. Under these conditions the smallest cable is seen to be cheapest. However, as the project lifetime is extended, the affect of losses becomes more apparent and beyond 13 years the smallest cable size is no longer the most economical. As the lifetime is further extended, then progressively larger sizes become the most economic.

Increasing the loss cost or project lifetime tends to favour larger cable sizes, which is intuitive and supported by this analysis. Conversely, shorter lifetimes and lower energy costs favour least first cost solutions. To put this in a proper context it should be remembered that wind farm equipment is designed for in excess of 25 years operating life and energy costs are presently increasing faster than general inflation.

CONCLUSIONS

Offshore wind farms are rapidly becoming an important source of energy. However, like all projects they are sensitive to economic factors. The electrical collection and transmission system is a critical part of an offshore wind project.

Electrical system design selection can have a large impact on the financial performance of a scheme. It is essential that it a rigorous comparison between designs includes appropriate representation of the economic implications of each design. These are typified by the installed cost and operational losses. A cost effective design is one that minimises the cost of ownership over the lifetime of a project.

Economic principles should be used to influence the selection of appropriate size equipment (eg. cable sizes) and also, where it is not subject to other constraints, the location of key elements of the design (eg. Transformer platforms).

A carefully designed, optimised electrical system is a vital requirement for a successful offshore wind farm development.

REFERENCES

1. Bailey D.I., Offshore Electrical Connections – Technologies and Costs, Electrical Aspects of Offshore Renewable Energy Systems, IEE Colloquium, NAREC, Blyth, Northumberland, February 2004

2. Walling R.A., Ruddy T., Economic Optimization of Offshore Windfarm Substations and Collection Systems, Fifth International Workshop on Large-scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Glasgow, Scotland, 7-8th April 2005.

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