A Comparison of Design Options for Offshore HVDC Networks through a Sequential Monte-Carlo Reliability Analysis

C. MACIVER
University of Strathclyde
UK

K. R. W. BELL
University of Strathclyde
UK

D. P. Nedic
Siemens PTI
UK

Abstract

There is growing interest in developing offshore HVDC networks to connect both offshore wind power and provide interconnection between regions. There are a number of technology, topology and protection options available to developers each with varying levels of design complexity, capital cost and system redundancy. This paper highlights some of the available options and outlines a methodology for investigating the performance of a number of these through an investigation of their reliability against a lifetime of expected fault conditions, principally through a calculation of the expected level of curtailed energy associated with each network design. A number of case studies are investigated to provide a comparison between options including designs with and without HVDC circuit breakers and with varying levels of interconnection and system redundancy.

The paper shows that there are potentially significant benefits in terms of reduction in curtailed energy through use of redundant paths for power transmission in the network design and that these can in certain cases outweigh the increased capital expenditure associated with their implementation. An investigation into the need case for HVDC circuit breakers is carried out through a comparison with an alternative sectionalised HVDC network topology and the impact on system reliability is found to be negligible in comparison to the cost of the breakers. Offshore network reliability is also found to be highly sensitive to input assumptions for failure and repair rates and the variability within the results was found to be large meaning it could be difficult to accurately predict the reliability of future offshore network implementations.

KEYWORDS: HVDC, Reliability, Offshore grids

1 INTRODUCTION

In recent years there has been a huge expansion in the number of offshore wind farm projects in European waters. This trend is due to continue with the number, scale and distance from shore of projects expected to grow significantly in the coming years. The European Wind Energy Association (EWEA) suggests that the installed capacity of offshore wind projects could expand from 4.5GW currently to as much as 150GW by 2030 [1].

Many proposed future offshore wind installations will be very far from shore. For example, Dogger Bank, a UK Round 3 designated area with up to 13GW of wind potential is located 125-290km from the UK shore [2]. Several studies have concluded that the use of conventional HVAC subsea cable solutions for the connection of wind farms becomes increasingly uneconomical and practically unfeasible due to reactive charging currents and the need for compensation around or before 100km from shore [3-5]. As such there is a general consensus that future offshore grids, in Europe at least, would be realised as High Voltage Direct Current (HVDC) projects. It is also very likely that, due to the ability to connect to 'weak' AC grids and the high level of flexibility and power control provided, Voltage Source Converter (VSC) technology will be utilised over more traditional Current Source Converter (CSC) technology that has widely been used in past HVDC point to point interconnection projects [6].

Although some aspects of how to deliver an offshore HVDC grid are becoming clear, there are still a great number of design and technology options available to potential developers and there is a requirement to compare the feasibility of these different options. For example, there are a number of different converter options available within the

VSC bracket with newer multi-level modular designs providing additional functionality over traditional 2-level and 3-level converter options at the expense of added complexity and uncertainty through lack of a proven track record [6]. In terms of grid topology offshore networks could be realised using a range of options from simple radial solutions to fully meshed HVDC networks capable of not only delivering renewable energy generation but also of providing interconnection capacity between regions.

Radial, point-to-point solutions when viewed in terms of a single project are often the simplest option and have been used extensively to date for wind farm installations that are isolated, relatively small scale and close to shore. However, as the offshore wind industry expands it begins to make sense to introduce greater co-ordination of design and sharing of infrastructure. This is part of the motivation for the UK Round 3 development zones which look to cluster wind developments together in order to make use, where possible, of shared resources including subsea transmission routes, onshore landing sites and electrical infrastructure.

A natural development of clustered wind farms would be the interconnection of multiple wind farm clusters which could act as the first step towards a meshed offshore HVDC network. Such expansion to a multi-terminal HVDC grid would also allow for the interconnection of multiple regions which could be utilised as a secondary priority to the delivery of wind power. Studies have shown that such co-ordinated design would bring significant savings in terms of overall capital cost compared with a scenario where Europe's wind potential and interconnection needs are met only through separate individual projects with no shared resources [7, 8]. It must be noted, however, that implementation of increasingly co-ordinated designs, although technically feasible would require a number of regulatory, financial and technical barriers to be overcome. This is discussed in more depth in [9].

Many major studies that have considered offshore HVDC grids have made the assumption that HVDC circuit breakers (DCCBs) will be utilised to create an offshore network that is protected in much the same way as existing onshore networks [4, 7]. DCCBs have not yet been realised on a commercial scale, however feasible design proposals have been submitted and demonstrated to scale [10, 11]. Assuming that full scale designs do become available there is still uncertainty as to their eventual cost with estimates ranging from between one sixth and one third of the price of a full HVDC converter unit meaning they are likely to be an expensive solution to use across a full system [12, 13] and there is a need for alternative methods to be explored [14].

The ISLES project proposes one such alternative, a multi-terminal HVDC grid solution between Great Britain and the island of Ireland that would be protected on the AC side [15]. This form of protection would require an entire HVDC grid to be temporarily shut down in the event of a fault. While this is often seen as being unacceptable, it is proposed that the network could be delivered as a set of parallel HVDC grids that are not electrically connected on the DC side meaning only one grid section needs to be removed from operation for any given DC side fault. A requirement of such a design is that each grid section should not transmit more power into a region than the designated loss of in feed limit for that region. Work on the TWENTIES project also concluded that such a network design was worth further investigation given the expected high cost of DCCBs [14].

Although other studies have sought to make comparisons of some of the different network options described, few to date have considered the reliability of different network options. There are a number of key open questions relating to the development of offshore grids including determining the value of creating highly redundant meshed networks offshore compared with simpler, lower cost investments which lack multiple transmission routes. An investigation into the need case for DCCBs is also of interest. As such the remainder of this paper describes a methodology that has been developed to calculate the reliability of a number of different network options under a lifetime of fault conditions and discusses the initial findings through examination of a number of specific case studies.

2 CASE STUDIES AND INPUT ASSUMPTIONS

The ISLES study highlighted previously was chosen as the basis for a number of initial studies [15]. ISLES proposed a sectionalised multi-terminal HVDC network topology without the need for DCCBs that could incorporate 2.1GW of offshore wind power between Great Britain and Ireland as well as providing the opportunity for cross-border energy trading. This ISLES base case was replicated along with two other case studies, the first representing a version of the ISLES network that incorporates DCCBs across the network and thus can be realised as a single grid rather than separate sectionalised grids. The final case study represents a semi co-ordinated design approach which clusters some wind farms but relies upon radial connections to shore and does not offer any interconnection between the sectionalised grid elements. The three case studies are depicted in Figure 1.

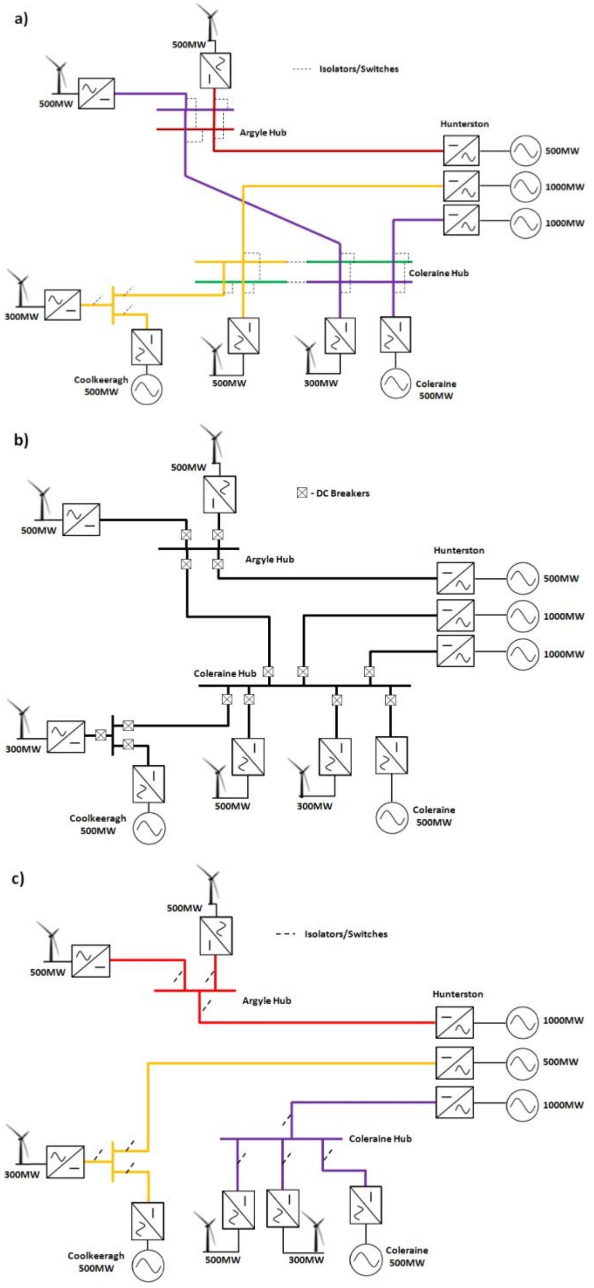

Figure 1 – Single line representation of case studies examined: a) ISLES Base case, b) ISLES DCCBs and c) ISLES radial+

As this initial study looks only to make broad comparison of the merits of the three presented case studies, faults were considered only on a number of key offshore network components as highlighted in Table 1 and all faults were assumed to cause full outage of that component. For all case studies it was assumed there was no inherent redundancy in the system, as for example could be provided by bi-pole connection of cable routes. Partly due to lack of appropriate data, at this stage of the analysis faults were not considered on substation components such as switchgear and bus sections, nor are they applied to DCCBs. Due to the infancy of the industry, there is very little published data as to the failure and repair rates for offshore network components so an approach was taken that gathered data that is available [16, 17] along with advice from industry experts, to generate three failure/repair rate scenarios based on the spread of information gathered.

These three sets of data represent best case, medium case and worst case scenarios in terms of the expected frequency of failures and duration of repairs. Due to the difficulty of accessing offshore sites to effect repairs, a need was identified to group repairs of offshore faults into two categories, those which are driven solely by the need for access weather windows and those which are also driven by the need to acquire a specialist vessel and procure replacement components. The second category includes major transformer outages and transmission branch failure and so for each of these faults there is not only a time to repair value associated with the required weather window but also a fixed delay based on estimates of the standard delay time associated with the repair of such components.

Also included in the calculation of energy not served is a delay related to the time of day in which a fault occurs which, due to offshore safety issues that require travel only during the day. This was calculated to be, on average, 7 hours from a time at which it would begin to be addressed. Finally an additional calculation was made for the two scenarios which do not include DCCBs which relates to the time required to shut down the effected grid section, isolate the faulted region, re-configure the network if appropriate and re-energise the healthy parts of the system. Given that individual wind turbines can be restarted within a few minutes of being shut down and that switching sequences for re-configuration of onshore networks can be applied within a few minutes it seems reasonable to assume that this process can be undertaken in, at most, tens of minutes. As a conservative estimate this work assumes the process accounts for one time step in the simulation, i.e. 1 hour.

Failure Rate and Repair Times for Three Reliability Scenarios (Hours)						
Component	**Best Case**		**Medium Case**		**Worst Case**	
	MTTF	**TTR + fixed delay**	**MTTF**	**TTR + fixed delay**	**MTTF**	**TTR + fixed delay**
Onshore Converter	5930	4	5930	6	5930	8
Offshore Converter	5930	4	5930	6	5337	8
Onshore Transformer	461368	96 +1440	365250	96 +4320	365250	96 +4320
Offshore Transformer	461368	120 +1440	365250	144 +4320	292200	168 +4320
Transmission Branch	417429	96 +2160	211636	120 +4320	5844	144 +4320

Table 1 - Failure rate and repair times for three reliability scenarios – derived from [16] and [17].

3 METHODOLOGY

To investigate different offshore network options a bespoke reliability modelling tool has been developed using Python software. The software tool utilises a Sequential Monte-Carlo based reliability analysis to compare different network options. Other studies have used Non-Sequential Monte-Carlo [14] or State Enumeration [18] techniques in relation to reliability of offshore networks however these do not account for the seasonal variations in weather that are experienced in offshore environments. Use of a sequential Monte-Carlo methodology allows simulated wind and wave time series to be integrated into the decision making processes within the reliability study. This allows, for example, repair times for offshore components to have a weather dependent element which reflects the reality that maintenance vessels and staff can only reach offshore components if conditions are within specified safety limits. The main characteristics of the Sequential Monte-Carlo process are described below.

3.1 System Inputs

Network cases are designed using PSS®E [19] and imported into Python for analysis. Also fed into the program are appropriate input wind and mean significant wave height time series along with the reliability input parameters shown in Section 2 to allow calculation of failure and repair times for components. Finally a wind speed – wind power curve is required to convert input wind speed time series to wind power output. The offshore specific wind speed – wind power curve first applied in [20] is used in this study.

The weather data used as input to the reliability model is derived from eight years worth of concurrent wind speed and wave height data taken by the FINO 1 offshore Met Mast [21]. The eight years of data have been processed using a Multivariate Auto-Regressive approach (MAR) outlined in [22] which captures not only the trends and attributes of the data itself but also the cross-correlations between the wind and wave height output. This is used to generate larger time series of wind and wave data that maintain the characteristics and correlations of the FINO 1 dataset. To estimate average curtailed energy accurately with a very high degree of confidence, the sequential Monte-Carlo simulation requires to be run for thousands of simulated years. This study makes use of 100 years worth of simulated wind and wave height time series which are repeated throughout the simulation. The time resolution of the data is one hour and as such this is the resolution used for the entire sequential Monte-Carlo process. In the absence of better information, it is assumed that the wind and wave input data applies equally to all parts of the network model.

3.2 Time to Fail Calculation

At the beginning of the process all systems components must be given a value for the expected time to fail, i.e. to change from the in service state to the out of service state due to a forced outage. There is some published evidence to suggest that faults may be more likely to occur in extreme weather conditions and that the likelihood of a fault occurring increases with component age [23, 24]. It is judged, however, that the seasonal variation of repair times is a more important element in terms of output results so for this initial study it was decided that time to fail values would be based on exponentially distributed randomised values which converge on published component mean time to fail (MTTF) data. The process used to generate failure times for each component is shown in equation (1):

$$TTF = -MTTF * \ln(R) \qquad (1)$$

where, TTF is the time to fail, MTTF is the given mean time to fail derived from published data and R is a randomly generated number.

3.3 Time to Repair Calculation

By basing the repair time of components on mean significant wave height data, it is possible to model the fact that it is more difficult to access and repair faults in seasons where the weather conditions are most difficult. These same seasons are also likely to be the most productive in terms of wind power output so this is likely to have a compounded negative impact on the observed curtailed energy when comparing to a purely random repair rate process.

When a fault occurs on an offshore component there are a number of criteria that must first be met before it can be repaired. These include the availability of a maintenance team and a vessel to transport them to the fault location and the availability of a replacement component if necessary. The study reported here has the aim of comparing different offshore network designs, not different repair resources and strategies so, in this modelling process, it is assumed that these elements are always in place. There must also be suitable weather conditions to allow access to the wind turbines and/or offshore platforms. The main industry standard criterion to allow maintenance vessels to access these offshore sites is that mean significant wave height should be below 1.5m [25]. More recent developments have seen some offshore asset owners make use of helicopters as a means of transportation whose access would be limited by visibility and wind speeds as opposed to sea state. Expert opinion however suggests that there is a large overlap between the occasions when sea vessels and helicopters are unable to access offshore structures so in this study only sea state is used as the means of determining the availability of an appropriate weather window.

The process used assumes perfect forecasting into the future using the simulated wave height data at the offshore site. When a fault occurs the repair time is calculated, after accounting for the average delay associated with the difference between the time a fault occurs and the time that it can begin to be dealt with, by searching out into the time series for the first time period in which the mean significant wave height is consistently below 1.5 m/s for at least the length of time specified as the required weather window to repair that component.

3.4 Fault Handling

In the event of 'active' faults, fault current interruption is assumed to be successfully achieved using the nearest available circuit breakers or, in the cases without DCCBs, through actions taken at the terminals of the DC grid either through use of AC side protection or the use of fault blocking VSCs such as those described in [26]. Network re-configuration is then assumed to occur such that the faulted component is isolated by the opening of appropriate isolators or circuit breakers, whichever succeed in minimising the number of components, other than the faulted one, that are also isolated. Given that such a re-configuration is assumed to occur in less than 1 hour and that the time resolution of the simulation is 1 hour, the objective of the fault handling algorithm is to identify the points of isolation. A recursive algorithm is used which steps through the network from the component that has failed until the nearest circuit breakers or isolators on either side are reached. This works by running through each branch that is adjacent to the fault. If that branch is a circuit breaker or an isolator, the function will open that element and continue searching along any remaining branches but if the branch is not a circuit breaker or isolator the function will continue on to the next bus and generate a new list of branches that are connected to this bus and will only stop once a circuit breaker or isolator are reached or the end of the line is reached. All buses that have been passed on the way are removed from service along with any connecting branches.

3.5 Grid Re-configuration

For offshore network designs that incorporate multiple switching options, and so have the capability for re-configuration in the event of system faults, it is necessary to calculate the most appropriate switching arrangement that should be applied for each fault scenario. This is achieved through an optimisation based method that tests every possible switching arrangement. To do this a number of criteria are set on which to judge the appropriateness of each configuration and so choose the optimal solution. The factors used relate to the ability of each configuration to deliver wind power to shore, minimise the need for curtailment and to allow for energy trading between regions. Given that some faults in particular can be expected to take a long time to fix, the assumption is made that any grid re-configuration could be in place for a significant period of time. This allows the optimisation to be based on the expected earnings from each configuration option given the average yearly cumulative distribution of power output at the site in question. As such the objective function, f, for the optimisation process is set out in equation (5) via (2), (3) and (4):

$$E_{del} = E_{gen} - E_{curtail} \quad (2)$$

$$p_{MWh} = p_{subsidy} + p_{market} \quad (3)$$

$$T_{cap} = T_{firm} + T_{flex} \quad (4)$$

$$f = Max\left(E_{del} * p_{MWh} + T_{cap} * p_{trade}\right) \quad (5)$$

Where the delivered energy, E_{del}, is the amount of energy expected to be generated over the time period, E_{gen}, minus the expected energy curtailment over the period, $E_{curtail}$; $p_{subsidy}$ and p_{market} are combined to give the value of generation per MWh, p_{MWh}, taken from renewable obligation payments and the wholesale electricity price; the total trade capacity, T_{cap}, is the amount of trade capacity that can be utilised at any time, T_{firm}, plus the amount of trade capacity that can be utilised when wind output is not using the cable capacity, T_{flex} and p_{trade} is the average price difference between the two markets in question. If more than one network configuration results in the same expected earnings the number of switching operations that are required to get to that configuration from the previous state is used as a further decision making factor. The contribution of all valid electrical islands in the system is added together for each possible configuration scenario and the optimal solution identified.

3.6 Locating Electrical Islands

Once a fault has occurred and the fault handling and, if required, grid re-configuration codes have completed the task of switching out all affected components and re-configuring the grid if necessary, a further function is applied in order to understand the new state of the system. This function acts to locate any distinct and valid electrical islands that are functional in the system. It uses a very similar methodology to the fault handling algorithm highlighted previously. The same recursive technique is used to step through the system from each conceivable start point. This time there is no stop criteria other than the fact that the function will not continue if it reaches a bus or branch that has been removed from service and the function is allowed to run through the entire system until all buses connected to the start point have been identified. If a wind farm converter bus and an onshore converter bus or two onshore converter buses are found to be part of the same island then this is a valid electrical island which allows either transmission of wind power or cross regional trading. The function continues until all such islands have been located. Buses which have not been identified must be part of electrical islands that are disconnected from the system and so cannot transfer power. These buses are removed from service. A count can be made of the number of wind farms that are no longer connected to active electrical islands.

3.7 Curtailed Energy

The level of undelivered energy can be calculated in the course of the Monte Carlo simulation and so an evaluation of the reliability of the network made. The total available energy at any point in the simulation can be calculated by running through the entire simulated wind time series and multiplying by a conversion factor derived from the input wind speed-wind power curve and the total available capacity of the system as shown below in equation (6):

$$E_{Tot} = \sum_{t=0}^{n} WF_{cap} * U_t * x_t \quad (6)$$

where n is the total time of the simulation in hours, WF_{cap}, is the total capacity of wind farms in the system, U_t is the Wind Speed at time t and x_t is the conversion factor for the wind speed at time t to wind power. A calculation is made at each change in system state during the simulation of the energy lost due to wind farm disconnections, E_{loss} using equation (7) based on the capacity of the disconnected wind farm(s), WF_{out} as well as the energy lost due to curtailment, E_{curt}, using (9). This latter term is only invoked when the power output at time t, P_t, is above the capacity of the available transmission lines and converters on each network section, P_{lim}, at that time as calculated from (8).

$$E_{Loss} = \sum_{t=T_{last}}^{T_{now}} WF_{out} * U_t * x_t \quad (7)$$

$$P_t = WF_{cap} * U_t * x_t \quad (8)$$

$$E_{curt} = \sum_{t=T_{last}}^{T_{now}} P_t - P_{lim} \quad (9)$$

4 RESULTS AND DISCUSSION

Figure 2 gives an indication as to the reliability of the three different network options considered through an examination of the annual average level of curtailed energy relating directly to faults on HVDC network components. The results are given in terms of the percentage of the annual average potential energy production which was found to be 7792.45 GWh.

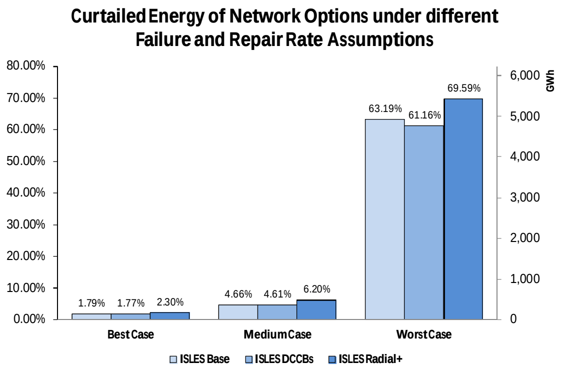

Figure 2 - Level of Curtailed Energy for Different Network Options and Reliability Input Assumptions

It is immediately noticeable that the results of the reliability analysis are extremely sensitive to the input assumptions used with results for the worst case reliability studies being exceptionally poor. This can largely be attributed to the increase in propensity of transmission branch faults in this study in conjunction with the long repair times associated with this. This shows that if the most pessimistic reliability assumptions are to be believed then there would almost certainly be the need for redundancy on major network components or the offshore wind farm investment would not be undertaken in the first place. If the best case or medium case scenarios are to be believed, however, then the level of curtailed energy is far more manageable. Comparing the performance of the three options it can be seen that the ISLES Base and ISLES DCCBs case studies give very comparable results over the three scenarios. The extra curtailed energy on the ISLES Base case and Radial+ case associated with switching and grid re-configuration time only account for around 0.06% of the total available energy in each of the cases. The radial network solution, however, suffers from significantly increased curtailed energy compared with the more integrated alternative solutions presented.

An initial investigation into the financial implications of these results was carried out by comparing the expected capital expenditure and cost of curtailed energy for each scenario with its ability to deliver energy to shore. Table 2 makes an evaluation of the annual cost of curtailed energy for each topology under the medium case reliability scenario. It is assumed that both Renewable Obligation Certificates (ROCs) and the wholesale value of electricity are each £50/MWh and placing a value on offshore wind energy of two ROCs plus the wholesale value, that is £150/MWh total. This cost is then evaluated over a 25 year period which reflects the expected lifetime of many offshore wind projects using a discount rate of 8% per annum. The capital expenditure (CAPEX) on each project is evaluated using the costing details set out in [15] along with an estimated cost of DCCBs based on [12] and scaled to the appropriate size. Finally an evaluation of the cost/MWh of delivered energy was derived by combining the CAPEX and cost of curtailment for each topology with the level of energy that each delivers. The results of this analysis are depicted in Figure 3.

Average Annual Curtailed Energy and Cost of Curtailed Energy under Medium Scenario

Scenario	MWh Curtailed Energy	Cost of Curtailed Energy (£m)
ISLES Base	362838	£54.43
ISLES DCCBs	358906	£53.84
ISLES Radial+	483282	£72.49

Table 2 - Level and Cost of Curtailed Energy for each Topology with Medium Scenario

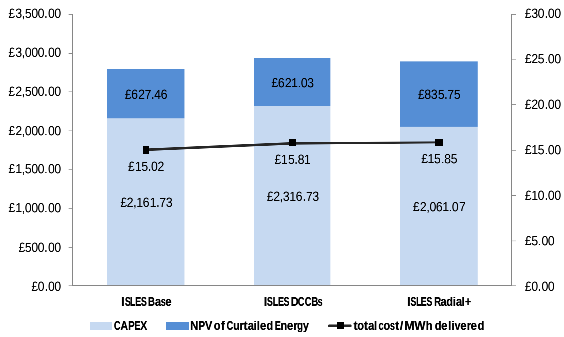

Figure 3 - Cost Evaluation of Network Topology Options for Medium Case

It can be shown that large CAPEX savings are made in the radial case due to the reduced amount of subsea cable used and that the cost of DCCBs adds significantly to the CAPEX for the case utilising this technology. When the CAPEX and NPV of curtailed energy are added it is found that the total costs (excluding internal wind farm network constraints, system losses and cost of maintenance) are broadly similar for both the Radial+ and DCCBs cases and that the cost of the ISLES Base case study is the lowest. The cost/MWh of delivered energy, which takes into account the level of energy actually delivered by each topology as well as the costs associated with it, again shows the ISLES Base case to be the favourable option and despite being the cheapest network topology to build outright, the Radial+ option is the least cost effective option overall due to higher curtailed energy. This highlights that there is potentially value in having increased levels of connection between wind farms and redundancy in offshore HVDC networks despite the extra requirement for capital investment.

A further examination of the results for the medium ISLES DCCBs scenario was considered to give an indication of the spread of results that could be expected over a 25 year project lifespan. Table 3 shows the spread of data over one hundred 25 year periods. This shows that the variation in curtailed energy can be very large for the same network topology over the relatively short timeframe considered. Although this result could, in part, be influenced by the exponential distribution of generated failure times, it also indicates that the reliability of offshore HVDC networks is potentially highly sensitive to the long outage times associated with major fault conditions such as transmission cable faults and transformer outages. An increase or decrease in the propensity of such events could potentially lead to very different reliability performance than may be expected if considering only average outcomes. Variations in the weather could also have a similar impact if there are large deviations in wind and wave conditions away from mean values for an extended period.

Variation in Curtailed Energy over 100 Consecutive 25 Year Periods			
Average	**Standard Deviation**	**Maximum**	**Minimum**
4.63%	1.36%	9.43%	1.59%

Table 3 - Variation in Curtailed Energy over Consecutive 25 Year Periods for Medium ISLES DCCBs Scenario

A final investigation was done to compare the results obtained using a methodology which uses purely randomised results for repair times of offshore components as opposed to the climate dependent methodology outlined in this paper and the results are presented in Table 4.

Comparison of Methodologies using Weather Dependent and Randomised Repair times		
Method	**% Curtailed Energy**	**% Difference**
Random	4.51%	
Weather Window	4.61%	2.10%

Table 4 - Comparison of Methodologies for Repair Time Calculation

The medium ISLES DCCBs case is used and the Monte-Carlo simulations run over a total of 30000 years with the aim of having two sets of results with similar average component downtimes. A slight adjustment was required to the results, even with this number of runs, such that the total average downtime per year for all components are equalised allowing for a fair comparison of the curtailed energy.

A small but appreciable difference is found in the two approaches with the method utilising weather dependent repair times estimating around 2% greater curtailed energy overall. This is explained by the fact that faults occurring in winter months will on average take longer to repair than those occurring in summer and on average the potential wind energy output will be higher in the winter months so use of purely random repair rates potentially underestimates the total curtailed energy for a given system. Even this small difference could equate to large financial implications if scaled up to modelling of much larger systems.

5 FURTHER WORK

Although this initial study provides a useful insight into the main drivers behind offshore network reliability there is scope for a number of improvements to be made. It has been shown that the results are highly dependent on the input assumptions made and as such there is a need for a full sensitivity analysis to advise on which components are integral to the overall reliability of the network. There is also the possibility of improving the level of detail being modelled in terms of calculation of offshore repair times. For example it is possible to incorporate features like the availability of heavy lift vessels and spare parts, the number of available personnel on the maintenance team, the number of available working hours and the delays incurred in transport time to and from the offshore wind farms. Many of these elements have been modelled in relation to individual wind turbine repair in [27] and can be shown to have significant impact on overall reliability levels. Accuracy could be increased through more detailed modelling of the systems such that substation equipment and any potential redundancies in the system are incorporated. Further to this, examination of a greater variety of offshore network technology and topology options is required to gain a better understanding as to which options are the most cost effective means of delivering offshore wind power. The value and availability of cross border trade energy could also be investigated.

6 CONCLUSIONS

This paper has presented a methodology for comparing the reliability of a number of options for offshore HVDC networks along with the initial results based on three credible offshore network topology options. It has been shown that there is potential value in having a level of redundancy between transmission routes in an offshore HVDC network although given the high cost of both cables and the expected high cost of DCCBs, it is unlikely to be worth designing an offshore HVDC transmission network with the same level of robustness to fault conditions as often displayed in onshore HVAC transmission systems. The results show that, for this case study, avoiding the use of DCCBs through use of multiple sectionalised HVDC grids can reduce capital expenditure significantly with only minor implications for overall reliability measured in terms of curtailed energy.

It was found that reliability is highly sensitive to input assumptions and that there is the potential for high variability in offshore network performance based on a number of factors including weather conditions and the site specific failure rate particularly of key components such as transformers and transmission cables given the long repair times associated with these.

REFERENCES

[1] A. Zervos and C. Kjaer, "Pure Power: Wind Energy Targets for 2020 and 2030," EWEA, 2009.

[2] Forewind. (10/12/13). *Dogger Bank: Overview*. Available: http://www.forewind.co.uk/dogger-bank/overview.html

[3] D. Van Hertem and M. Ghandhari, "Multi-terminal VSC HVDC for the European supergrid: Obstacles," *Renewable and Sustainable Energy Reviews,* vol. 14, pp. 3156-3163, 2010.

[4] National Grid Electricity Transmission, "Offshore Development Information Statement: Appendix 4," 2011.

[5] ENTSO-E, "Offshore Transmission Technology," 2011.

[6] Chen-Ching Liu*, et al.*, "Preliminary Analysis of HVDC Networks for Off-Shore Wind Farms and Their Coordinated Protection," 2011.

[7] J. De Decker and P.Kreutzkamp, "OffshoreGrid: Offshore Electricity Infrastructure in Europe," 2011.

[8] National Grid and The Crown Estate, "Offshore Transmission Network Feasibility Study," 2011.

[9] K.R.W. Bell*, et al.*, "Considerations in design of an offshore network," presented at the CIGRE Paris Session, paper C1-206, Paris, 2014.

[10] J. Hafner and B. Jacobson, "Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids," in *The Electric Power System of the Future - Integrating Supergrids and Microgrids International Sysmposium*, Bologna, 2011.

[11] Twenties, "Feasibility tests of Direct Current Circuit Breaker prototype in DEMO3-DCGRID: breaking test demonstration," 2013.

[12] Working Group B4-52 CIGRE, "HVDC Grid Feasibility Study," 2013.

[13] D. Jovcic*, et al.*, "Feasibility of DC transmission networks," in *Innovative Smart Grid Technologies (ISGT Europe), 2011 2nd IEEE PES International Conference and Exhibition on*, 2011, pp. 1-8.

[14] T. Houghton*, et al.*, "Drivers for Offshore Network Design and Benchmark Scenarios," Twenties, Deliverable 5.2A, 2012.

[15] TNEI Services Ltd, "Irish-Scottish Links on Energy Study (ISLES): Route Development and Cost Estimation Report," 2012.

[16] B. Linden*, et al.*, "Reliability study methodology for HVDC grids," presented at the CIGRE Paris Session, paper B4-108, Paris, 2010.

[17] R. Hodges and R. Bryans, "Reliability Analysis of Electrical Systems for Offshore Wind," in *42nd ESReDA Seminar on Risk and Reliability for Wind Energy and other Renewable Sources*, Glasgow, 2012.

[18] D. P. Nedic*, et al.*, "Software tool for automated design and cost benefit analysis of offshore grid," in *Innovative Smart Grid Technologies (ISGT Europe), 2011 2nd IEEE PES International Conference and Exhibition on*, 2011, pp. 1-8.

[19] Siemens. (10/12/13). *Siemens Energy: PSS® Product Suite*. Available: http://www.energy.siemens.com/us/en/services/power-transmission-distribution/power-technologies-international/software-solutions/pss-e.htm

[20] TRADEWIND. (2009). *Integrating Wind: Developing Europe's Power Market for the Large Scale Integration of Wind Power*.

[21] *Bundesamt für Seeschifffahrt und Hydrographie (BSH). FINO - Datenbank [Online].* . Available: http://fino.bsh.de/index.cgi?seite=anmeldung_formular;cookie=1

[22] I. Dinwoodie*, et al.*, "Development of a Combined Operational and Strategic Decision Support Model for Offshore Wind," *Energy Procedia,* vol. 35, pp. 157-166, 2013.

[23] P. J. Tavner, *et al.*, "Study of weather and location effects on wind turbine failure rates," *Wind Energy,* vol. 16, pp. 175–187, 2013.
[24] P. Tavner, *et al.*, "Influence of Wind Speed on Wind Turbine Reliability," *Wind Engineering,* vol. 30, pp. 55-72, 2006.
[25] P. J. Tavner, *Offshore wind turbines: Reliability, availability and maintenance*. Stevenage: Institution of Engineering and Technology, 2012.
[26] G. Mondal, *et al.*, "Design and simulation of a modular multi-level converter for MVDC application," in *Industrial Electronics (ISIE), 2011 IEEE International Symposium on*, 2011, pp. 200-205.
[27] I.A. Dinwoodie; D. McMillan, "Heavy lift vessel strategy analysis for offshore wind," presented at the EWEA Annual Wind Energy Event 2013, Vienna, Austria, 2013.

ACKNOWLEDGMENTS

Special thanks are reserved for the technical discussions and insights offered by Jonathan Ball of Siemens Transmission and Distribution Ltd. For data from the FINO project, we thank the BMU (Bundesministerium fuer Umwelt, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) and the PTJ (Projekttraeger Juelich, project executing organisation). This work was supported by EPSRC Grant No.EP/G037728/1, Centre for Doctoral Training in Wind Energy Systems.