Programme Area: Energy Storage and Distribution

Project: Offshore Connection 1

Title: Individual Offshore Connection Report

Abstract:

Drawing on the earlier generation scenarios and technology state of the art reports, it identifies and assesses options for intra-array and export network architectures for the connection of individual offshore renewable energy farms. It also describes the associated challenges and technology development opportunities (to augment those in the Technology Report). Section 5 summarises the conclusions regarding optimum architectures, issues of control and compliance with electricity system standards, and technology development opportunities. Appendix C also includes key analysis of harmonic and fault ride-through performance.

Context:

This project examined the specific challenges and opportunities arising from the connection of offshore energy to the UK grid system and considered the impact of large-scale offshore development. It also looked into the novel electrical system designs and control strategies that could be developed to collect, manage and transmit energy back to shore and identified and assessed innovative technology solutions to these issues and quantified their benefits. The research was delivered by Sinclair Knight Merz, a leading projects firm with global capability in strategic consulting, engineering and project delivery. The project was completed in 2010.

Offshore Connection Project

INDIVIDUAL OFFSHORE CONNECTION ARCHITECTURES REPORT

- Final
- 23rd July 2010

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1. Introduction

1.1. Project Outline

The Energy Technologies Institute (ETI) has engaged Sinclair Knight Merz (SKM) to identify the opportunity for the development of innovative solutions for the collection of electrical energy from individual and multiple offshore renewable energy farms, and the transportation of bulk electrical energy from these offshore farms to the onshore power system.

The work is being carried out to allow the ETI to focus their subsequent research, development activities and funding initiatives on technologies that will increase energy efficiency, reduce greenhouse gas emissions, and help achieve energy and climate goals.

The study being undertaken by SKM comprises of four main tasks that will enable the required project outcomes to be delivered:

1) Offshore renewable scenarios – to define the timeline of the expected volumes of offshore renewable generation capacities, an important aspect to allow the quantification of the potential benefits of future technology development opportunities. In addition, as indicated in the Statement of Work paragraph 2.2, this task will produce matrices that outline key variables that will allow the generalisation of a range of potential wind, wave, and tidal developments. These matrices will further be used to define a number of specific development cases for analysis in the subsequent project tasks.
2) State of the art of offshore network technologies – establishment of the current state of the art of offshore network technologies and their prospective future development path (through discussions with equipment manufacturers and suppliers), including an assessment of technical and economic characteristics.
3) Analysis at individual farm level – identification of the challenges and resultant technology opportunities (based on the state of the art review) that could arise in respect of the connection of individual large-scale offshore wind or marine energy farms to the UK grid system, and provision of recommendations for connection solutions worthy of further development and analysis.
4) Analysis at multiple farm level – building on the analysis at individual farm level, evaluation of the optimal architecture(s) that could be developed to collect, manage and transmit back to shore the electrical energy produced by multiple, large-scale offshore renewable energy farms.

1.2. Analysis at Individual farm level

The purpose of this report is to present the analysis performed at individual farm level and the identification of the challenges and resultant technology opportunities (based on the state of the art review) that could arise in respect of the connection of individual large-scale offshore wind or marine energy farms to the UK grid system, and provision of recommendations for connection solutions worthy of further development and analysis in subsequent projects.

The report includes:

- Description of the approach taken towards the modelling activities and the models developed and the software tools utilised, an overview of the studies performed (including performance, high level impact on the onshore system), details of the raw inputs and outputs of the studies, and an interpretation of these outputs.
- Methodologies for the optimal design and selection of the electrical infrastructure for individual offshore renewable energy farms, both for connections within a farm and for connections to the onshore system. This includes comments for potential new grid connection specifications relating to these infrastructure approaches and proposals for new and/or revised Grid Code requirements.
- Control system implications of the selected individual offshore renewable energy farm configurations.
- Preliminary comparative economic assessments of the connection of individual offshore renewable energy farms into the onshore UK grid. Data used has predominately been derived from previous[1]SKM studies for the ETI. Where new assumptions are made these are included in this report.
- Specific architectures from the scenarios report and the state of the Art Technology reports were considered in the report together with some additional ideas such as polyphase systems and storage solutions.
- Following on from the State of the Art Technologies report further recommendations of the technology development opportunities for ETI.

In the Scenarios task, completed as the first stage of the overall project, from the entire spectrum of potential developments seven specific Development Cases have been selected. The sample of developments is specific enough to enable the detailed analysis in this phase of the project but varied enough to allow for cross comparison, optimisation of variables and ultimately produce recommendations that are relevant for an appropriately large number of developments.

The seven Development Cases from the Scenario report are shown in Figure 1.

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[1] State of the Art Offshore Network Technology Report SKM January 2010

Figure 1 Development Cases from Scenarios report

	Technology	Offshore Distance (Km)	Onshore Distance (km)	Energy Park Capacity (MW)	Distance Between Farms (km)	Onshore Network Strength	Water Depth (m)	Turbine Rated Output (MW)
Case 1	Wind	30-100	30-80	500	50-100	Weak	25-50	3.6
Case 2	Wind	>100	30-80	2000	50-100	Strong	25-50	5
Case 3	Wind	>100	>80	5000	>100	Strong	25-50	7.5
Case 4	Tidal/Wave	<30	<30	20	10-50	Weak	<40	0.5-1
Case 5	Wave	30-100	<30	200	10-50	Strong	>40	1
Case 6	Tidal	30-100	30-100	500	10-50	Strong	>40	1
Case 7	Tidal Wind	30-100 30-100	30-80 30-80	500 500	10-50 10-50	Weak Weak	>40 >40	1 3.6

1. Based on these Development Cases and the conclusions from the State of the Art Technology report, specific architectures were identified to be assessed and specific optimisation issues resolved as follows: 132kV AC export with 33kV intra-array[2] arrangement
    - Optimised Study 1 or Base Case
2. 132kV AC export with optimisation of AC intra-array voltage
    - Optimised Study 2.
3. Assessment of 220kV and 400kV AC export as well as GIL with optimised AC intra-array voltage
    - Optimisation Study 3
4. Impact of HVDC export with optimised AC intra-array voltage
    - Optimisation Study 4
5. HVDC export with frequency optimisation of AC intra-array arrangement
    - Optimisation Study 5
6. Medium voltage DC collection to a high voltage converter for export
    - Optimisation Study 6

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[2] Intra-array is used here to describe the system within an array (group of strings) although it is recognised that Inter-array is in common usage to describe such a system.

7. Novel DC design to eliminate requirement for offshore platform
    - Optimisation Study 7

Using the Development Cases and the above architectures some specific questions were identified during the Stage 1 Design Review to be addressed in this study.

- Assess the impact of utilising an AC intra-array voltage other than 33kV for future developments, including non-standard or non-traditional voltage levels.
- Determine the point at which HVDC is a preferred export technology over HVAC export technologies
- Impact of utilising an intra-array frequency other than 50Hz when connected to a HVDC export system
- Benefits of a fully DC offshore systems
- Influence of capitalised cost assessments on connection architecture

Specific groups of studies have been undertaken to optimize and investigate each of these areas.

Additionally during the Design Review on 5th January some further ideas were identified and it was agreed that these should be considered during this phase of the project. Preliminary considerations being given to:

a) Polyphase systems for inter array collection to provide a high level view as to the potential benefits, problems, challenges and opportunities of such an approach.

b) The potential benefit and likely ratings of offshore storage systems for the connection architectures identified.

2. Methodology

2.1. Technical Model

Technical models have been built upon an initial base case. This 500 MW, 33 kV intra-array, 132 kV export case represents an existing state of the art windfarm and has been modelled in detail. This base case architecture allows validation of the model and data against a current design and provides a base for future architecture designs to be built upon.

All significant studies have been carried out in the network analysis software package DIgSILENT Power Factory. Where appropriate, studies have been carried out in whole or in part by a simplified spreadsheet analysis.

Data used to populate technical models has been sourced from a wide range of documents and resources ranging from our contracted sub consultants to supplier literature. Where characteristics are required for equipment which does not exist information has been extrapolated from the costs available and known cost trends.

2.2. Economic Model

The economic model utilised throughout this study is based upon a database of unit costs collated from a number of sources including internal SKM databases, sub consultants and the interview activities carried out as part of the State of the Art Technologies Report. The economic model was also reviewed with the recently published National Grid ODIS report[3]. Where a direct cost comparison is not available costs are extrapolated on a closest match basis taking into account any known cost trends. All costs are based on present day value. Losses have been capitalised which involves assigning a value to each unit of power loss (£/MWh) and also the period of time (years) over which the discount rate will operate. For the purpose of this analysis the following parameters have been used which provide a reasonable current basis for the comparative economic assessments required, given uncertainties that could influence detailed results for specific projects:

- Value of Losses£105/MWh[4]
- Capitalisation Period25 Years
- Discount Rate10%
- Loss Load Factor (LLF)30%[5]

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[3] National Grid, ‘Transmission Networks: Offshore Development Information Statement’, December 2009

[4] Typical figure used by Developer in assessing offshore renewable cost of losses for Round 2 projects

[5] LLF represents the integral of cable loading^2 with respect to time and is equivalent to the average I2R losses in the offshore windfarm and is a typical value.

2.3. Approach

All technical modelling has been carried out to a level of detail appropriate for the studies undertaken; this ranges from spreadsheet analysis of losses and costs to detailed transient and harmonic DIgSILENT models.

Models have been produced by modifying the aforementioned base case. The extent of modelling undertaken for each set of studies is detailed in the relevant section however full renewable development models have only been built for optimised studies as detailed in Appendix A. All other studies use isolated sections of the base case modified to meet the study criteria.

Load flow studies have been used throughout the optimisation and the optimised architecture studies.

Detailed studies such as fault ride-through, harmonic voltage distortion and grid impact have been considered only for the optimised architecture studies.

Economic modelling has been carried out to a degree of detail necessary for the study being undertaken. Detail on the aspects taken into account for each set of studies can be found in the relevant section however general approach has been to include only those pieces of equipment that are affected by the variables being altered in the study.

All economic modelling is by necessity generalised and high level intended to be comparative highlighting cost trends and indicating optimal solutions, it is not intended to be an accurate capital expenditure model which is not possible given the nature of the studies.

3. Studies

3.1. AC Intra-array voltage optimisation

3.1.1. Objective

At present offshore wind turbines are connected in ‘strings’ at a medium AC voltage, typically 33kV. The aim of this section of the connection architectures optimisation is to assess the impact of increasing the voltage level from this typical value to illustrate if advantages can be made.

3.1.2. Model

3.1.2.1. Technical Assessment

Initial studies assessing string architectures (no of turbines per string, no of strings, etc.) have been carried out as spreadsheet studies given the simplicity of the subjects.

Load flow studies have then been carried out in DIgSILENT using the outcome of the initial studies to guide the modelling of the strings by adaption of the base case. In all cases the strings have been modelled and studied as single strings with the results scaled to match full development capacity.

3.1.2.2. Economic Assessment

The cost assessment includes a number of aspects such as the capital cost of the cabling, cost of switchgear, cost of turbine transformer, installation costs and cost of losses. In addition there are a number of other economic factors that have been considered such as the impact on reliability and practical considerations such as the number of connections at the offshore platform (related to the number of strings required).

3.1.3. Methodology

Technical considerations are primarily based on losses and whether the use of higher voltage levels can significantly reduce this to provide a more efficient system. More importantly however is the economic assessment and the trade-off in cost for technical advantage.

In order to assess AC intra-array voltage levels, the standard IEC voltage ratings were considered initially with further non-standard voltage levels to be assessed only if the preliminary work provided sufficient indication of the potential benefits for doing so. This approach has been taken as cable manufacturers currently construct IEC standard voltage rated cables which are available off the shelf in large quantities. If a non-standard voltage was to be selected then bespoke cable would require to be constructed or IEC standard cable would need to be operated outside of its normal regions. There would need to be a significant technical advantage to using a non-standard voltage as the costs introduced by manufacturing a bespoke cable and switchgear would be notable.

With this in mind the preliminary work is based on the following IEC standard voltage levels as seen in Table 1below:

- **Table 1 IEC Standard Medium Voltage Levels**[6]

Rated Voltage (kV)	Nominal Voltage (kV)
36	33
40.5	35
52	45
72.5	66

The first study assessed the maximum number of turbines that can be connected on a string for a given voltage level and turbine rated output. Turbine outputs are taken from those outlined in the scenarios report relating to 3.6MW, 5MW and 7.5MW. Respectively these turbine sizes also relate to a total wind farm size of 500MW, 2000MW and 5000MW. This information has been used to assess the total number of strings required to build the wind farm based on strings consisting of the maximum number of turbines possible.

A single cable cross-sectional area of 630mm^2 is assessed to reduce the number of variables and give a more accurate comparison between the impacts of different voltage levels. Cable tapering is also not included in the assessment as this is a specific design aspect which is carried out to optimise the cost of a specific wind farm construction. By reducing the number of variables the assessment of voltage level is much more focussed. Offshore platforms use J-tube terminations and de-rate the cable by approximately 12% which has been reflected in these studies.

In order to assess intra-array losses an average cable span has been calculated for strings given turbine capacities and associated array spacing. An average intra-array cable span of a typical offshore development utilising 3.6MW turbines with an average minimum array spacing of 0.7km has been estimated using detailed designs of current offshore developments. Span calculations include connection to the offshore platform, additional cable length for raising and lowering from platforms and a contingency of 4% length for termination. This average span was further used to estimate the average intra-array cable spans for 5MW and 7.5MW turbines given the relationship between turbine capacity and array spacing. Average string length has been calculated given average span and number of turbines.

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[6] IEC60038

The parameters defined by the above studies have been used to model the intra-array architectures for the given development capacities of 500MW, 2000MW and 5000MW to which load flow studies have been used to assess losses and reactive compensation requirements.

In practice it is very unlikely that a 5000MW or even 2000MW wind farm would be constructed as a single design and would more likely be made up of modules of smaller developments. The reasons for this would be to increase reliability, comply with grid code stipulations on maximum in-feed losses, other technical considerations such as the maximum capacity of the export cabling/design and economic considerations related to the funding of such large single developments. For this reason an alternative case has been assessed to illustrate the impact of intra-array voltage level based on a 1000MW windfarm using both 5MW and 7.5MW turbines. These modules would then make up the Development Cases of large and very large windfarms through 2x1000MW and 5x1000MW designs with 5MW and 7.5MW turbines respectively. Providing this assessment gives a more realistic view of how very large energy farm connections would be comprised.

Ultimately the economic model has been used to compare the viability of defined intra-array architectures and identify the optimum solutions.

3.1.4. Results

Table 2 below illustrates the maximum number of turbines for a string with cabling data primarily supplied by Cable Consulting International (CCI) and verified against manufacturer's technical data catalogues.

- **Table 2 Calculation of maximum number of turbines on a single string**

					Maximum Turbines on a String		
Cable Voltage (kV)	**Cross-Sectional Area (mm^2)**	**Current Rating in Air (A)**	**Current Rating in J-Tube (A)**	**Power Rating in J-Tube (MVA)**	**3.6MW Turbines**	**5MW Turbines**	**7.5MW Turbines**
33	630	867	762.96	43.61	12	8	5
35	630	867	762.96	46.25	12	9	6
45	630	867	762.96	59.47	16	11	7
66	630	867	762.96	87.22	24	17	11

Table 3 below shows the total number of strings which make up the entire windfarm.

- **Table 3 Required Number of Strings for Specified Wind Farm Size**

	Maximum Capacity of Single String (MVA)			Required Number of Strings for Wind Farm Size		
630mm^2 Cable Voltage (kV)	3.6MW Turbine	5MW Turbine	7.5MW Turbine	500MW Wind Farm	2000MW Wind Farm	5000MW Wind Farm
33	43.2	40	37.5	12	50	133
35	43.2	45	45	12	44	111
45	57.6	55	52.5	9	36	95
66	86.4	85	82.5	6	24	61

Average intra-array cable spans for the turbine sizes investigated are summarised in Table 4.

- **Table 4 Intra-array cable length assumptions**

Turbine Size (MW)	Minimum Array Spacing in Prevailing Wind (km)	Intra-array Average Cable Span (km)
3.6	0.70	1.40
5	0.85	1.70
7.5	1.00	2.00

- **Figure 2 Total System Losses of AC intra-array cable**

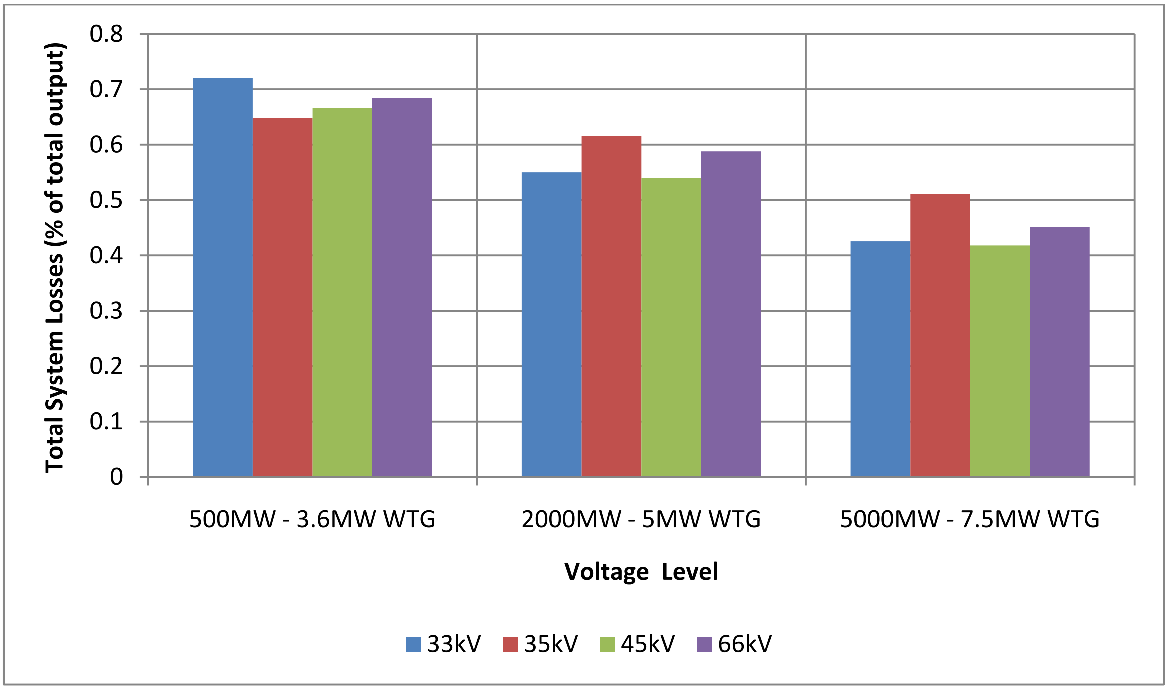
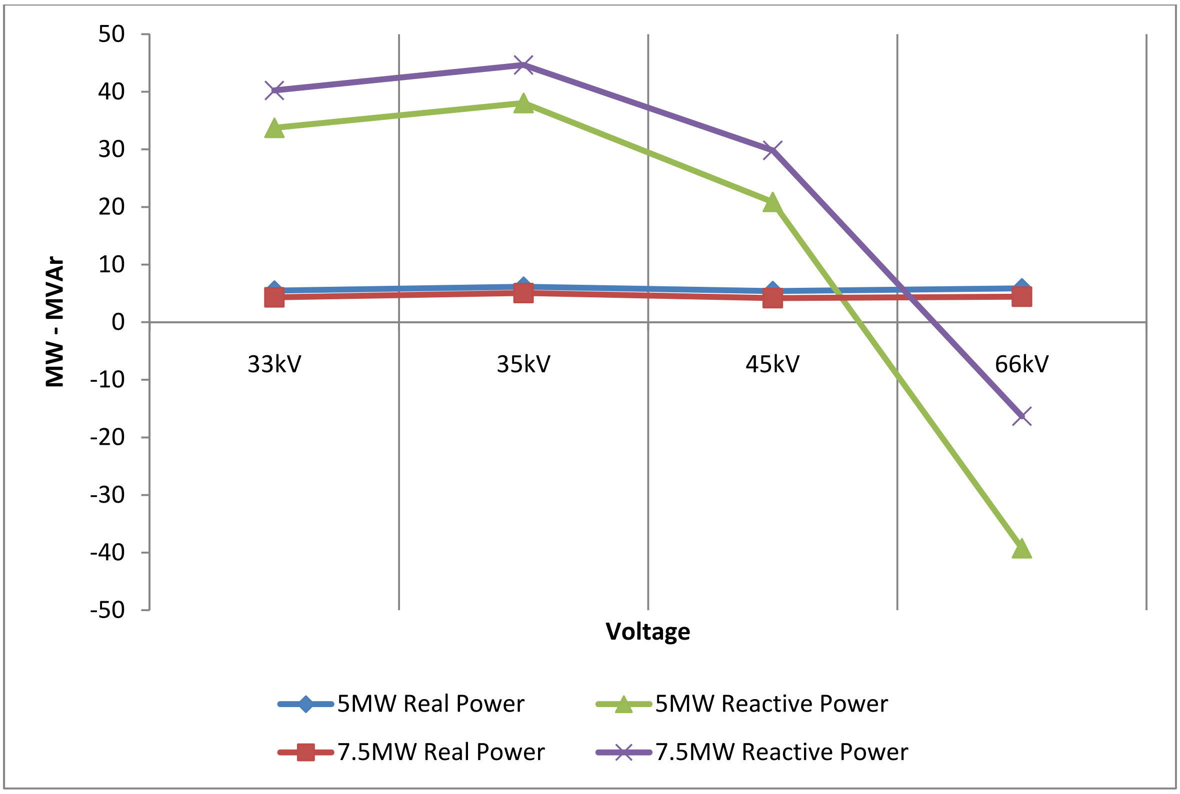


Figure 2 may give a counter-intuitive result to that expected whereby system losses decrease with increasing voltage due to reduced I^2R losses. This is generally the case but specific results can be seen, where losses have been influenced by a number of variables affecting the voltage level over and above the basic resistive losses. The construction of the cable, inductive and capacitive components, string length and other variables significantly impact on the losses throughout the entire system. It is important to note the % relative loss difference between voltages is very small at less than 0.1%, the relative loss difference between voltage levels can therefore be defined as comparable and completely dependent on detailed design. A more significant observation is that losses decreases across all voltage levels with increase in turbine capacity.

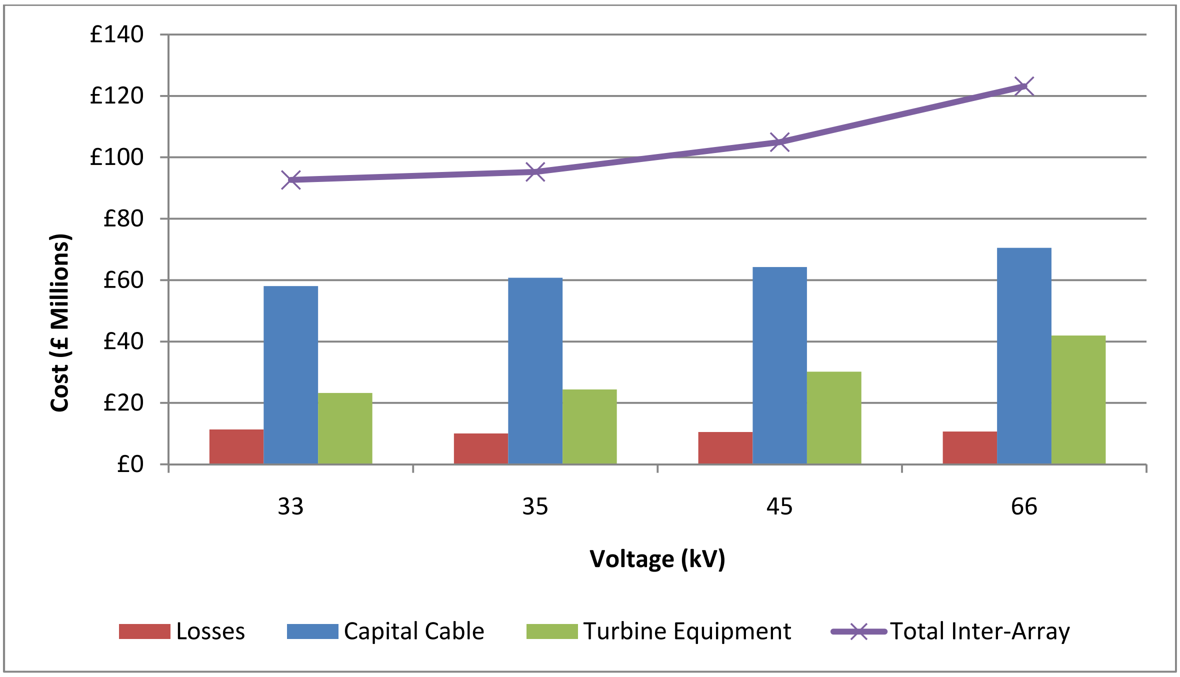
Figure 3 below illustrates the real power losses and reactive power contribution from the 1000MW system. It can be seen that in terms of losses there is very little difference in increasing the voltage level, however the reactive power contribution decreases dramatically which has advantages in reducing the amount of offshore reactive compensation required.

- **Figure 3 1000MW Windfarm Loss and Reactive Power Assessment**



Initial technical assessment has shown that 45kV has marginally lower real power losses and reactive power contribution than present 33kV designs. These advantages are minimal however and it must be economically advantageous to be a feasible solution. Figure 4 below illustrates the costs involved with intra-array voltages and is based on the base case architecture designed to be a benchmark for all Development Case architectures. The main impact of 66kV being the reactive power contribution.

- **Figure 4 Base Case Intra-array Costing**



It is clear to see that there is a rising trend in cost as intra-array voltage increases. This reflects the increased capital cable and turbine equipment costs which far outweigh the savings made through reduced losses. This would show therefore that although 45kV is marginally a better option in a technical sense it is clear that 33kV is still the preferred option due to savings in the region 20% that can be realised.

A limiting factor on AC platform capacity is the number of possible connections which is limited by cost. Given a fixed development capacity lower intra-array voltages result in a greater number of strings which in turn requires an increased number of connection points at the platform. By doubling the voltage the number of connections is halved. The maximum number of connections available at 33kV is approximately 15 which relates to a power of 600MW assuming maximum string length can be achieved on all strings. Hence for a 1000MW module which whilst not a development case has been considered for its importance as a building block, it will be necessary to have two 33kV offshore platforms or one 66kV platform.

A simple costing analysis of a 1000MW system utilising 33kV and 66kV collection voltages illustrates that the additional cost of 66kV architecture is in the region of £25M with the use of 5MW turbines and £15M with 7.5MW turbines. This includes the necessity for two offshore platforms at 33kV and only one at 66kV and illustrates that 33kV is the most cost effective solution for both architectures and will be used as the optimised intra-array voltage for further studies. It should be noted however that savings are minimal and will be subject to cost sensitivities and on the design of a specific development.

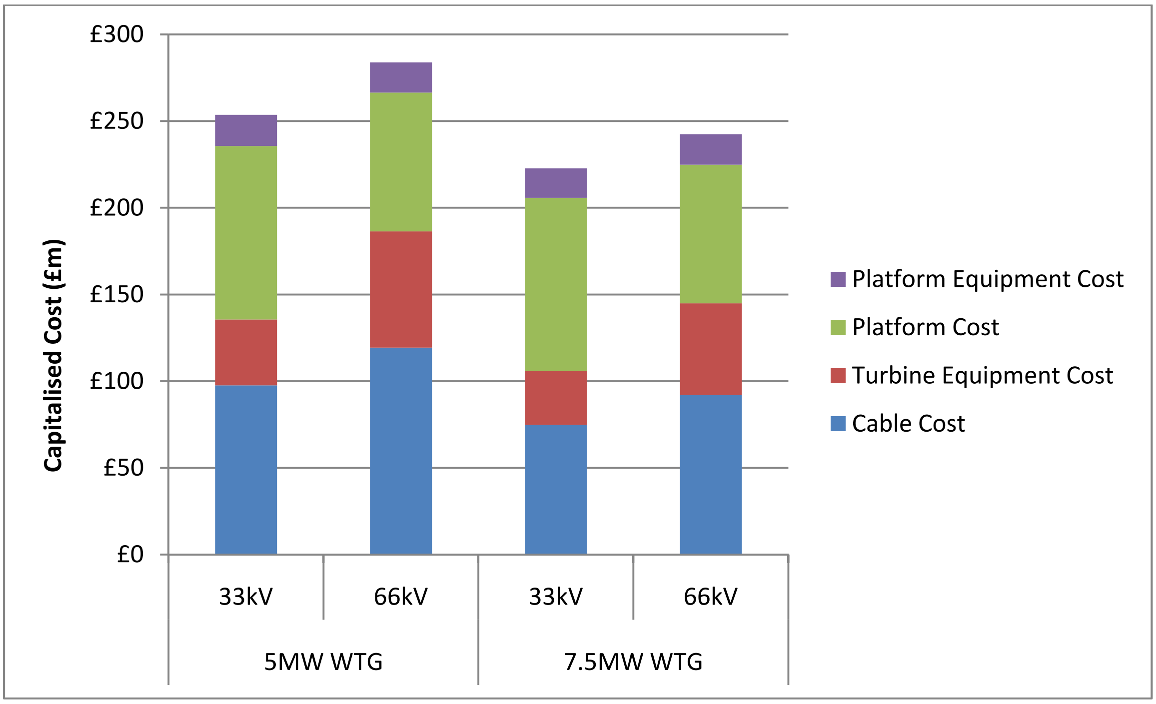
3.1.5. Analysis

In both the full system and reduced module assessments it has been seen that there is a small technical benefit in increasing the voltage level. The optimum being 45kV which provides reduced real power losses and reduced reactive power contribution. Both of these factors relate to an overall reduction in losses within the system, however when considering the relative cost assessments it can be seen that 33kV intra-array voltage is optimal across all cases, factoring the additional cost of losses which this voltage brings. This is primarily due to the reduced cost in turbine equipment and cabling which far outweighs the increased losses. The optimised intra-array voltage is therefore seen to be 33kV and will be used for further optimised studies where AC intra-array technology is used.

3.1.6. Analysis Sensitivity

A simple sensitivity analysis on Figure 4 shows that the main cost drivers are the turbine equipment (switchgear and transformers) and cable capital cost. Should these costs be reduced by 20% and 10% respectively for 45kV then there would be reason to see this voltage as a more optimal solution.

- **Figure 5 Breakdown of Costs of 1000MW intra-array Architecture.**



The use of 66kV over 33kV on a 1000MW system is mainly influenced by the individual energy farm design where multiple platforms may be more economical due to long string lengths required to connect to a single platform. Figure 5 illustrates the cost breakdown for such a design and the savings in platform cost at 66kV in the region of £20M can be seen, however the added cable and turbine equipment costs at this voltage level make it overall a more expensive option.

3.2. Export Connections

3.2.1. Objective

With regard to offshore renewable export connections two main aims have been identified, firstly to identify the optimum AC export voltages for given windfarms, and secondly to identify the break point between AC and DC technologies. Break point refers to the distance and power at which one technology becomes technically and/or economically superior to another. With AC (132kV) and HVDC the breakpoint is generally accepted to be 1000MW and 70km[7]. A series of studies have attempted to confirm or question this convention. Further the effect that non-standard AC solutions could have on the break point has been investigated; this includes higher voltage connections (220kV and 400kV), reactive compensation platforms and gas insulated lines (GIL). A more detailed account of results is included in Appendix A and B with a summary included in this section.

3.2.2. Study Model

3.2.2.1. Technical Assessment

In all studies the export connection has been isolated from the intra-array connections with the windfarm modelled with an equivalent lumped power source only. In the AC export studies reactive compensation has principally been applied in two configurations, 100% onshore, and a 50/50 split onshore/offshore with some selective consideration given to intermediate compensation platforms. All AC studies have been carried out in DIgSILENT PowerFactory with the results collated and analysed via spreadsheets.

For HVDC the majority of technical modelling has been carried out in spreadsheets given the comparative nature of the studies and the simplicity of the loss model associated with HVDC connections and converters. A selective number of studies have been replicated in DIgSILENT PowerFactory to verify the spreadsheet results.

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[7] General consensus across a number of manufacturers and reports. Quoted in “Electrical Cables Handbook” BICC Cables 1997

3.2.2.2. Economic Assessment

The economic assessment has been carried out to quantify the cost implications of applying the technical solutions analysed in the technical assessment. A connection option that is technically superior to another is unlikely to be the preferred option if it is also the most costly option (assuming both options meet all relevant regulatory requirements).

Cost estimates include the cost of export cable, HV switchgear, collector platform transformer and onshore/offshore reactive compensation including related additional platform costs, converter platform and onshore converter station for HVDC and capitalised cost of converter and cable losses.

3.2.3. Methodology

The following AC options were considered as part of this study group;

- Load flows on single circuits determining cable capacity (received power with thermal loading at 100%) against distance carried out for 132kV (1200mm^2 3 core), 220kV (1000mm^2 3 core), 400 kV (1200mm^2 single core), 280kV GIL and 550kV GIL for the aforementioned reactive compensation arrangements.
- Load flows and comparative costs on export architectures for 500 MW and 1000MW developments applying 132kV, 220kV, 400kV and 280kV.
- The export connections of developments greater than 1000MW and smaller than 500MW have been investigated from a high level perspective adapting the detailed information acquired as part of the 500MW and 1000MW studies. In general it has been assumed that developments of 2000MW or greater will be constructed as multiple smaller blocks of 1000MW in the short to medium term (up to 2030.

The above studies have been compared to identify the relative advantages and disadvantages of one technology or voltage over the others. Where optimum connection costs have been quoted for a given voltage, optimum refers to the cheapest option between 100/0 reactive compensation split and 50/50 reactive compensation split utilising shunt reactors.

Shunt reactor reactive compensation has been optimised for cable performance maintaining an onshore bus voltage of 1pu while maintaining an acceptable offshore bus voltage of 1pu +10% margin. Standard nominal AC voltages have been used for conventional AC export, for GIL the voltages and capacites used represent the full range available as quoted by the manufacturers.

HVDC losses have been calculated for 500MW and 1000MW bi-pole connections for use in economic modelling. 500MW and 1000MW have been selected as technical restrictions limit HVDC single circuit connections to just over 1000MW which aligns closely with SQSS[8] limitations on normal and infrequent infeed loss risk of 1000MW and 1320MW respectively. However even taking into account expected regulatory changes (new nuclear 1800MW) and technical advances single circuit connections are unlikely to exceed 2000MW without a level of redundancy. Capitalised costs of HVDC up to 2500MW have been estimated assuming the development of the necessary cables and devices as outlined in the State of the Art Report.

For HVDC export connection voltage is assumed to be the minimum voltage required to facilitate the export power given the converter current rating. Existing voltage source converter current rating is around 1800A equating to around 540MW at ±150kV and 1152MW at ±320kV aligning with the selected converter capacities. Cable size has been selected as the smallest required to accommodate the export current for each 500MW/1000MW block.

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[8] Note that the SQSS must be considered in terms of the assumptions it is based upon, namely limited to windfarms up to 100km offshore and up to 1500MW. The developments considered within this report would fall outside of these assumptions and therefore a review of the regulations will be required.

3.2.4. Results

3.2.4.1. Technical Analysis

- **Figure 6 Summary of Single Circuit Export Technical Limits**

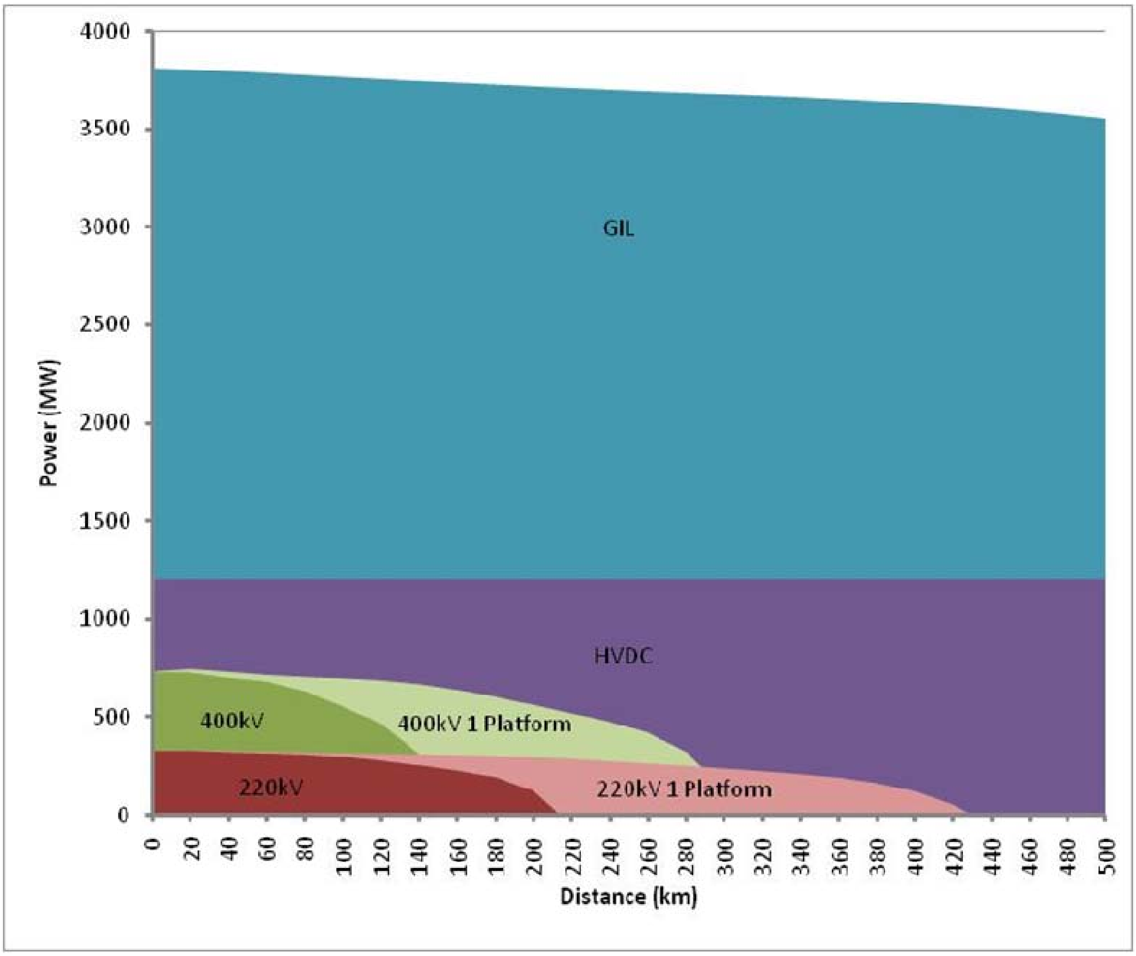


Figure 6 shows the technical limitations of the considered range of export technologies. 220kV and 400kV AC capabilities have been given based on a 50/50 onshore/offshore reactive compensation split as well as the shown case with a single reactive compensation platform 50% along the export connection circuit. The Capabilities of HVDC shown are based on present bi-pole maximum capacity limited currently by the XLPE cable export voltage. The GIL capability shown is indicative based on a 550kV connection.

It is evident from Figure 6 that export distance of standard AC connections is limited. This distance can be extended by introducing reactive compensation platforms. However this incurs a significant cost that will impact on the cost viability of the option. It is important to recognise that although an AC cable may be capable of exporting a power over a given distance, the amount of reactive compensation that is required may make it uneconomic to do so. The point at which the reactive compensation exceeds 50% of the export real power could be considered as the point at which this becomes significant, and consequently begins to impact adversly on the cost of the option. This value is similar in either 100/0 or 50/50 split of reactive compensation and is approximately 70km for 220kV and only arround 40km for 400kV.

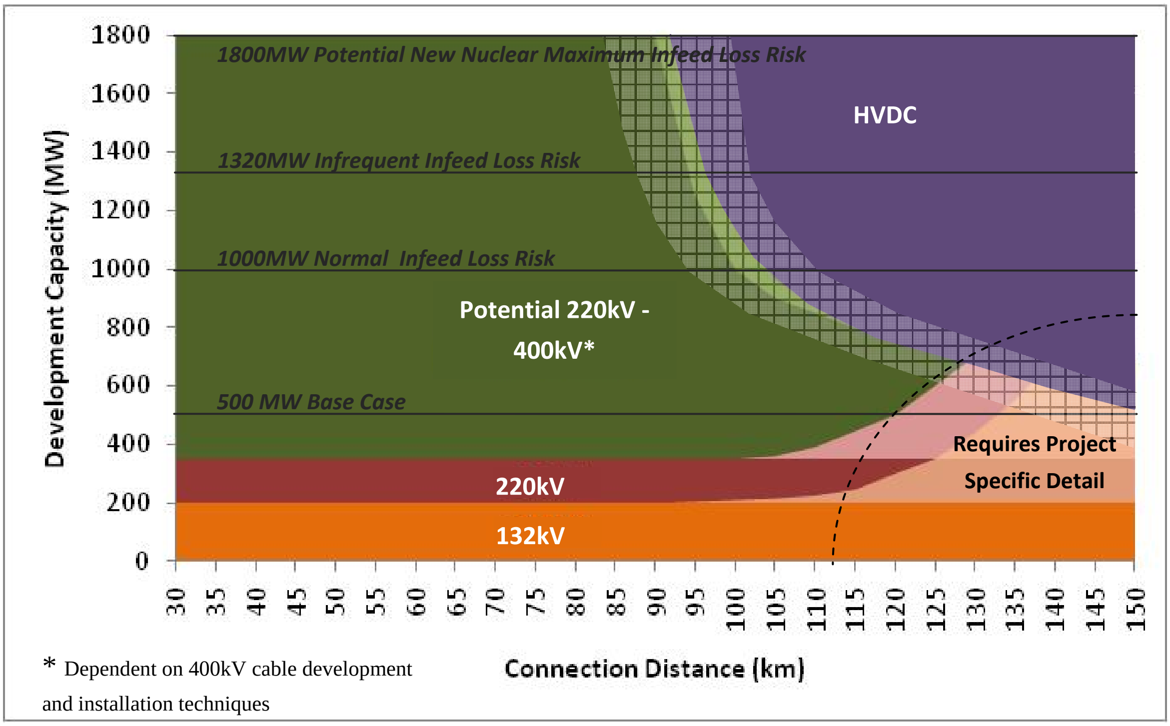
For presentational clarity 132kV has been ommited from Figure 6, however it has an export characteristic similar to 220kV and 400kV, with a maximum export power of arround 200MW and a technical distance limit for 50/50 reactive compensation split of arround 300km. It is expected that 132kV will still be economicaly viable for developments smaller than 200MW and could be adopted extensively for small wave and tidal projects.

There is no distance related restriction for HVDC export conections for the cases considered. That said at present offshore application of HVDC has been limited to relatively small capacity converters and connections with limited opperational history. However, there has been a large amount of development time comitted by suppliers to address the present technical limitations and cosequently the application of high capacity HVDC is considerd to present only a moderate risk.

Unlike HVDC, GIL export capacity reduces with distance, as with convetional AC. However, over the distances considered in this report and the corresponding offshore developments likely in UK waters over the next twenty to thirty years there is only a modest reduction in export capacity with relatively insignificant reactive compenstaion requirements. It is clear that GIL has a very high bulk export capacity, however the technology is unproven offshore attaching significant risk to its application.

3.2.4.2. Economic Analysis

- **Figure 7a Summary of Export Economic Analysis**



* Dependent on 400kV cable development and installation techniques

Figure 7a shows the economic bias for the considered export technologies, over a range of development capacities and connection distances. Indicative breakpoints for the range of technologies are clearly indicated.

The potential for using higher voltage AC is clearly shown as preferable for windfarms over 200MW, with 400kV potentially viable over 350MW. The advantage of 400kV (dark and light green) over 220kV is relatively limited and requires the development of 400kV three core cables of significant conductor size or the development of laying vessels/techniques to facilitate the simultaneous laying of three single core cables. Without these developments there is no significant advantage of using 400kV over 220kV. The application of 400kV increases the breakpoint between AC and HVDC by only around 5km. Should 400kV not be viable, 220kV would replace 400kV on the figure up to the limit of the Dark Green.

The effect of offshore reactive compensation platforms is loosely indicated in the lower right hand corner of the figure. The sloping lightly shaded areas indicate the economic bias without the application of platforms, the continuation of the flat solid areas indicate the application of a single platform. This area of the figure is the most variable with a number of factors potentially affecting the recommended technologies and consequently further analysis would require detailed design.

The main potential variation would be for intermediate reactive compensation platforms to increase the breakpoint distance between HVDC and AC for low capacity long connection distance developments. However, the reality is that developments smaller than 500MW at distances greater than 130km are considered unlikely in UK waters over the next 20 to 30 years and so not considered further.

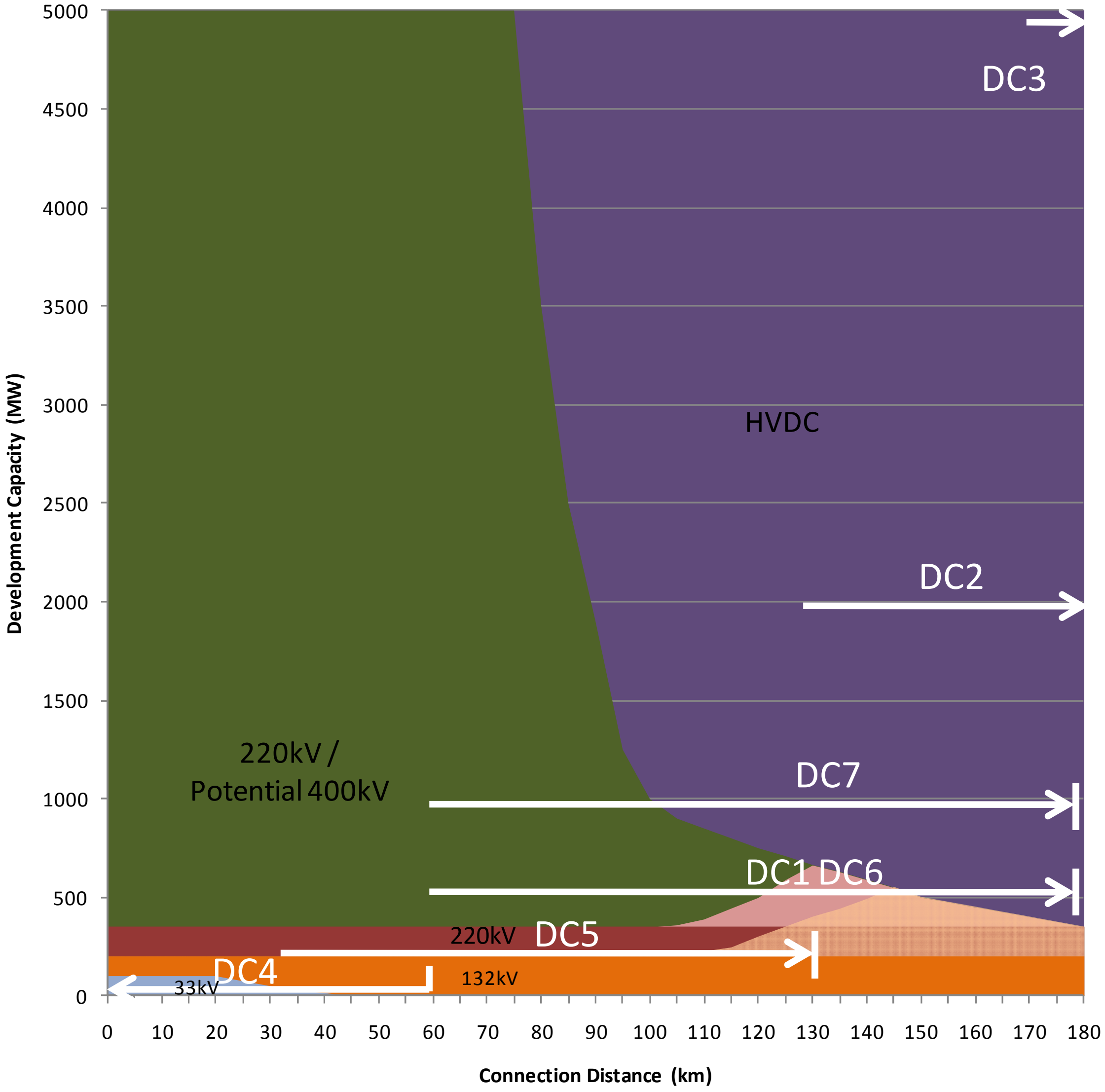
Based upon a 1000MW development reactive compensation platforms do not become cost effective at 400kV until over 110km. HVDC becomes viable at around 100kmso there is no advantage to using reactive compensation platforms for 400kV connections. Platforms become viable for 220kV connections over 100km making them similarly uneconomically attractive.

The break point between AC and HVDC is shown with a crosshatch area indicating a degree of variability based on the economic factors (such as energy and commodity costs) considered in this analysis.

HVDC is based on a bi-pole arrangement with no metallic return. This method is the most cost effective, but has availability issues. A cable or converter fault would result in the whole connection being taken out of service. The addition of a metallic return would improve availability slightly, by allowing 50% capacity in the event of a single cable or converter loss. This advantage is limited by the bundled laying of the cables which make the likelihood of a fault effecting more than one cable high. The additional cost of installing a metallic return would be approximately 50% the total cabling cost without the metallic return and consequently the advantage of the option is limited. More reliable arrangements can be used, however all involve laying cables separately which will increase costs further. Another option is to use marine electrodes, effectively replacing the metallic return with water. This option would be significantly cheaper than using a metallic return, however potential significant environmental issues make such an arrangement unlikely to be adopted in the future. Note that the HVDC area in Figure 7a assumes a single bi-pole connection.

Figure 7b shows a summarised and simplified representation of the analysis presented in Figure 7a to illustrate where the Development Cases (DC 1 to DC7) from the original Scenarios Report, and listed again in Figure 1of this report, would be represented on this scale. It should be noted that this is for illustrative purposes only and the tipping points outside of the scale presented in Figure 7a are not based on specific studies.

- **Figure 7b Summary of Export Analysis Summarised to Highlight Development cases**



- **Figure 8 1000MW 132kV, 220kV, 280kV GIL Comparison & 3500MW Optimised 220kV AC and 550kV GIL Comparison**

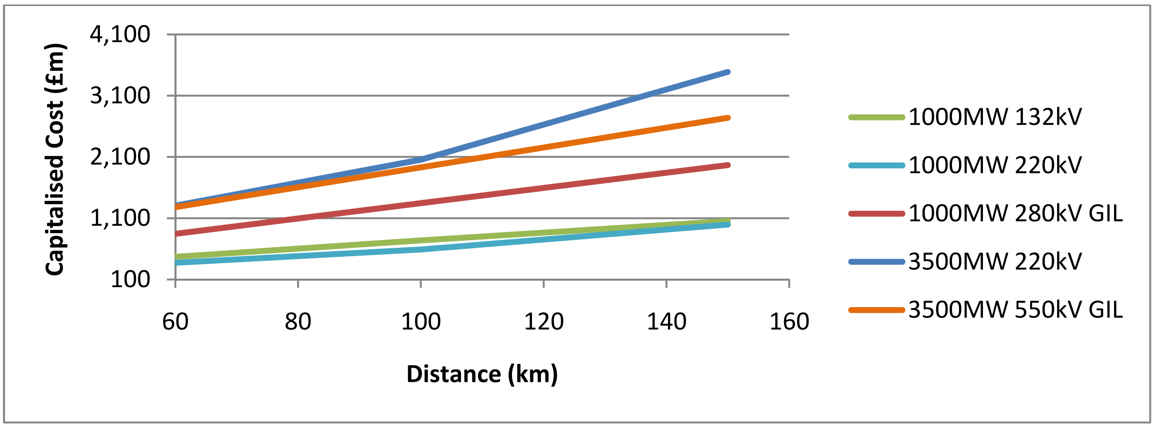


Figure 8 shows optimum connection architecture costs for the 132kV, 220kV and 280kV GIL export of a 1000MW development between 60km and 150km. GIL is consistently the most expensive option at this capacity despite requiring very little reactive compensation and only a single circuit.

Figure 8 also presents an indicative capitalised cost for a 3500MW energy farm connection as a single 550kV GIL circuit or as standard 220kV AC. GIL is relatively cheap in this application as the increase in connection cost is small compared to increase in connection capacity, although this aspect of GIL could prove problematic for large connections in terms of SQSS compliance.

3.2.5. Commentary on Results

Our studies have shown the HVDC, AC breakpoint for 132kV AC to ba around 1000MW and 70km confirming the generally accepted value. Increasing AC voltage will reduce connection cost significantly, 220 kV which has already been developed as prototype appears to represent the optimised AC export voltage for Development Case ‘distributed smaller windfarm’, replacing the 132 kV export of the base case. 400 kV export could provide further savings up to 100km connection distance however significant development of export AC cables and installation techniques is required to facilitate its application.

The above results show that GIL is technically a very attractive proposition. However, with each phase required to be laid expensively and separately as a pipe, it is the cost and practical issues that limits its viability not taking into account issues with present and anticipated SQSS requirements. The primary benefit of GIL is the ability to have high capacity circuits that require relatively little reactive compensation to export very long distances. Current SQSS infrequent in-feed loss limits make a 1320MW connection the largest possible at present and so GIL will never be attractive. For GIL to become attractive regulations would have to be changed to allow much larger capacity single connections, larger even than the revised SQSS that may be introduced to accommodate new single shaft nuclear generation. This study is based upon very basic GIL cost data due to the lack of previous applications and only serves to show the potential for GIL in bulk export that could warrant further investigation.

By applying 220kV AC export the 1000MW 70km break point identified for 132kV AC could be pushed closer to around 1000MW 100km. 220kV AC XLPE submarine cables have been developed and tested making their wider application in the future likely given the above results. The cost difference between 220kV AC and HVDC is relatively small over 90km and there is potential for HVDC to be chosen in preference to AC due to the operational benefits such as complete control over converter output despite the additional cost. Over the distances considered AC is always the cheapest option for 500MW developments. For windfarms of 2000MW or larger the export is most likely to consist of multiple 1000MW connections given the combination technical, economic, and regulatory issues talked about previously and so the break point remains the same. A 3 core 400kV export cable could increase the break point; however the reactive compensation requirement above 100km ensures that the increase in break point will be limited.

Both the 220kV and 400kV export options require large amounts of reactive compensation to be installed offshore. The cost estimate in this report has taken into account platform cost related to the reactive compensation placed offshore however no limit on platform topside area has been applied. Practical limitations on platform size could result in multiple smaller platforms at significantly greater cost.

3.2.6. Commentary on Project Development Costs

- **Figure 9 Breakdown of Costs for 500MW Architecture Comparison**

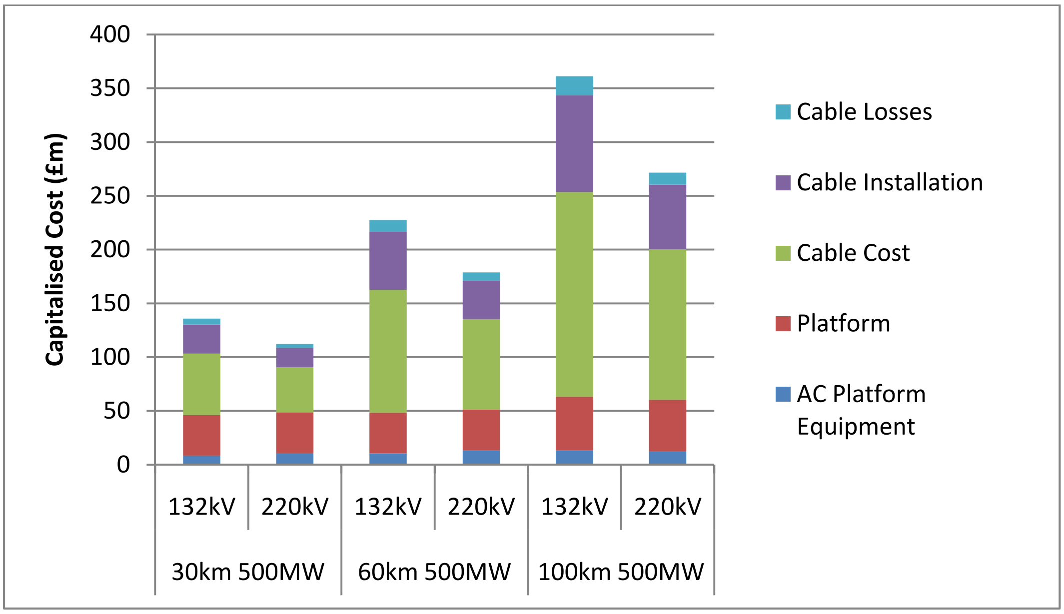
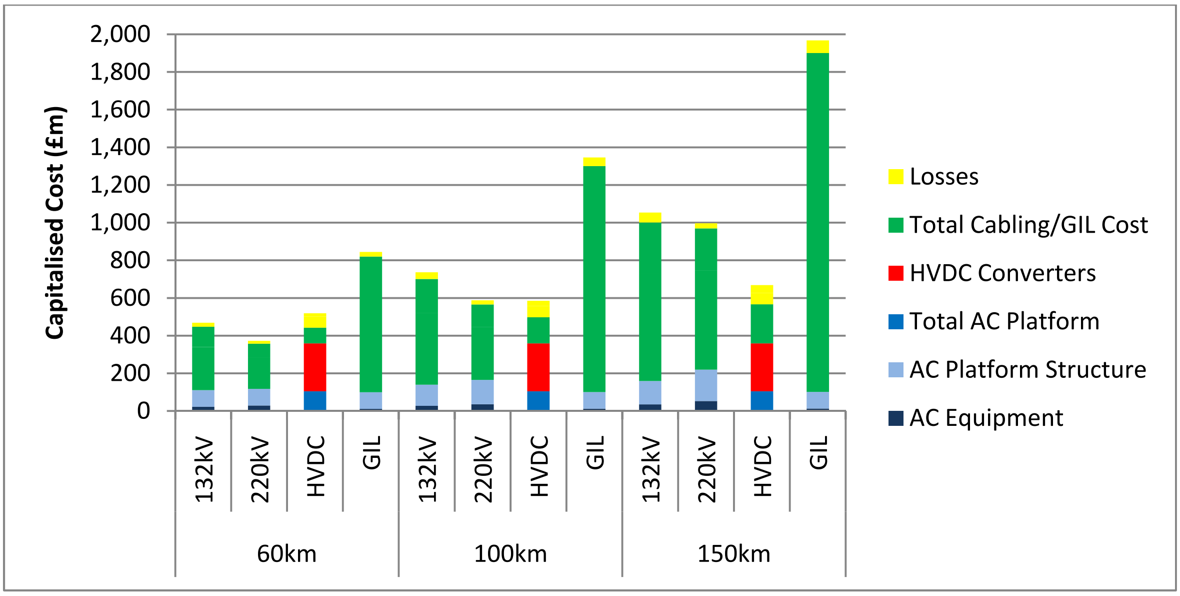


Figure 9 shows the relative significance of connection architecture equipment for a 500MW development. Immediately apparent is that cabling costs (both cable cost and installation cost) are the distinguishing factor between alternative project connection distances. Any Variation in cabling costs will directly impact on the overall development cost. That said variations to the cable capital, installation and associated costs would impact on all the connection options shown in Figure 9 and would not thus be expected to cause the outlined capital cost trends to change.

Losses and the considered offshore platform equipment costs are relatively small such that any variance would not be significant in the overall cost comparisons.

Platform costs are a significant factor for a given development size, that said platform costs are relatively constant only increasing noticeably for longer distance 400kV connections due to reactive compensation requirements.

- **Figure 10 Breakdown of Cost for 1000MW Architecture Comparison**



The above Figure 10 presents a breakdown of costs for the alternative export connection technologies. The chart shows clearly the relative weighting of cost components of the connection. The most significant cost components are cabling/GIL costs as well as converter costs associated with the HVDC options.

Variance in AC equipment and platform costs will be reflected across all architectures making the overall conclusions insensitive to such changes. Electrical losses are too small a cost to influence the selection of one technology over another but would be expected to influence the final detailed design of the connection.

Very high cabling costs for AC architectures results in a strong sensitivity to variance in cabling costs. For example the AC/HVDC break point (1000MW 90km) shifts in inverse proportion to the % increase in AC cabling costs, i.e. a 20% increase in cabling costs results in an approximate 20% decrease in breakpoint distance.

HVDC cabling costs are less significant than converter costs. The break point increases and decreases proportionally with HVDC converter costs (capital and installation) however with a ratio of only ¼, i.e. a 20% increase in HVDC converter cost relates to only an approximate 5% increase in break point.

3.3. Frequency Optimisation

3.3.1. Objective

With the application of HVDC connections the windfarm effectively becomes isolated from the grid raising the possibility of applying a frequency on the windfarm other than the standard 50Hz. The change is simplified further with the present use of ‘back-to-back’ AC/DC/AC converters used at the turbine. These converter frequencies could be increased relatively easily to accommodate a new intra-array operating frequency. The objective of this group of studies is to identify the viability of a range of frequency options.

3.3.2. Model

Various aspects of frequency variation have been assessed using spreadsheet analysis given their simplicity. The characteristics defined in these preliminary studies have then been applied to DIgSILENT models to assess reactive power flows and cable losses.

3.3.3. Technical Assessment

3.3.3.1. Advantages of increasing frequency

The advantages seen in increasing operating frequency are mainly in the physical size and weight of components, specifically transformers. This is given by the relationship seen below which illustrates that the core cross-sectional area of a transformer is inversely proportional to the frequency.[9]

$$A \propto \frac{VPT}{f} \quad \text{Where A = Core cross-sectional area and VPT = Voltage per Turn}$$

As the core is the major component in a transformer it can be approximated that the total transformer size and weight will reduce in proportion to an increased frequency. In an offshore environment where the size and weight of offshore platforms to support this equipment is expensive it could be of advantage to increase the frequency.

3.3.3.2. Disadvantages of increasing frequency

Skin Effect Losses
As frequency increases then issues can arise in terms of effective and efficient power transfer. Skin effect reduces the effective conductor size of cables and increases AC resistance. This has a considerable impact on very high frequency applications (MHz – GHz region) but due to the high power transfer nature of the offshore network, small changes in resistance due to skin effect could

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[9] O.Elgerd and P.Van der Puije, ‘Electric Power Engineering’, Springer, 1997, pp.196

also have a high impact. The reduction in skin depth and concurrent increase in AC resistance due to increased operating frequency is shown in Table 5. These calculations are based on a solid core conductor as have been used throughout these studies. Should a stranded conductor be used skin effect may be reduced as the total surface area of a stranded conductor is greater than that of a single core conductor, however due to the air gap between the conductors the average resistivity is increased and proximity effect may be more prominent.

- **Table 5 Impact of Skin Effect on Frequency**

Operating Frequency (Hz)	Skin Depth (mm)	Effective AC Resistance (Ω/km)[10]	Percentage AC Resistance increase against 50Hz
50	10.70	0.030	0.00%
60	9.81	0.032	5.61%
75	8.78	0.034	11.59%
100	7.60	0.037	22.43%
200	5.37	0.048	58.88%

It can be seen that the skin depth dramatically reduces as operating frequency increases, reducing the overall usable conductor size and hence increasing the effective AC resistance. For a small increase in frequency this is relatively small, however at 100Hz and particularly 200Hz there is a considerable increase in resistance which will in turn impact on I^2R losses.

Reactive power contributions

The reactive components of equipment are highly affected by a change in nominal frequency and subsequently impact on the reactive power transfers. The relationships given below illustrate how capacitive reactance is inversely proportional to operating frequency and inductive reactance is directly proportional.

$$X_l = \omega L = 2\pi f L \qquad X_c = -\frac{1}{\omega C} = -\frac{1}{2\pi f C}$$

Hence by increasing the frequency the capacitive reactance will decrease, however the inductive reactance will increase resulting in a shift in the reactive power flow from capacitive to inductive.

Figure 11 below illustrates the impact frequency has on reactive power flow at the collector platform for the base case architecture. It must be noted that for the purpose of all analysis a single conductor size of 630mm^2 is used to provide a simple comparison of the effect that varying operating frequency level has on system reactive power flow for a range of voltage levels. In practice there will be more optimum solutions to the design based on restricting conductor size or a

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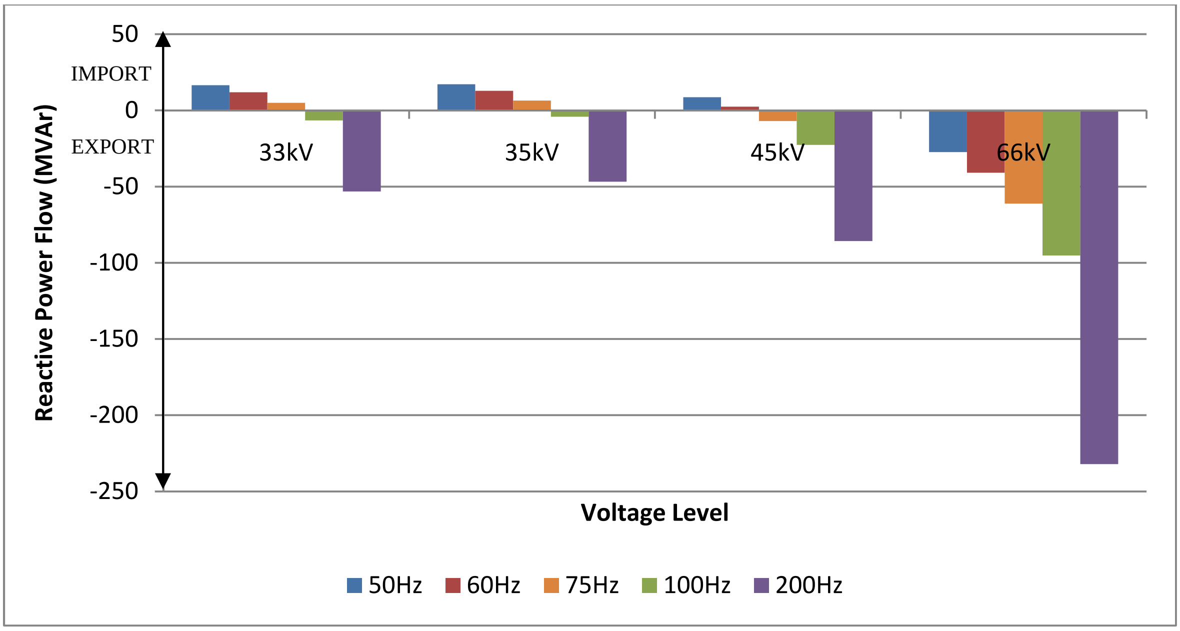
[10] DC Resistance 630mm^2 0.0283Ω/km 33kV– ABB Cable Datasheet

range of other techniques, however these are design specific details which are not assessed in this work. It can be seen that increasing frequency levels changes the system flow of reactive power from capacitive to inductive. Additionally, with increasing voltage levels, the cable construction due to increased insulation means that increased reactance and reduced capacitance further accentuates the impact which increased frequency has on reactive power flow.

- **Figure 11 Total System Reactive Power Flow for 500MW wind farm using 3.6MW WTG**



Other losses

There are a number of other losses that are apparent in AC systems and dependent on frequency. As the use of a non 50Hz frequency on the intra-array network requires the use of HVDC as an export technology to isolate the offshore and onshore grids there are additional switching losses that can be assumed to increase proportionally to the frequency. In addition to the VSC switching losses, there will also be switching losses in the generator converters which will increase with frequency.

As well as switching losses there are also hysteresis and eddy currents present within transformers which are related to supply frequency. The relation between these losses and frequency are given below and illustrate that hysteresis losses in transformers are proportional to the frequency whilst eddy current losses are a complex function of the square of supply frequency and Inverse Square of the material thickness.[11]

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[11] M.J.Heathcote, 'The J&P transformer book: a practical technology of the power transformer', Newnes, 1998, pp.41

Hysteresis loss, $W_h = k_1 f B_{max}$ watts/kg

Eddy current loss, $W_e = \frac{k_2 f^2 t^2 {B_{eff}}^2}{\rho}$ watts/kg

Combining the losses in this section gives a increased total loss which has been estimated at 20% for use in the subsequent economic assessment for an increased frequency of 100Hz.

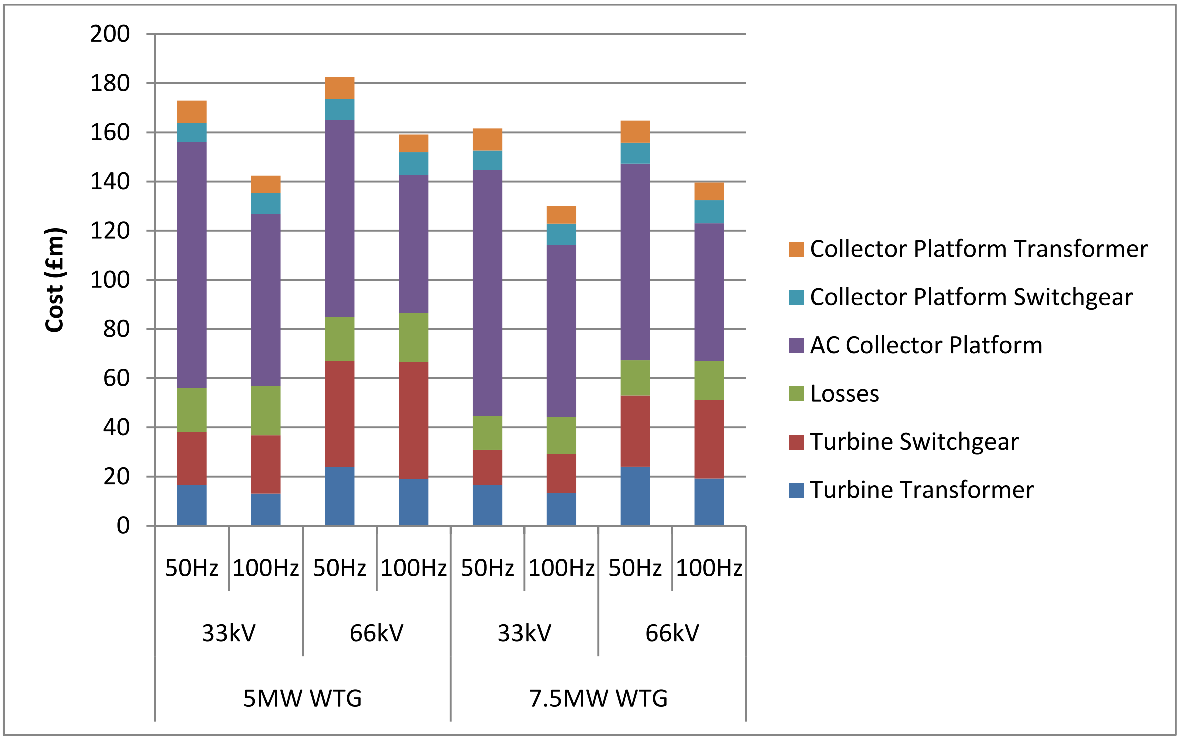
3.3.4. Economic Assessment

By changing the operating frequency away from common 50/60Hz operation there may be difficulties in procuring bespoke equipment. This may be particularly applied to switchgear which is generally taken as a commodity item. In addition the development of switchgear equipment may be required to operate at the faster times dictated by a higher frequency system. As this equipment is not generally available, cost assumptions have been made based on the availability of standard equipment and savings in materials that can be made. For instance, transformers and cables for large scale offshore projects are largely going to be designed for purpose and so cost prices are based purely on other savings/expenses. In contrast as switchgear is a commodity item, bespoke equipment not usually required will need procurement and the added costs implicated with this. The following assumptions have therefore been made for 100Hz operation based against 50Hz equipment and can be scaled appropriately for interim frequencies:

- Transformers-20%
- Platforms-30%
- Switchgear+10%
- CablingNo Change
- Losses+20%

A simple cost comparison between a 1000MW, 33kV AC collector system at 50Hz and 100Hz has been completed using the assumptions given above and is shown in Figure 12. It can be seen that the main savings are made on the capital cost of the platform and that the cost of losses is much less significant. Therefore it is seen that a 33kV collection system operating at 100Hz could provide savings to the sound of 15% compared to that operating at 50Hz. With a higher collection voltage of 66kV the savings made on platform cost are reduced by half as only a single platform is required. Savings in the region of only 5% can be seen which provides indication that cost sensitivity is high with this architecture.

- **Figure 12 Cost comparison of 50Hz and 100Hz intra-array operation**



3.3.5. Analysis

Review and analysis of Figure 11 confirms that the use of an intra-array frequency greater than 100Hz does not appear to be technically feasible, principally due to the increase in reactive power contribution which greatly increases the capital cost of the necessary reactive compensation equipment (including platform costs) or requires the export cable to be over-sized, either of which will offset the savings made through operation at increased frequency. Interim frequencies between 50Hz and 100Hz could provide some potential advantages over operation at 50Hz, although the cost savings would be less significant and the benefits could be marginal (i.e. adopting a non-standard operational frequency will inevitably result in additional equipment design, manufacture and type testing costs over currently available 50Hz equipment, which may offset frequency related cost savings if the frequency chosen is not high enough). Therefore, if considering the adoption of an alternative intra-array operational frequency, the optimum, based on preliminary costs, would appear to be 100Hz which provides the greatest savings in equipment weight whilst balancing the costs of reactive compensation equipment, export cable(s) rating and size and intra-array electrical losses.

However, whilst this analysis has shown that a higher intra-array operational frequency can provide some benefits, as intra-array equipment is not commonly available at frequencies >60Hz the costs shown are informed estimates based on the expected reduction in equipment materials and increased transmission/conversion losses. The main cost savings realisable are in the platform and transformers, largely due to the reduction in equipment weight through the design which can significantly reduce their associated capital cost, more so than other items of equipment. If on more detailed analysis it is found that the true cost savings through operation of intra-array equipment at higher frequencies are found to be less than around 20% of the comparative 50Hz design, there would appear to be little merit in pursuing this avenue of technology design change further.

3.4. DC Collection Systems

3.4.1. Objective

To explore the potential feasibility and benefits of a DC collection system in conjunction with a DC export system.

3.4.2. Model

3.4.2.1. Technical

Initial studies assessing string architectures (number of turbines per string, number of strings, etc.) have been carried out as spreadsheet studies given the simplicity of the subjects.

Load flow studies have then been carried out in DIgSILENT using the outcome of the initial studies to guide the modelling of the strings by adaption of the base case. In all cases the strings have been modelled and studied as single strings with the results scaled to match full development capacity.

3.4.2.2. Economic

The cost assessment includes a number of aspects such as the capital cost of the cabling, cost of switchgear, cost of converters, installation costs and cost of losses. In addition there are a number of other economic factors that have been considered such as the impact on reliability.

3.4.3. Methodology

With the expected significant use of HVDC as an export technology it is possible to create a fully DC offshore network. The main advantages of this would be to reduce the number of conversion stages and hence losses seen in the collector system. There are two approaches which have been assessed in this section of the report, namely a parallel and a series connection arrangement which will be discussed further below.

An issue which was brought to light in the manufacturers interviews and has been realised in these studies is the need for DC operating voltage standardisation. It has become apparent that should

DC grids become fully realised then standardisation will need to be carried out to allow the fast progression and development of new equipments, specifically switchgear. For this task a range of DC voltage levels have been assessed to show the impact of high and low voltage intra-array DC connections.

The DC voltage level has a large influence on both parallel and series designs. In a parallel design the string length is determined by the current flow along the string and by increasing the voltage level allows a larger number of turbines to be connected to a string. In a series design the addition of voltages along the string allows higher export voltages to be achieved in more manageable string lengths but introduces the issues of insulating high voltage converters within the turbine.

Current offshore turbine technologies generally utilise a low voltage generator whose output is fed into a ‘back-to-back’ AC/DC/AC converter and increased in voltage to that specified by the intra-array system via a turbine transformer. The task of the back-to-back converter is to allow maximum flexibility including full real and reactive power control, improved fault ride-through capability and reduced harmonic contribution. It is the aim of the DC network to be able to remove a number of these elements by simplifying the number of transformations. Ideally this could be achieved by connecting a high voltage AC generator directly to the AC/DC converter removing a DC/AC and transformer conversion process, both of which introduce losses and cost into the system. The maximum turbine output developed at present is the ABB ‘windformer’[12] technology with an AC output of 12kV which can be rectified to DC at approximately ±7.5kV. This technology however has not been commercialised since 2000 though there is potential to develop the technology to 35kV AC output or higher[13]. At this voltage DC rectification could be seen at ±22.5kV.

If this could not be realised then the use of high power DC/DC converters would be required to increase the intra-array DC voltage level. The introduction of an additional conversion step begins to add significant costs and electrical losses and any real advantage over a traditional AC system becomes questionable. In addition, the application of high power DC/DC converters is limited primarily to traction applications with the current state of the art designs rated at 25kV-1800A. This would require significant development to allow a boost converter to be feasible in increasing the intra-array voltage of a DC system further.

For the purpose of these studies the following voltage levels have been assessed based primarily on current and possible future generator output voltages. Additional higher voltages have also been assessed to discover if any significant advantage can be realised bearing in mind the additional costs and losses incurred by introducing boost converters at the turbines. The conversion factor of

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[12] http://www.abb.com/cawp/seitp202/C1256C290031524BC12568F800295931.aspx
[13] http://www.offshorewindenergy.org/ca-owee/indexpages/Offshore_technology.php?file=offtech_p7.php

78% AC voltage rectification has been applied in all cases and is based on a typical thyristor rectifier. New IGBT rectifiers may have the potential to increase this conversion efficiency further.

- **Table 6 DC intra-array voltages assessed**

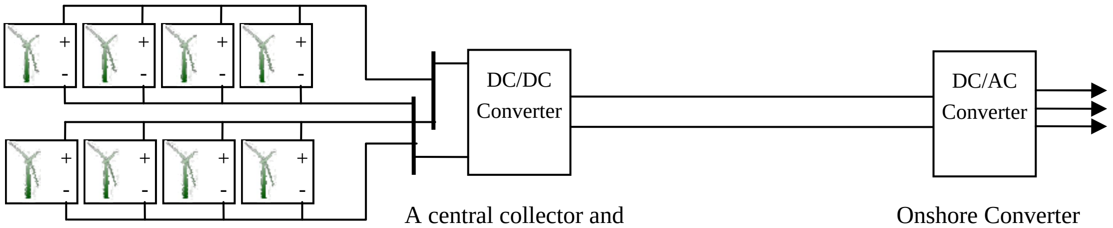
Turbine AC Voltage (kV)	Intra-array DC Voltage (kV)	Comments
11.7	±7.5	Maximum present turbine output voltage
23.4	±15	
35.1	±22.5	Potential turbine output voltage with developments
46.8	±30	Use of boost converters
70.2	±45	

3.4.4. Parallel DC Collection Architecture

3.4.4.1. Technical Assessment

A parallel collection DC architecture would operate and be designed in a similar way to that of a traditional AC collection and transmission system seen in offshore environments today. This involves collecting a number of turbines together at a medium voltage in a string which are in turn collected at a central platform used to increase the voltage to a much higher transmission level and exported to shore.

- **Figure 13 Parallel DC Collection Architecture**



In this arrangement the generators are collected in parallel at a relatively low inter-array voltage.

A central collector and DC / DC converter platform increases the voltage to export level

Onshore Converter for AC connection to Grid

Although the architecture is similar in design to a traditional AC offshore system, the development of DC equipment is much more limited which restricts the advantages such a network could bring without significant investment in DC switchgear and DC/DC converters. The main limitation seen is the high power DC/DC converter used to increase the intra-array voltage to a suitable export voltage. At present the maximum converter size is a 45MW, 25kV design and shows that significant advances in converter design would be required to allow the architecture to be implemented on a large scale. Assuming that a DC/DC converter could be developed then the export connection is the same in design to a traditional HVDC link which has been discussed previously.

In terms of the intra-array system, the main limiting factor is the operating voltage of the intra-array network which is driven by the AC/DC converter in the turbines and potentially voltage boost converters. The reason that the voltage level is so important is due to the current limits of the intra-array cabling. As the turbines are connected in parallel then the current accumulates along the string as more turbines are added. At lower voltage the current contribution from each turbine is higher which increases losses and reduces the number of turbines that can be connected on a string. By having short string lengths there are increased costs associated with the additional cable required to connect to the offshore platform and the number of connections at the platform can become a restricting factor.

3.4.4.2. Economic Assessment

At present the DC/DC converter required to boost the collector voltage to a suitable export voltage is a major development and it is unclear whether such a component could ever be made economically for the high power rating required by offshore energy park developments. Present costs for a 5MW 0.69kV to 5kV converter would be in the region of £90,000[14] which could be used to boost the collector voltage at the turbine following an AC/DC conversion. These components can be fitted together in a parallel connection to increase the power rating and voltage required for the high power rating converter however at a large cost. A 25MW 75kV converter could be expected to cost £900,000[14] with the power rating way below that required. In conclusion the high power DC/DC export converter is the limiting factor in this design and makes the parallel connection an unfeasible architecture.

3.4.5. Series DC Collection Architecture

3.4.5.1. Technical Assessment

By utilising a fully DC network it is possible to envisage new designs which do not conform to traditional AC ideas. An example of such an innovative design is the DC series collection system. Instead of connecting the turbines in a parallel arrangement they are connected in series which can provide significant advantages. An outline of this kind of design is illustrated in Figure 14.

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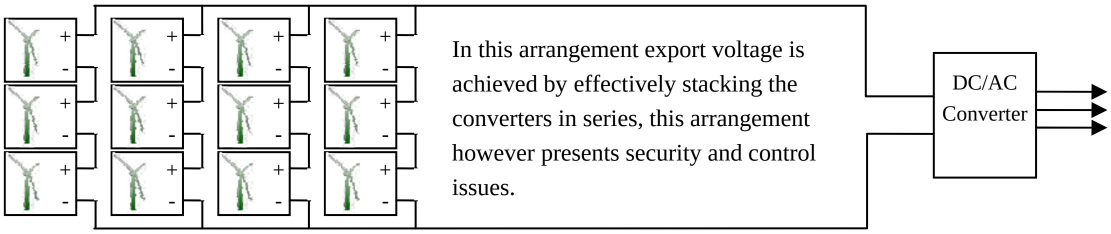
[14] “Energy Evaluation for DC/DC Converters in DC Based Wind Farms” Lena Max, Thesis Chalmers University of Technology 2007.

- Figure 14 Series DC Collection Architecture



In this arrangement export voltage is achieved by effectively stacking the converters in series, this arrangement however presents security and control issues.

The main advantage of this system is that the offshore collector platform has the potential to be removed entirely. By connecting the turbines in a series arrangement the voltage accumulates along the string. It is therefore possible, by managing the string length, to increase the voltage to a suitable export level at the end of the string which can be connected directly to shore, removing the need for expensive offshore platform and converter stations.

A careful trade-off needs to be made in specific designs as to the string lengths desired and the export voltage that can be achieved. By utilising a low converter voltage, a large number of turbines in a string are required to achieve a suitable export voltage; however few strings are needed for a high power output. Conversely if a high converter voltage is selected then the current in the cabling is much lower which can reduce costs by allowing smaller cable sizes to be used. In addition short string lengths are required to reach export voltage; however large numbers of strings are required for the rated power output of the energy farm. The issues involved in raising the intra-array voltage to a high level through DC/DC converters as discussed previously also apply.

The main technical issues to be overcome associated withsuch a system are insulation, security and control issues. As the voltage increases along the string the amount of insulation required significantly increases and is taken by the local AC/DC converter in the turbine. In addition the AC/DC converter must also be highly flexible and capable of operating at a range of voltages. This is to provide a constant export voltage in times of low energy output when some turbines will need to compensate for turbines which are not operating. Alternatively the loss of a single generator would lead to the loss of the complete string. The traditional looping of strings would not be possible in this design and the only option would be to install multiple cable by-passes along the string to provide redundancy in the case of a cable failure. This would significantly increase the cost of the architecture.

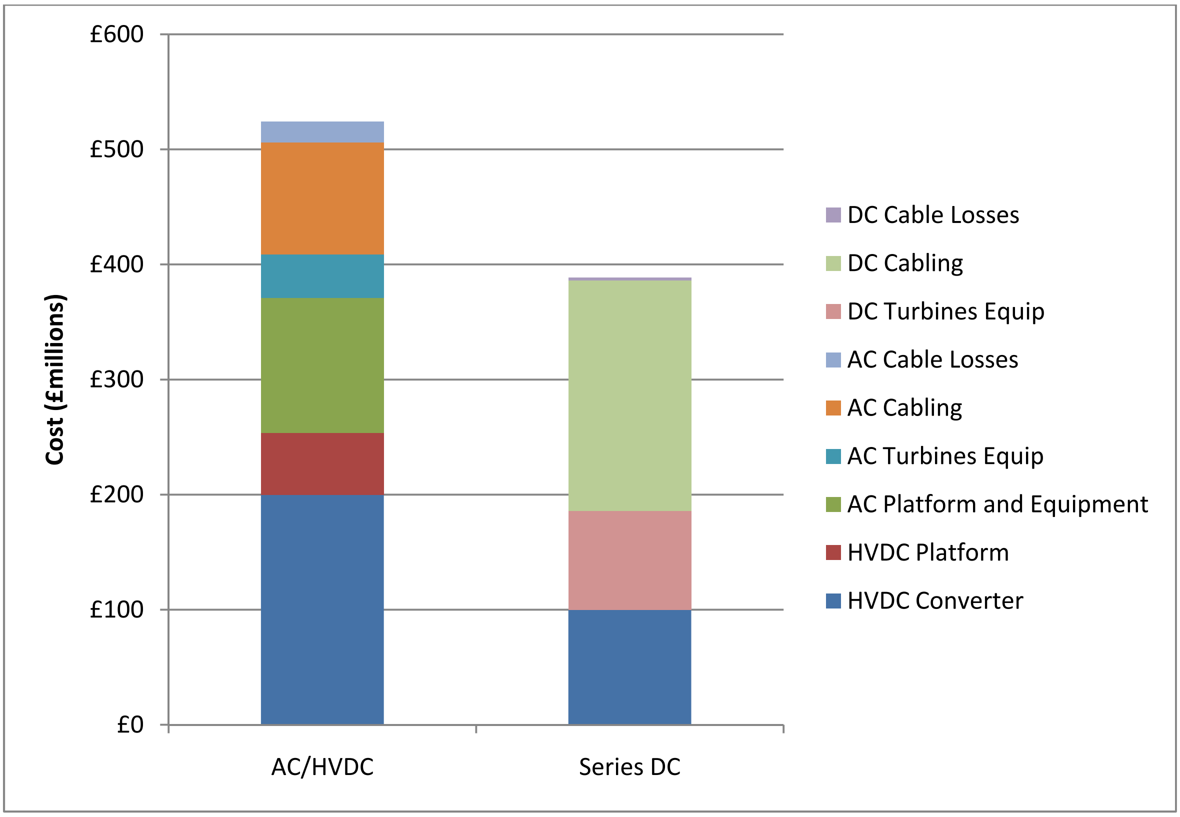
Although there are significant barriers to overcome in terms of high voltage insulation, control and security, significant cost reductions could be achieved due to the use of DC cabling for intra-array and export and the removal of offshore platforms and only an onshore converter required.

3.4.5.2. Economic Assessment

A series DC connected design can make large savings in construction and operation cost by minimising the number of conversion stages, utilising DC cabling and removing the requirement for offshore converter platforms. A basic cost analysis comparing a 1000MW AC intra-array with HVDC export link and a 1000MW series connected DC design has been carried out and is shown in Figure 15. DC switchgear costs, which have relatively small impact on the conclusion, have been approximated to be double that of 72.5kV AC switchgear of equivalent ratings and refer to the average voltage along the 150kV string. In addition, DC cable cost has been approximated to be comprised of an average string voltage of 75kV. HVDC export cable cost has not been included in the analysis as this is constant for both designs.

It can be seen clearly that savings in the region of 20% can be made with the series DC architecture and that the bulk of the cost is on DC intra-array cabling. Dramatic savings are made by halving the number of converters required and the offshore platforms for both the offshore HVDC converter and AC collection.

- Figure 15 Cost Comparison between 1000MW Series DC and AC/HVDC Architectures



3.4.6. DC Connection Arrangements Summary

It has been seen that the parallel DC design has very little if any technical advantage over a common AC design and the cost implications required to design new converters are prohibitive to this architecture being economically feasible.

Analysis shows that savings in platforms and HVAC and HVDC export equipment relate to £250m for a series DC design and cost of losses are halved due to the use of DC cabling throughout and a reduction in conversion processes. Overall the series DC architecture shows a saving of some 20% in cost in comparison to a similar hybrid AC/HVDC design. Technical barriers relating to control, insulation requirements and security do need to be noted however.

4. Additional Considerations

During the Connection Architectures Design Review held on 5th January 2010 it was agreed that some brief consideration would be given to the additional aspects of a) Potential polyphase systems and b) Offshore storage. These would not be full studies but briefly identify the potential benefits and likely requirements.

4.1. Polyphase

Three phase systems are near universally used for AC power transmission and distribution, although this is convention sometimes reviewed for specific applications. High phase order systems (6 or 12 phase) have been investigated for bulk power transmission in constrained rights of way situations. The general advantages relative to 3 phase systems are listed below;

1. Increased thermal loading capacity of lines.
2. The more phases the lower the line to line voltage relative to phase voltage resulting in a reduction of phase to phase insulation and so increased right of way utilisation, of course this is not relevant to cable systems.
3. Reduced stress on the conductor surface leading to reduced corona effects for a given conductor size and tower configuration, again not relevant to cable systems.
4. For overhead lines transmission efficiency is higher as existing double circuit lines can be converted to 6 phase single circuit lines with a resulting increase in capacity. [15]

The above advantages are from an overhead line onshore perspective, similar published work involving the application of High Phase order systems using cables as would be needed offshore, was not found.

Onshore high phase order transmission has been successfully applied to a utility transmission system[16] with positive results. A 2.4km stretch of New York State Electric and Gas Corporation's existing 115kV Goudey-Oakdale double circuit line was converted to 93kV six phase. The conversion raised the phase to ground voltage from 66kV to 93kV resulting in a 40% increase in thermal power rating. The arrangement required 6 phase switchgear and buswork as well as 3 to 6 phase conversion transformers at each end. High phase order power transmission was first proposed in a 1973 CIGRE publication[17] and has been proved in concept with prototype 6 and 12

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[15] BM Weedy "Electric power systems, Third Edition".

[16] "Six-Phase Successfully Applied to Utility Transmission System", CIGRE doc ref. 22/33/36-01. Authors; R Brown T. Landers J. Stewart L. Oppel.

[17] "High Phase Order Power Transmission" presented by CIGRE SC 31,Electra, No 24, 1973, pp 139-153. Authors L.O. Barthold and H.C. Barnes

phase lines however questions over successful integration with a three phase system, substation design, and adequate relay protection had remained. The Goudey-Oakdale application operated correctly as predicted by analytical studies proving the technical viability of such arrangements as well as proving to be more commercially viable than a 3 phase re-conductoring to achieve the same capacity.

For offshore application the main issue is the construction of 6 or more phase cables. Overall cable diameter is limited by installation techniques meaning that unlike overhead line applications, increasing the number of phases results in reduction of possible conductor cross section. The alternative would be to simply use two three core cables though this would reduce the cost benefit by increasing installation costs.

Polyphase systems have proved to be a viable onshore alternative to over head line reconductoring however the application offshore poses additional issues in terms of the cable connection. The construction of high phase order cabling would have to be fully considered before the potential advantages of polyphase connections could be considered. There is however the potential for some advantage over 3 phases though the advantage is likely to be small so based on this initial assessment it is suggested that further consideration of this concept is not pursued.

4.2. Offshore Storage

It is well known that due to the intermittency of renewable sources that storage could have a significant role to play in the design and operation of onshore networks incorporating high levels of renewable energy sources.

Consideration of onshore aspects is beyond the scope of this particular project; however consideration also has to be given to the potential for offshore storage schemes.

For offshore storage the potential benefit is more limited to the capability to minimise the costs of export connections based on the recognition that average renewable outputs only represent typically some 33% of the maximum installed generating capacity.

On the basis that electrical connections are generally designed to cater for 100% capacities, it is clear that the application of offshore storage could reduce the size, and therefore the costs of the export connection system significantly. This is why schemes such as the Inverse Offshore Pump

Accumulation Station[18], hydrogen generation schemes[19], or potential ideas to store compressed air within wind turbine structures or even ammonia generation[20] are being considered.

The evaluation of the practicalities of such storage techniques is beyond this study. Factors that would have to be considered in a comprehensive study would include:

1. Detailed understanding of farm output over significant time intervals (up to 12 months) but with time discrimination to short periods.
2. Characteristics of storage system including hours of storage capability, response time, conversion capacity, conversion efficiencies, costs, etc.
3. Basis for assessing any additional benefits other than simple connection cost saving, such as, improved operational security, increased availability, reduced CO^2 emissions, etc.

However what this study can provide are some targets for the practical viability of such storage schemes.

A simplified analysis has been undertaken which considered a theoretical output from a wind farm and allowed a connection limit to be set as a percentage of the total wind farm capacity, which was equivalent to a storage conversion capacity. By setting the limit of connection capacity below the rated value, all output above the limit requires to be stored and released when the output falls below the connection limit, thus trying to maintain the farm output close to the reduced connection limit.

Of course the lower the connection limit the increased level of storage required.

In a simplified case with a 1000MW farm and a connection limited to 900MW indicates that a storage capacity of some 10GWh could be required with a 100MW storage conversion capacity. If a connection cost saving of £500k – 800k per MW is assumed fromFigure 10 of Section 3.2.6, then the viability of such a scheme would be very dependent on the cost of storage envisaged which is expected to be very much higher than the £5 – 8 per kWh that would be needed to make this analysis break even based on this simplified approach considering only connection costs.

Achievement of storage costs at an economic level will ultimately determine the viability of the application of storage techniques offshore and to which types of architectures could most benefit from such technologies. A separate study as to the potential impact and benefits of future storage technologies on connection architectures and ratings could be a requirement linked to storage research developments. These developments have not been included in the scope of this study but

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[18] http://www.kema.com/Images/091307%20KEMALievenseEnergyIslandWebFINAL.pdf
[19] http://ocsenergy.anl.gov/guide/hydrogen/index.cfm
[20] http://www.otcnet.org/2009/pages/schedule/documents/otc200761.pdf

the methodologies developed combined with more detailed assessment of actual farm output would make such studies possible.

5. Conclusions

5.1. Main Conclusions from Development Cases Studied

Within Section 3 the specific studies and results have been discussed and conclusion drawn, these are repeated here and summarised in Table 7.

- **Table 7 Summary of Conclusions from Development Cases Studied**

Factor	Case 1 Now	Case 2 Now	Case 3 Near Future	Case 4 Possible Future	Case 5 Possible Future
Farm Size	500MW	500MW	1000MW	1000MW	Up to 4000MW Single Connection
Array Voltage	33kV AC	33kV AC	Project Specific AC	DC	Project Specific AC
Export Distance	Up to 150km	>150km	All	All	All
Export Voltage	220kV	±150kV	±300kV	Up to ±300kV	Up to 550kV
Export Technologies	AC Cable	DC VSC Cable	DC VSC	DC Series Cable	AC GIL

5.1.1. 132kV AC export with 33kV intra-array arrangement

This is the current state of the art and is considered as the base case. Compliance with Grid Code requirements has been confirmed.

5.1.2. 132kV AC export with optimisation of AC intra-array voltage

- For 500MW farms the optimal intra-array voltage is 33kV irrespective of generator size. This conclusion applies to Development Cases 1, 6 and 7.
- For larger farms of 2000 or 5000MW then the individual block size will likely increase to 1000MW. At these sizes the selection of optimal intra-array voltage is marginal with lower platform and equipment costs being balanced by increased turbine switchgear costs. This sensitivity to turbine switchgear costs means that the optimal voltage will depend on project specific layouts of the generators and platform locations.

5.1.3. Assessment of 220kV and 400kV AC export as well as GIL with optimised AC intra-array voltage

- Assuming the availability of suitable 220kV AC XLPE cables it is concluded that for the base case 500MW up to 100kM offshore connection distance then 220kV is a preferred export voltage in comparison with the base case 132kV export.

- GIL is technically a very attractive proposition for larger power transfers and compared with HVDC does not require an expensive converter platform. However with anticipated very high GIL installation costs it is also clear that potentially GIL would only be of benefit with a requirement for very large single circuit connections (up to 5000MW) with relatively small amounts of reactive compensation. Such connections would require significant changes to the present limits in the grid code for single circuit loss which are applied to offshore connections.

5.1.4. Impact of HVDC export with optimised AC intra-array voltage

- Utilising 132kV AC export for 1000MW it has been confirmed that the break point at which HVDC VSC technology currently is the preferred choice is 70km. By applying 220kV export the 1000MW 70 km break point could be extended to around 1000 MW 100 km.

5.1.5. HVDC export with frequency optimisation of AC intra-array arrangement

- A range of frequencies have been evaluated, taking advantage of the isolation provided by a HVDC export link between the offshore collector system and the onshore grid. Losses and impacts on equipment design and cost were evaluated, however it has not yet been possible to validate the assumptions made on equipment costs with manufacturers.
- At frequencies above 100Hz the losses become excessive and demonstrate that the combination of converter, skin effect and reactive power flow losses make such a system unattractive.
- At 100Hz the initial analysis suggests that there could be economic advantages with such an approach. However the cost information used has not been fully validated by equipment manufacturers, so this would require further consideration as to the potential cost impact of 100Hz operating frequency.

5.1.6. Medium voltage DC collection to a high voltage converter for export

- It is concluded that the architecture based on parallel intra-array DC has very little if any technical advantage over a common AC design and the cost implications required to design new converters are prohibitive to this architecture being economically feasible.

5.1.7. Novel DC design to eliminate requirement of offshore platform

The architecture based on a series connected intra-array DC design shows that significant economic savings in platforms and HVAC and HVDC export equipment could be realised. However the additional costs for DC switchgear and insulation requirements are not trivial and in the analysis done some significant assumptions have been made as what the costs of technical solutions might be. Nevertheless it would appear that the elegant solution of the series architecture could provide some economic advantages compared to current HVDC VSC prices. Of course a comparison of the "should cost" elements of the solutions has not been possible.

5.2. Control System Implications

As discussed in the State of the Art Technologies Report the main implications regarding control systems concern the HVDC elements of the proposed architectures and this is further restricted in terms of the issues being more appropriate for interconnected DC systems.

A generator or transmission facility controlled by fast responding power electronics can by itself be designed to operate with a stable response to power order changes and disturbances. When a second and different controller or transmission facility is located electrically close to the first, degraded overall system stability may result, notwithstanding that each facility on its own may be quite stable.

In terms of the individual connections architectures that have been considered in this report the main interactions that need further review are those associated with the series DC intra-array architecture that has been identified.

At this stage this series DC intra-array architecture is somewhat speculative. The preliminary analysis seems to suggest that there could be economic and reliability advantages with such an approach. However there are some significant issues to overcome in terms of cost and availability of DC equipment and how to make HV cable terminations within each turbine at effectively export voltages.

In terms of control, one challenge will be how to maintain a constant voltage across each string of generators given different outputs from each machine. The output voltage across each wind turbine depends on the ratio between the output power from each wind turbine, and the mean power production of the wind turbines in the string. Effectively this means that wind turbines that have an output power higher than the mean power in the stack, will have a higher output voltage and vice-versa.

Furthermore the rated output voltage of the wind turbine, i.e. the highest voltage the wind turbine generator is designed to operate with continuously, is of course limited. Therefore the power production would have to be reduced in order to limit the output voltage to the rated voltage. Due to this fact, the output power of the wind turbines in one stack will be limited by the wind turbine with the lowest production.

This would be especially severe if the production in one wind turbine goes down to zero, because then the production in the whole stack could be lost unless the remaining machines can withstand the voltage across the active machines. Practically some voltage overrating must be done, in order to limit the energy production loss in the wind farm due to the uneven power production that naturally occurs.

In conclusion it would appear that not only would a DC collection system provide challenges for DC equipment and insulation technology but the control systems necessary would require significant development.

The control implications when connecting multiple farms will be part of the next phase of the project when Multiple Offshore Connections are considered.

5.3. Grid Code and SQSS Considerations

Studies have been undertaken to assess the impact of different connection architectures on Grid Code and SQSS issues. The studies do not assess the issues faced by generators of frequency and voltage control which are beyond the scope of this connection architectures study.

The Guidance Notes for Power Park Developers[21] published by National Grid provides an overview of the preferred connection process Generators may follow to achieve the Operational Notification required to allow Generators to synchronise and export power onto the transmission system.

To achieve Operational Notification the Generator must demonstrate compliance with the Grid Code by reference to a combination of using Type Registered modules, Simulation Studies utilising project specific data and Compliance Tests

Power Park Modules are generally comprised of a number of identical units which have a uniform performance subject to manufacturing tolerances. It is therefore possible to register various aspects of performance and then reference the design and data for all sites which use the particular type of unit. Areas which are suitable for Type Registration of individual types of equipment include:

a) Fault Ride Through Capability
b) Reactive Capability
c) Voltage Control
d) Frequency Control
e) Power Park mathematical model
f) Fault in-feed contribution.

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[21] Guidance Notes For Power Park Developers September 2008 Issue 2

Items a) to d) are based on test data submitted whilst for e) and f) will be based on simulations and mathematical models.

Simulation Studies are required where it would be impractical to undertake to demonstrate site specific capability through testing. Model used have to be identified to National Grid along with site specific values and Grid Entry point assumptions. Simulation Studies include:

a) Steady State Reactive Capability across the voltage range
b) Voltage Control and Reactive Power Stability
c) Fault Ride Through

National Grid may require specific Compliance Testing to confirm site specific technical requirements. Tests that may be required would be:

a) Reactive Capability
b) Voltage Control
c) Frequency Controller Response Performance
d) Fault Ride Through, Fault Contribution and Power Recovery

As can be appreciated from the above discussion and the detail contained in the National Grid Guidance Notes the generic validation of power park compliance with Grid Code requirements is dominated by generator and generator control characteristics. During the Design Review held on 5th January 2010 it was agreed that 7 specific architectures would be optimised and for each of the optimised architectures specific Grid Code compliance studies would be performed together with subjective assessments of Grid Code compliance in some respects where performance would be dominated by project specific or generator specific detail.

The seven architectures to be optimised were:

1) 132kV AC export with 33kV inter-array arrangement
2) 132kV AC export with optimisation of AC inter-array voltage
3) Assessment of 220kV and 400kV AC export as well as GIL with optimised AC inter-array voltage
4) Impact of HVDC export with optimised AC inter-array voltage
5) HVDC export with frequency optimisation of AC inter-array arrangement
6) Medium voltage DC collection to a high voltage converter for export
7) Novel DC design to eliminate requirement of offshore platform

Appendix C shows that all of the optimised architectures which have been studied in detail comply with the requirements of the Grid Code in respect of those areas considered i.e. Fault Ride Through and Harmonic Distortion. Therefore no modifications to the Grid Code in these respects seem necessary.

The studies and analysis reported in Section 3 of this report has considered the existing requirements within the National Electricity Transmission System Security and Quality of Supply Standard (NETS SQSS). This details the planning and operational design criteria applicable to both the onshore and offshore electricity transmission systems, including connections for offshore energy farms.

The SQSS details how for offshore energy farms:

- With HVDC connections, the allowable infeed loss risk is currently 1000 MW (normal infeed loss risk) due to faults or outages of the HVDC converter, and 1320 MW (infrequent infeed loss risk) due to faults or outages of HVDC cable transmission circuit.
- With AC connections, the allowable infeed loss risk due to a transformer fault or outage is currently 50% of the offshore grid entry capacity up to a maximum of the normal infeed loss risk (1000 MW), and 1320 MW (infrequent infeed loss risk) due to faults or outages of the HVAC cable transmission circuit.

In practice the first point will have the impact of limiting a single HVDC development to 1000 MW in size, irrespective of the fact that the HVDC cable transmission circuit could have a higher rating, unless two 660 MW converters were used together. However, the usage of two individual converters for each side of the HVDC cable circuit would add significantly to the cost of the scheme and hence it is not likely to be considered attractive. At present this is not likely to be a significant issue as the maximum theoretical HVDC (VSC) converter size is not significantly greater 1100 MW. However, it is expected that VSC offshore converters will be available with maximum ratings up to and beyond 1320 MW within the next ten years. Clearly to take advance of these potential technology gains and improvements in HVDC converter ratings it will first be necessary to raise the loss risk associated with faults or outages of HVDC converters to a higher value if single developments greater than 1000 MW are to be realised.

GB SQSS Review Request GSR007 – Review of Infeed Loss Limits (02/2009) details how a potential modification of the SQSS limits is to increase the normal infeed loss risk value to 1320 MW and simultaneously increase the infrequently infeed loss risk value to 1800 MW, this latter value being necessary to accommodate potential future new nuclear reactors with single shaft generators. However, even if this change is enacted it will still restrict the maximum size of a single HVDC converter to 1320 MW, potentially much less than the technology would be capable of delivering. If this is the case, the only remaining option to allow larger single HVDC connections (with single converters on each side) would be to reclassify the infeed loss risk of HVDC converters due to a fault or outage as an infrequent infeed loss and consequently the proposed 1800 MW rating would apply. For this change to be considered there would need to be sufficient evidence to support the claim that a fault outage of an offshore HVDC converter can be considered as “infrequent” and at the present time there is little if any operational data to support this assertion. It should also be noted that the maximum infeed loss risk for a single AC offshore transformer is also currently a maximum of 1000 MW, and a transformer is likely to be more reliable offshore than a HVDC converter.

For AC connections the current SQSS rules have little impact, except to effectively rule out GIL connections which have been shown to not be cost effective until individual connections of around 2000 MW or more are considered, far in excess of the present and even the future proposed SQSS rules . Currently, 400 kV cable technology cannot support a circuit rating much beyond 700 MW (assuming in any case that installation issues can be overcome) and consequently there is sufficient scope for further advances in 400 kV cable ratings (or higher voltages) before the present SQSS limitations would be reached, and significant technological advancement will be necessary to come close to the possible future 1800 MW infrequent infeed loss risk value proposed.

Longer term, increases in infrequent infeed loss limits might become possible with onshore network developments and possible increased levels of interconnection.

5.4. Technology Development Opportunities

The basic conclusions are that the technology opportunities identified in the State of the Art Network Technologies report are still valid. However some further comments can be made:

- Importance of HVDC technologies has been reinforced. So all comments made previously in respect of HVDC technologies still apply.
- Potential from DC series connected intra-array system warrants further investigation. Issues to be overcome in terms of :
    - Insulation on connection strings and turbines
    - DC switchgear
    - Control systems
- GIL provides potential but only if significantly larger capacity connections are envisaged and allowed.
- Importance of intra-array equipment cost in the total cost of a scheme is significant; therefore significant opportunities for cost reduction of intra-array equipment exist. Of particular interest would be intra-array switchgear at higher rated voltages which presently limits the potential benefits of increased intra-array voltages.

- Further consideration of the impact on connection architectures of offshore storage would be justified if it can be envisaged that large scale storage technologies could be cost effectively applied in an offshore environment.
- Use of 100Hz intra-array frequency for AC/DC connection architectures justifies further investigation.

The Technology Development opportunities identified in addition to those within Table 18 of the State of the Art Technologies report are detailed in Table 8.

- **Table 8 Additional Technology Development Opportunities**

Technology Area	Potential Benefit of Technology	Development Need	Potential ETI Input
Series DC intra-array systems	DC/DC system eliminating offshore converter platform	High Voltage insulation connections on turbine strings Control systems	More detailed feasibility studies to investigate challenges and potential benefits
Alternative frequency systems for inter array systems	Reduced overall system costs and reduced losses	Equipment design and system implications	More detailed feasibility studies and verification of concepts
Offshore storage	Improved utilisation of electrical connections	Establish potential benefits linked to likely storage developments	Detailed study to optimise connection ratings and architectures based on storage technology data and actual farm outputs
Inter array AC equipment	Reduced costs to facilitate use of higher collector voltages	Equipment specifications and designs to meet application need	System studies to establish new specifications that could enable lower equipment costs compared to conventional equipment.

Appendix A AC Export Detailed Results

A.1 Objective

With regard to offshore renewable export connections two main aims have been identified, firstly to identify the optimum AC export voltages for given windfarms, and secondly to identify the break point between AC and DC technologies. Break point refers to the distance and power at which one technology becomes technically and/or economically superior to another. With AC (132kV) and HVDC the breakpoint is generally accepted to be 1000MW and 70km. A series of studies have attempted to confirm or dispute this convention. Further, the effect that non-standard AC solutions could have on the break point has been investigated; this includes higher voltage connections (220kV and 400kV), reactive compensation platforms and gas insulated lines (GIL).

A.2 Model

A.2.1 Technical Assessment

In all studies the export connection has been isolated from the intra-array connections with the windfarm modelled with an equivalent lumped power source only. In the AC export studies reactive compensation has principally been applied in two configurations, 100% onshore, and a 50/50 split onshore/offshore with some selective consideration given to intermediate compensation platforms. All AC studies have been carried out in DIgSILENT PowerFactory with the results collated and analysed via spreadsheets.

A.2.2 Economic Assessment

The economic assessment has been carried out to quantify the cost implications of applying the technical solutions analysed in the technical assessment. A connection option that is technically superior to another is unlikely to be the preferred option if it is also the most costly option (assuming both options meet all relevant regulatory requirements).

Cost estimates include the cost of export cable, HV switchgear, collector platform transformer and onshore/offshore reactive compensation, including related additional platform costs, and capitalised cost of cable losses.

A.3 Methodology

The following AC options were considered as part of this study group;

- Load flows on single circuits determining cable capacity (received power with thermal loading at 100%) against distance carried out for 132kV (1200mm^2 3 core), 220kV (1000mm^2 3 core), 400 kV (1200mm^2 single core), 280kV GIL and 550kV GIL for the aforementioned reactive compensation arrangements.
- Load flows and comparative costs on export architectures for 500 MW and 1000MW developments applying 132kV, 220kV, 400kV and 280kV.

- The export connections of developments greater than 1000MW and smaller than 500MW have been investigated from a high level perspective adapting the detailed information acquired as part of the 500MW and 1000MW studies. In general it has been assumed that developments of 2000MW or greater will be constructed as multiple smaller blocks of 1000MW in the short to medium term.

The above studies have been compared to identify the relative advantages and disadvantages of one technology or voltage over the others. Where optimum connection costs have been quoted for a given voltage, optimum refers to the cheapest option between 100/0 reactive compensation split and 50/50 reactive compensation split.

Reactive compensation has been optimised for cable performance maintaining an onshore bus voltage of 1pu while maintaining an acceptable offshore bus voltage of 1pu +10% margin. Standard nominal AC voltages have been used for conventional AC export, for GIL the voltages and capacites used represent the full range available as quoted by the manufacturers.

A.4 Results

A.4.1 AC Cables

- Figure 16 Submarine Cable Export Capability Against Distance

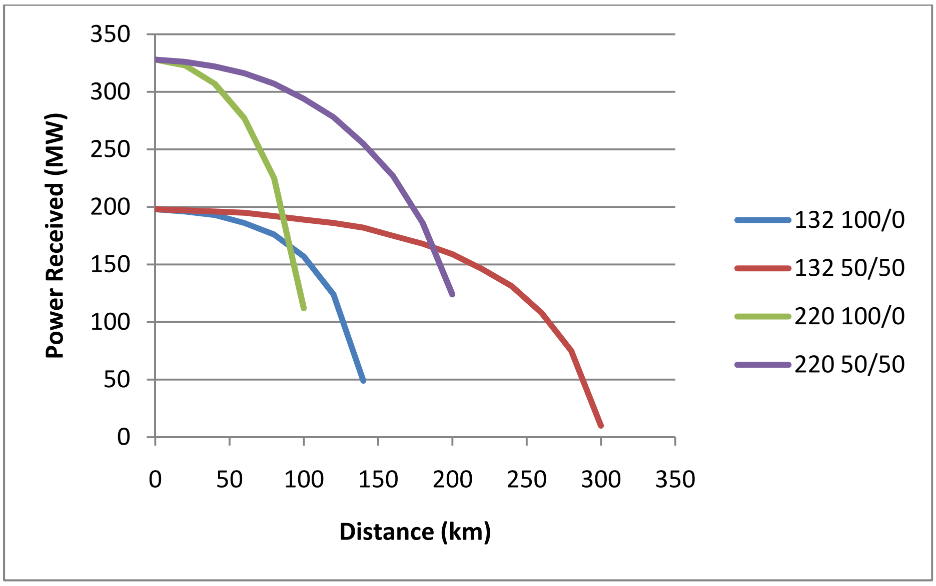
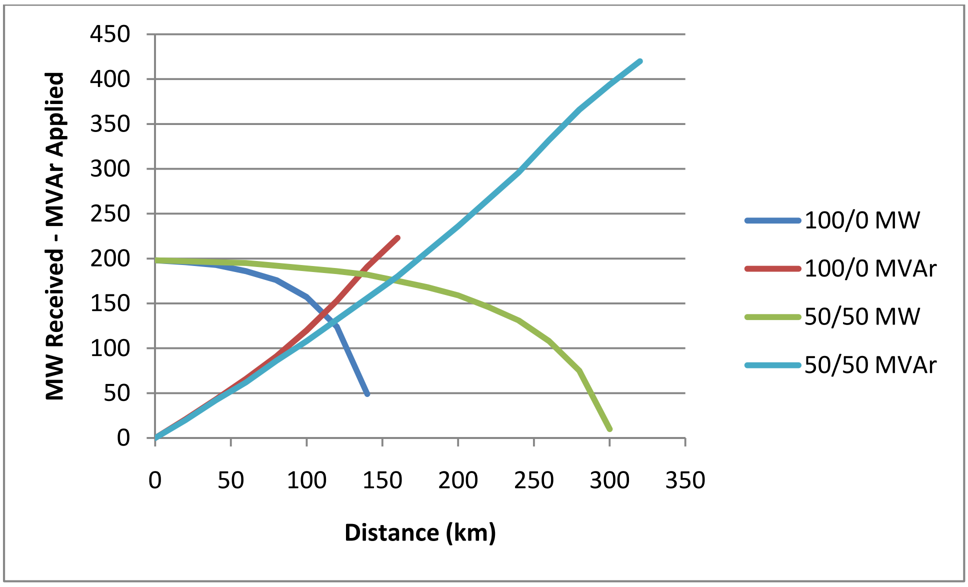


Figure 16 shows the power received profile of 132kV (1200mm^2) and 220kV (1000mm^2) three core submarine cables. Clear from the above graph is that with fully onshore reactive compensation, cable efficiency drops off dramatically around 50-100km for 220kV and 132kV connections respectively and at around 100-150km for 220kV and 132kV connections respectively with a 50/50 split of compensation. 132kV cable capacity reduces significantly less against distance compared to 220kV due to the increased reactive compensation requirements.

- **Figure 17 132kV Submarine Cable Capacity Against Reactive Compensation Applied**



- **Figure 18 220kV Submarine Cable Capacity Against Reactive Compensation Applied**

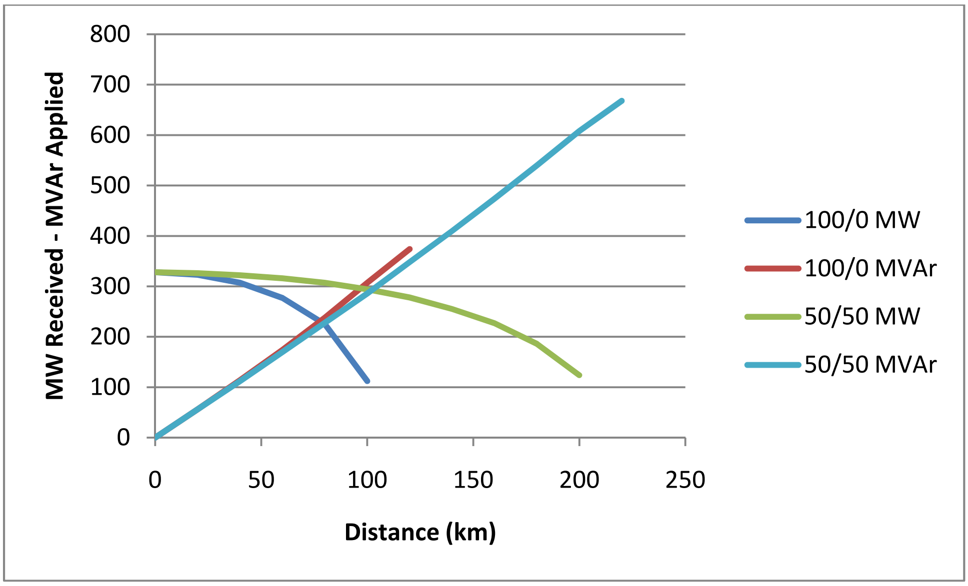


Figure 17 and Figure 18 show applied reactive compensation and the recieved real power over a range of distances on the same axis. It is important to recognise that although a cable may be capable of exporting a power over a given distance, the amount of reactive compensation that is required may make the solution economically unviable. The point at which the reactive compensation exceeds 50% of the export real power could be seen as the point at which becomes significant. This value is similar in either 100/0 or 50/50 split of compensation and is approximately 90km for 132kV and only 70km for 220kV.

A.4.2 High Voltage AC

- **Figure 19 Submarine Cable Export Capacity Against Distance**

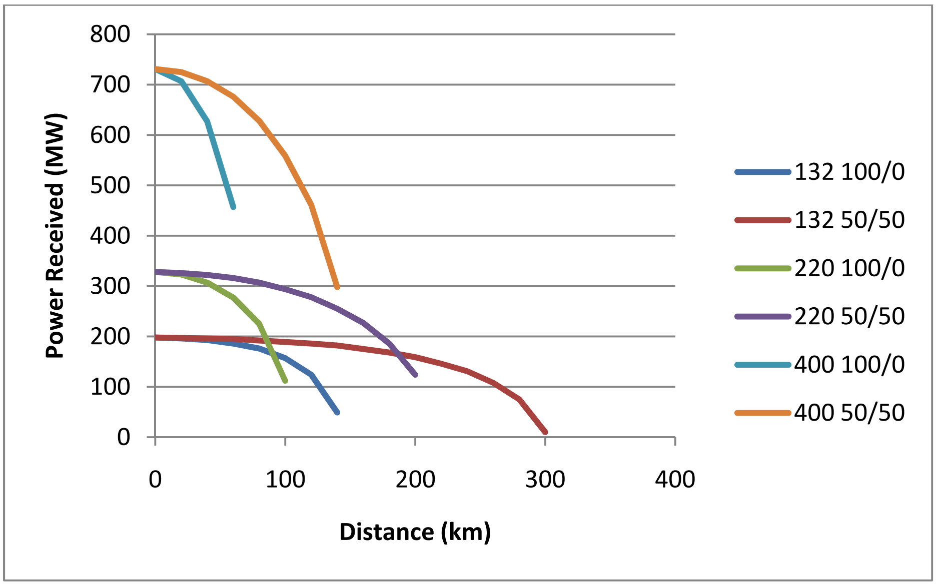


Figure 19 shows 400kV (1200mm^2 single core) real power export capacity against distance, also shown are the results for 132kV and 220kV for comparison. As would be expected the fall in capacity against distance is more pronounced than the lower Voltage cables due to greater reactive compensation requirement. Real power capacity drops dramatically at around 20km and 60km for 100/0 and 50/50 reactive compensation arrangements respectively.

- **Figure 20 400kV Submarine Cable Capacity Against Reactive Compensation Applied**

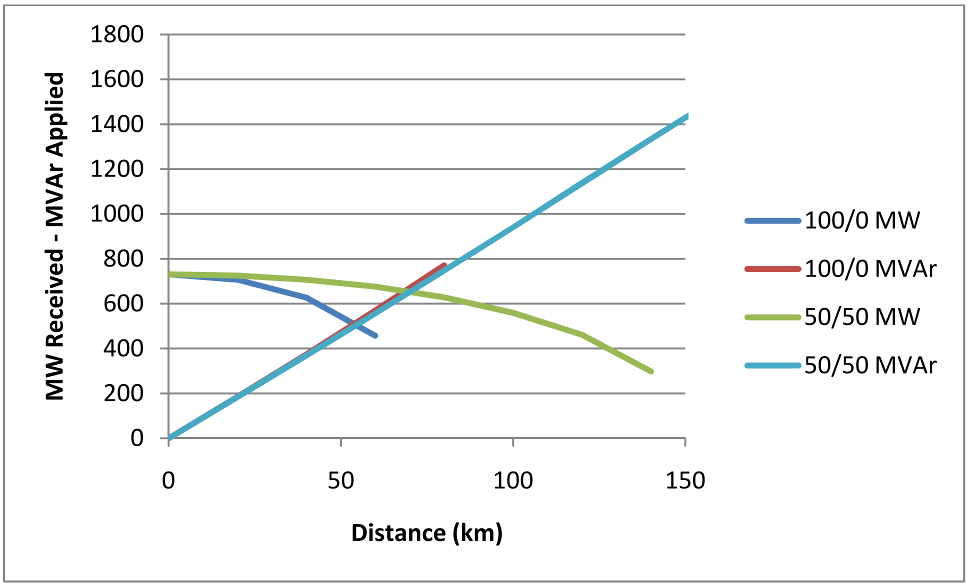


Figure 20 shows that at 400kV reactive compensation requirement exceeds 50% power received at only around 40km exceeding full power received at only around 55km and 70km for 100/0 and 50/50 reactive compensation split respectively. These levels of reactive compensation are highly likely to effect the economic viability of using 420kV cables at long distances where large quantities of reactive compensation will be required offshore.

A.4.3 Effect of Reactive Compensation Platform

- **Figure 21 Effect of Reactive Compensation Platforms on 220kV AC Export**

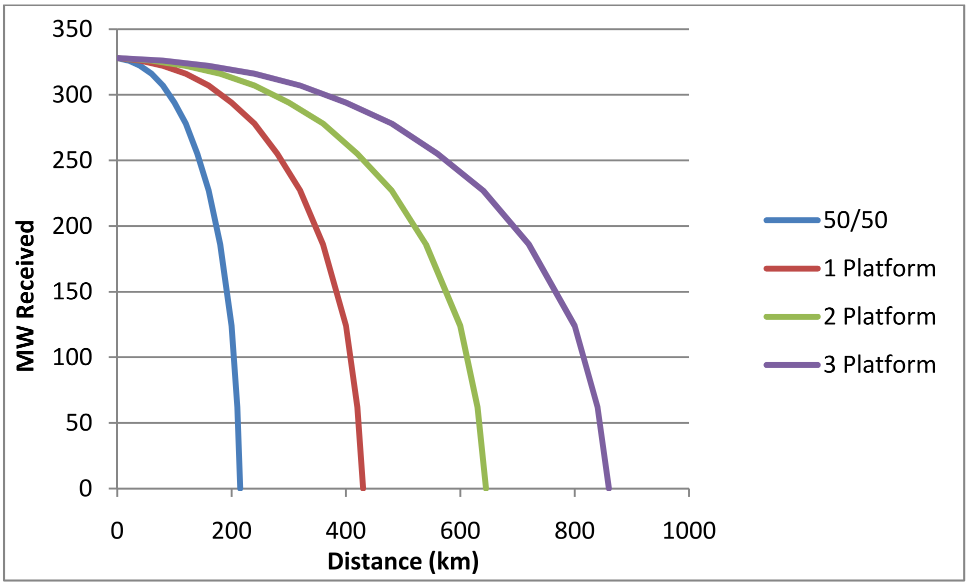


Figure 21 demonstrates the effect of reactive compensation platforms on AC export. The limit on export distance is attributable to the required reactive compensation taking up the full thermal capacity of the cable. By introducing a reactive compensation platform 50% along the connection export distance can be doubled with the addition of each subsequent platform increasing the total export distance by the same distance. The major problem with this method is the cost of each additional platform.

A.4.4 Normalised Cable Capacities

- **Figure 22 Submarine Cable Export Capacity Against Distance Limited at 200MW**

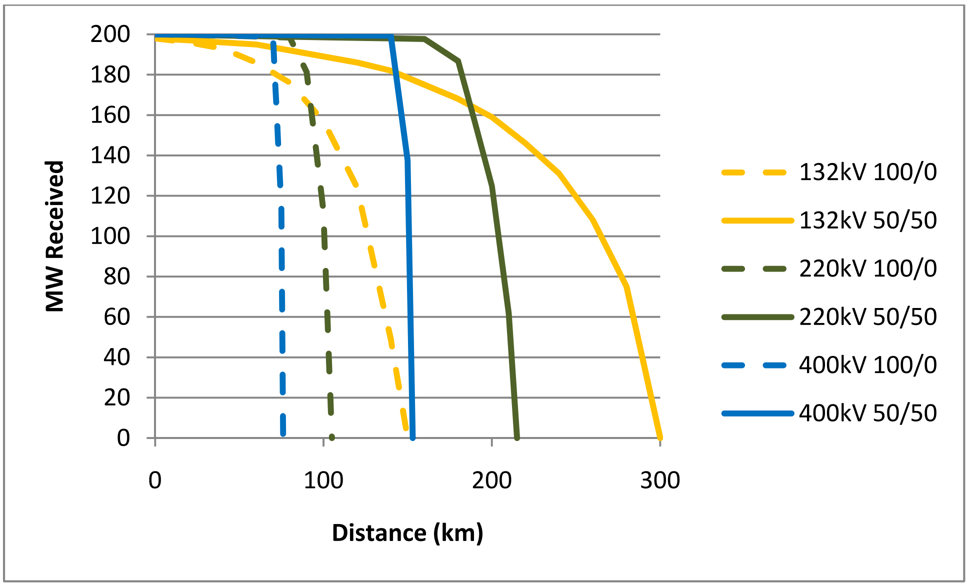
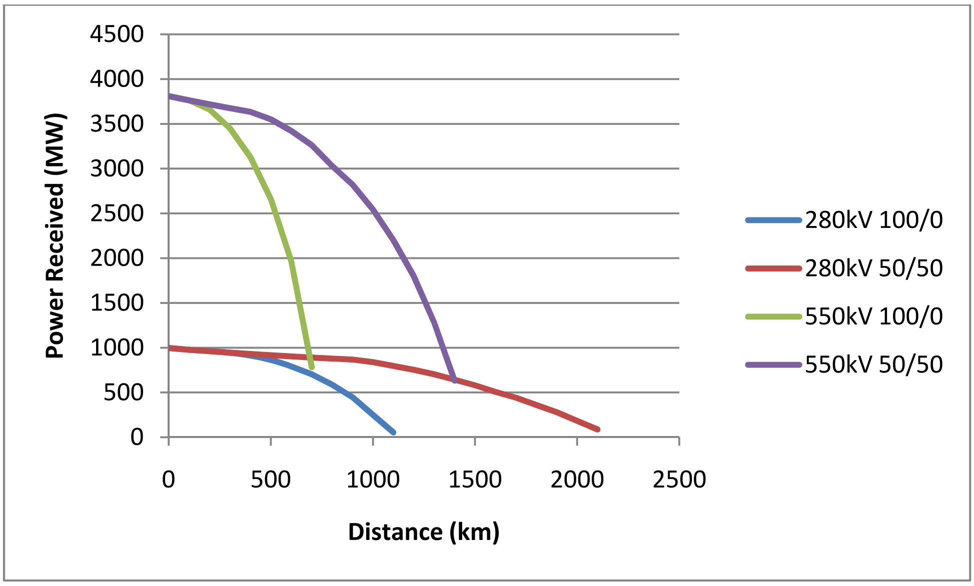


Figure 22 has been compiled to clearly demonstrate the effect of voltage and distance on cable capacity. The technical superiority of higher voltages is the potential for higher capacity circuits. The above graph shows that for a 100/0 reactive compensation split 400kV loses this advantage at around 80km and 220kV at around 100km. With a 50/50 reactive compensation split 400kV loses its capacity advantage at around 125km and 220kV at around 200km. Though the higher voltages retain a technical advantage up to the above stated limits the reactive compensation requirements and additional switchgear and cable costs will inevitably lead to the higher voltages losing economic advantage at significantly shorter distances.

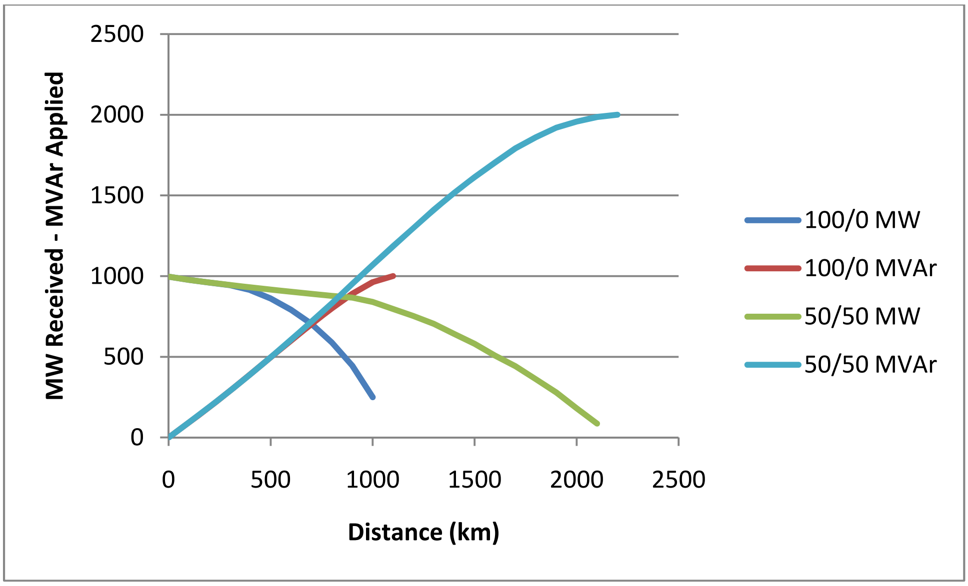
A.4.5 Gas Insulated Line

- **Figure 23 GIL Export Capacity Against Distance**



Clear from Figure 23 is the high capacity of single circuit GIL compared to standard AC even at the relatively low voltage of 280kV, the above range of voltage and capacity represents the full range of GIL technology. Also notable are the relatively long distances possible without significant loss of capacity due to very low reactive compensation requirements. At 280kV capacity does not begin to significantly reduce until around 500km and 1000km for 100/0 and 50/50 reactive compensation arrangements respectively.

- **Figure 24 280kV GIL Capacity Against Reactive Compensation Applied**



- **Figure 25 550kV GIL Capacity Against Reactive Compensation Applied**

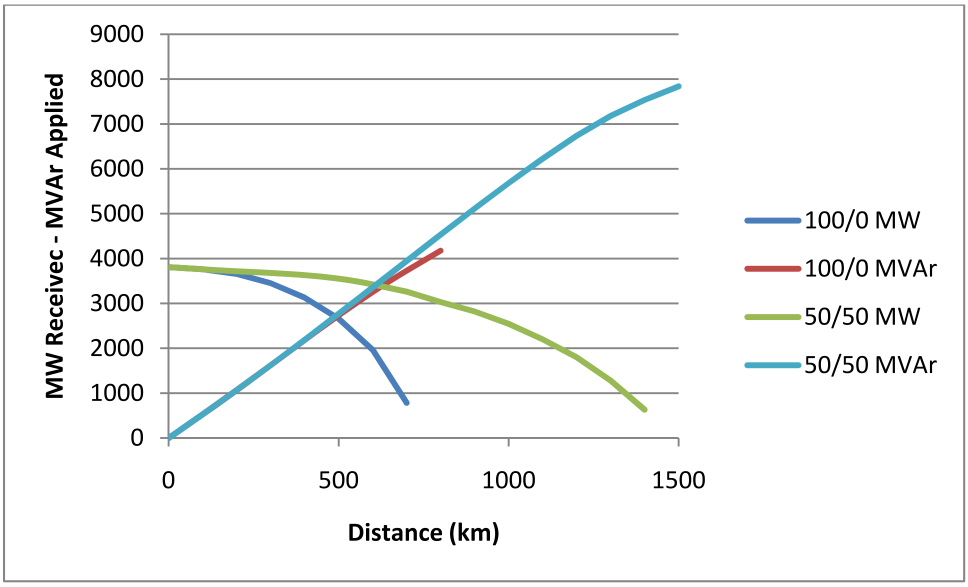


Figure 24 and Figure 25 show that for GIL the reactive compensation requirement against distance is massively reduced relative to standard AC. For the distances relevant to this study (i.e. up to 150km) reactive compensation requirement is insignificant.

A.5 Economic Results

- **Figure 26 500MW 132kV, 220kV Comparison.**

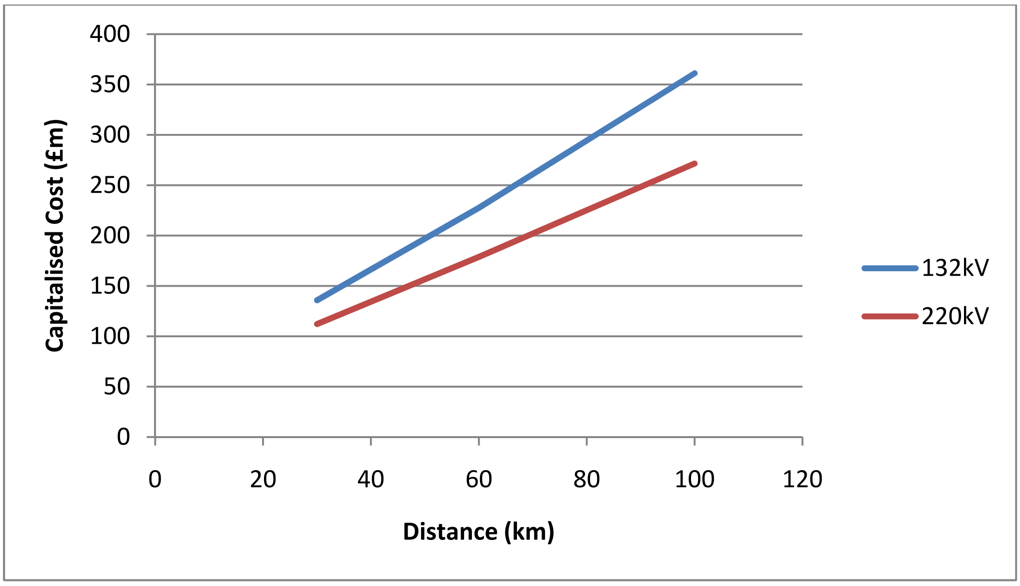


Figure 26 shows optimum connection costs for the 132 kV and 220 kV export of a 500 MW development between 30 km and 100 km. Clear from the results is that as the voltage increases the overall connection cost decreases this is due to a requirement for fewer circuits which make up the majority of the connection cost and outweigh additional switchgear and per unit cable cost.

- **Figure 27 1000MW 132kV, 220kV, 280kV GIL Comparison**

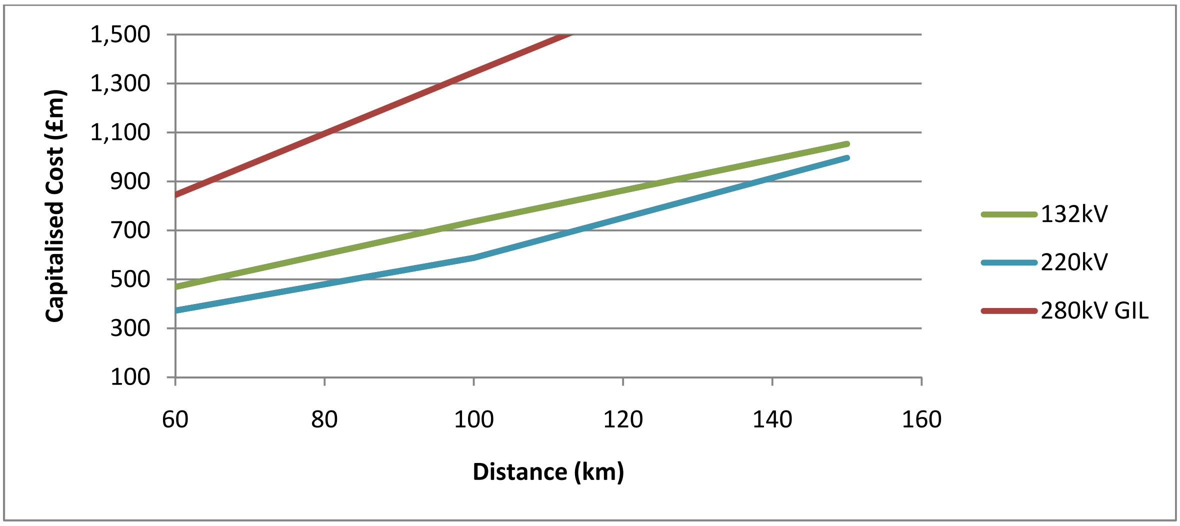


Figure 27 shows optimum connection architecture costs for the 132 kV, 220 kV and 280 kV GIL export of a 1000 MW development between 60 km and 150 km. Only 280kV GIL has been included as its smallest quoted capacity is around 1000MW, 550kV would only be applied to a significantly larger capacity connection. Clear from the results is that as the voltage increases the overall connection cost decreases up to 100km. Over 100km the reactive compensation requirement increases the cost of the 220kV voltage options relative to 132kV. GIL is consistently the most expensive option despite requiring very little reactive compensation and only a single circuit.

- **Figure 28 Potential Advantage of Higher Voltage AC**

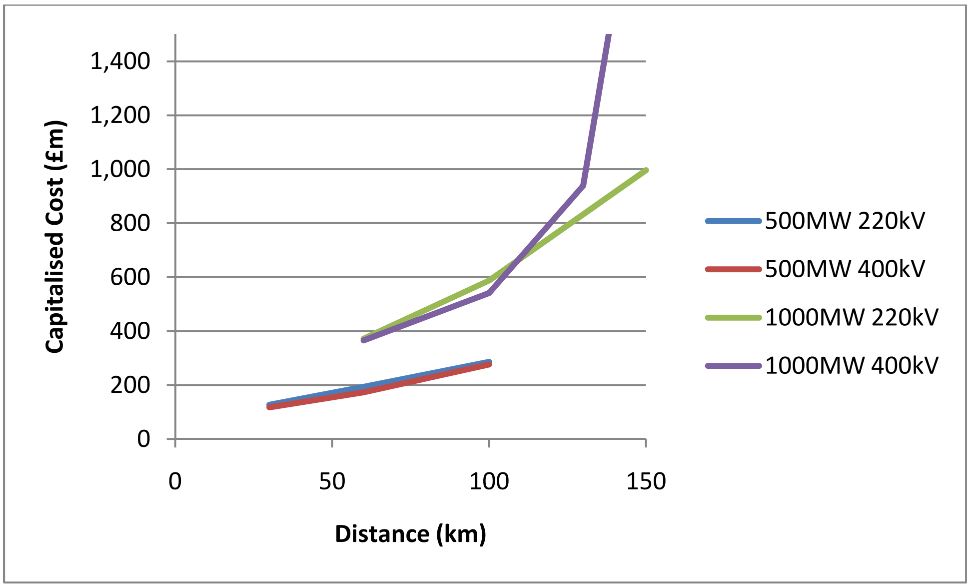


Figure 28 shows the small potential cost advantage of using 400kV up to around 110km. As with the advantage of 220kV compared to 132kV the major cost saving related with 400kV is a need for fewer circuits. Over 100km the reactive compensation requirement increases to a point where more circuits are required relative to 220kV, eliminating the economic advantage of 400kV. It should be noted however that the results assume that the 400 kV cable is either 3-core which does not as yet exist or that three single core cables are laid simultaneously for a similar cost to single core cable. Neither option is at present possible with no 400kV submarine cables yet available.

- **Figure 29 Potential Advantage of 400kV Given Requirement to Lay Phases Individually**

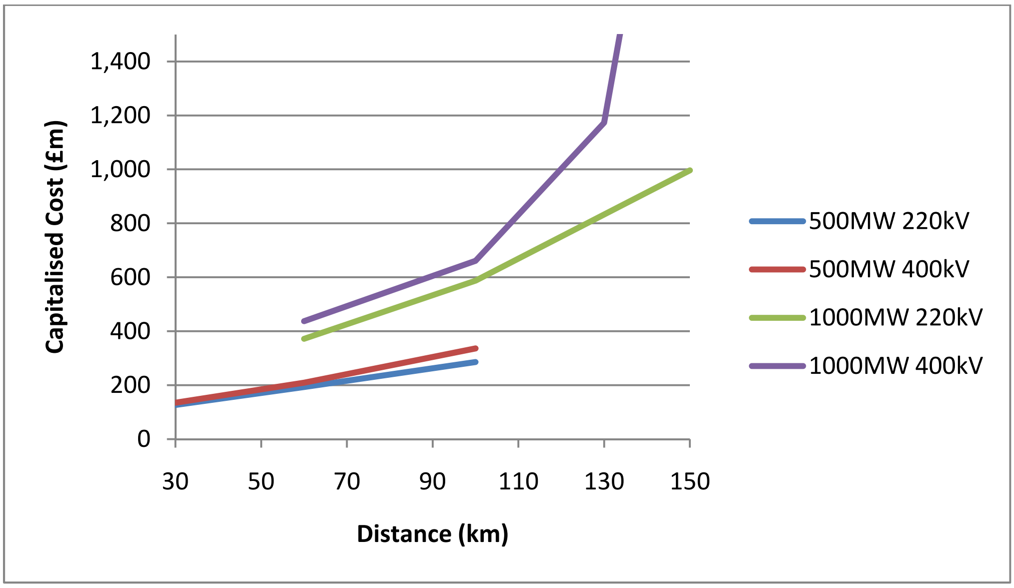


Figure 29 shows that laying single core cables individually removes any cost advantage of using 400kV as the installation costs are a significant proportion of the overall cost.

- **Figure 30 Potential Advantage of Reactive Compensation Platforms**

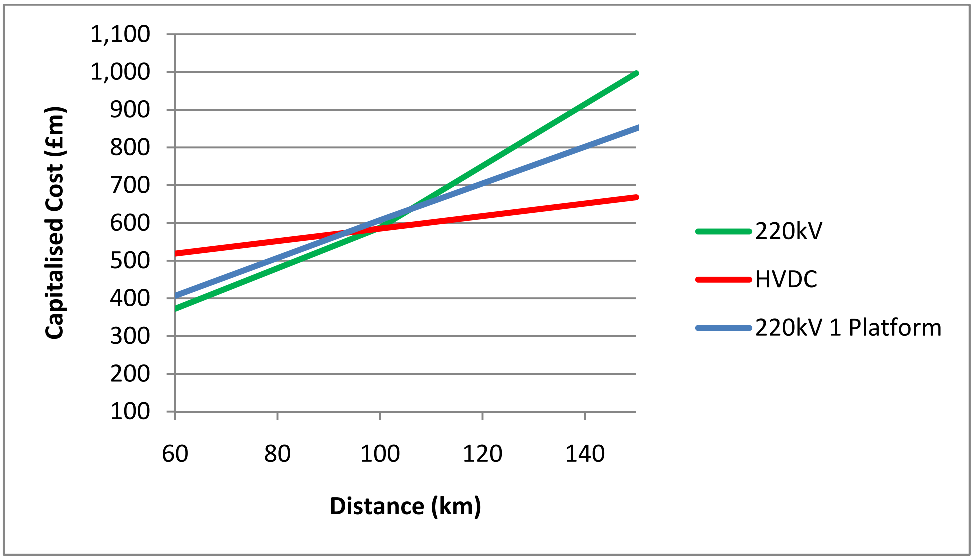


Figure 30 shows the cost comparison between HVDC, 220kV 50/50 reactive compensation split, and 220kV with one intermediate reactive compensation platform, for a 1000MW connection. Although reactive compensation platforms are economically viable over standard AC at long distances they are not likely to be an alternative to HVDC.

- **Figure 31 3500MW Optimised 220kV AC and 550kV GIL Comparison**

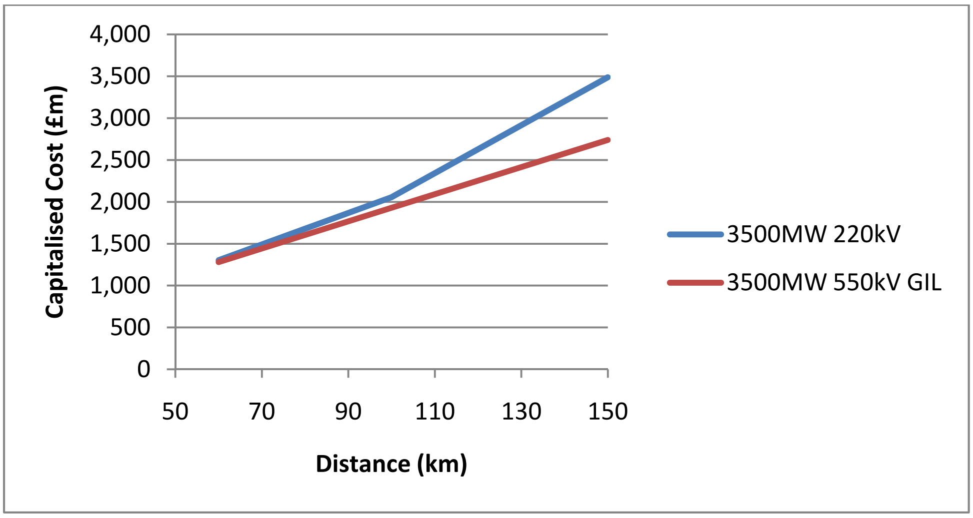


Figure 31 presents an indicative capitalised cost for a 3500MW energy farm connection as a single 550kV GIL circuit or as standard 220kV AC. GIL is relatively cheap in this application as the increase in connection cost is small compared to increase in connection capacity, although this aspect of GIL could prove problematic for large connections in terms of SQSS compliance.

A.6 Analysis

Increasing AC voltage will reduce connection cost significantly, 220 kV which has already been developed as prototype appears to represent the optimised AC export voltage for Development Case ‘distributed smaller windfarm’, replacing the 132 kV export of the base case. 400 kV export could provide further savings up to 100km connection distance however significant development of export AC cables and installation techniques is required to facilitate its application.

The above results show that GIL is technically a very attractive proposition. However, with each phase required to be laid expensively and separately as a pipe, it is the cost and practical issues that limits its viability not taking into account issues with present and anticipated SQSS requirements. The primary benefit of GIL is the ability to have high capacity circuits that require relatively little reactive compensation to export very long distances. Current SQSS infrequent infeed loss limits make a 1320MW connection the largest possible at present and so GIL will never be attractive. For GIL to become attractive regulations would have to be changed to allow much larger capacity single connections, larger even than the revised SQSS that may be introduced to accommodate new single shaft nuclear generation. This study is based upon very basic GIL cost data due to the lack of previous applications and only serves to show the potential for GIL in bulk export that could warrant further investigation.

Both the 220kV and 400kV export options require large amounts of reactive compensation to be installed offshore. The cost estimate in this report has taken into account platform cost related to the reactive compensation placed offshore however no limit on platform topside area has been applied. Practical limitations on platform size could result in multiple smaller platforms at significantly greater cost.

A.7 Analysis Sensitivity

- **Figure 32 Breakdown of Costs for 500MW Architecture Comparison**

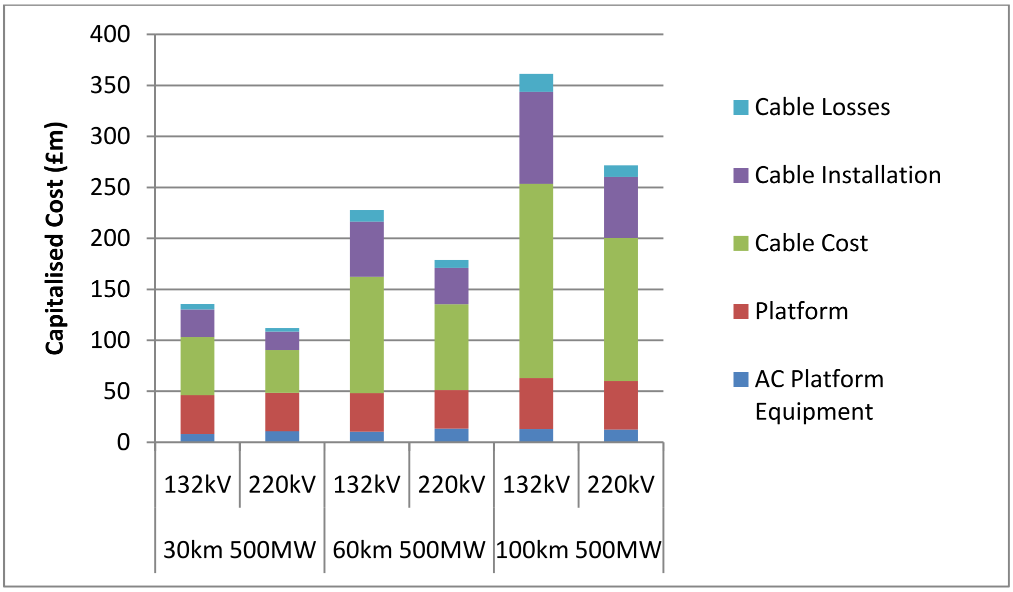


Figure 32 shows the relative significance of connection architecture equipment for a 500MW development. Immediately apparent is that cabling costs (both cable cost and installation cost) are the distinguishing factor between alternative project connection distances. Any Variation in cabling costs will directly impact on the overall development cost. That said variations to the cable capital, installation and associated costs would impact on all the connection options shown in Figure 9 and would not thus be expected cause the outlined capital cost trends to change.

Losses and the considered offshore platform equipment costs are relatively small such that any variance would not be significant in the overall cost comparisons.

Platform costs are a significant cost factor for a given development size, that said platform costs are relatively constant only increasing noticeably for longer distance 400kV connections due to reactive compensation requirements.

Given that cabling costs are the most significant single aspect, and overall sensitivity of the analysis to variation is attenuated by the fact that any variation in cabling is likely to be reflected in all cases, the analysis is considered insensitive to variation.

Appendix B HVDC Export Detailed Results

B.1 Objective

To undertake studies with optimised intra-array system but with HVDC export to determine the break points at which HVDC becomes the preferred export solution based on distance to shore and export power.

B.2 Model

B.2.1 Technical Assessment

For this part of the study, technical modelling has been carried out only to attain losses for economic assessment, with the majority of modelling being carried out in spreadsheets given the requirements of the studies and the loss model associated with a HVDC connections and converters. A selective number of studies were replicated in DIgSILENT PowerFactory to verify close agreement with the spreadsheet results.

B.2.2 Economic Assessment

The economic assessment has been carried out to quantify the cost implications of applying the technical solutions analysed in the technical assessment. A connection option that is technically superior to another is unlikely to be the preferred option if it is also the most cost option (assuming both options meet all relevant regulatory requirements).

Cost estimates include the cost of export cable, HV switchgear, collector platform transformer and related platform costs, converter platform and onshore converter station, and capitalised cost of converter platform and cable losses.

B.3 Methodology

HVDC losses have been calculated for 500MW and 1000MW bi-pole connections for use in economic modelling. 500MW and 1000MW have been selected as technical restrictions limit HVDC single circuit connections to just over 1000MW which aligns closely with SQSS[22] limitations on normal and infrequent infeed loss risk of 1000MW and 1320MW respectively. However even taking into account expected regulatory changes (new nuclear 1800MW) and technical advances single circuit connections are unlikely to exceed 2000MW without a level of redundancy. Capitalised costs of HVDC up to 2500MW have been estimated assuming the development of the necessary cables and devices as outlined in the State of the Art Report.

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[22] Note that the SQSS must be considered in terms of the assumptions it is based upon, namely limited to windfarms up to 100km offshore and up to 1500MW. The developments considered within this report would fall outside of these assumptions and there for a review of the regulations will be required.

For HVDC export connection voltage is assumed to be the minimum voltage required to facilitate the export power given the converter current rating. Existing voltage source converter current rating is around 1800A equating to around 540MW at ±150kV and 1152MW at ±320kV aligning with the selected converter capacities. Cable size has been selected as the smallest required to accommodate the export current for each 500MW/1000MW block.

B.4 Results

- Figure 33 HVDC Cost by Capacity for 100 km Connection

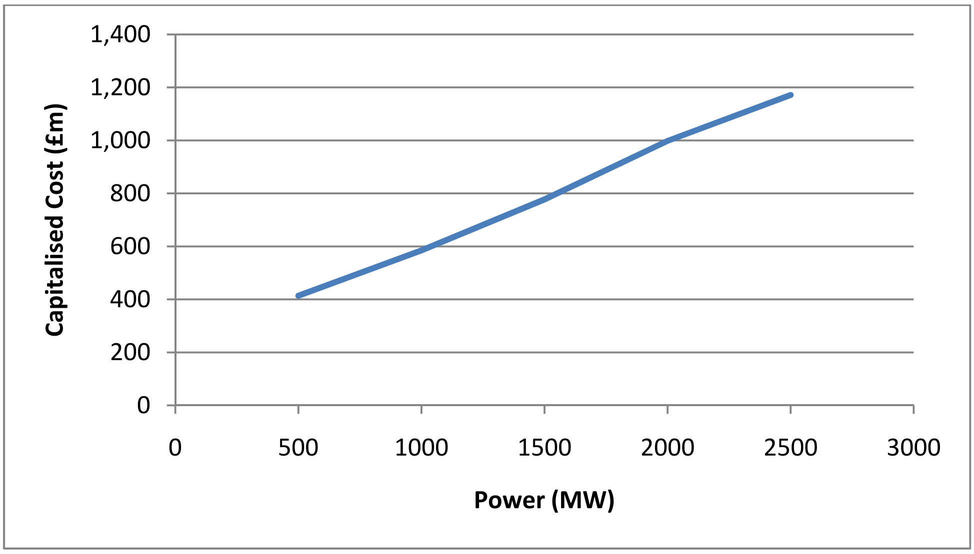


Figure 33 is an indication of HVDC connection cost against export power, the cases costed are 500MW ±150kV, 1000MW ±320kV, 1500MW ±400kV, 2000MW ±400kV and 2500MW ±500kV.

- **Figure 34 Optimised AC Solution against HVDC Solution**

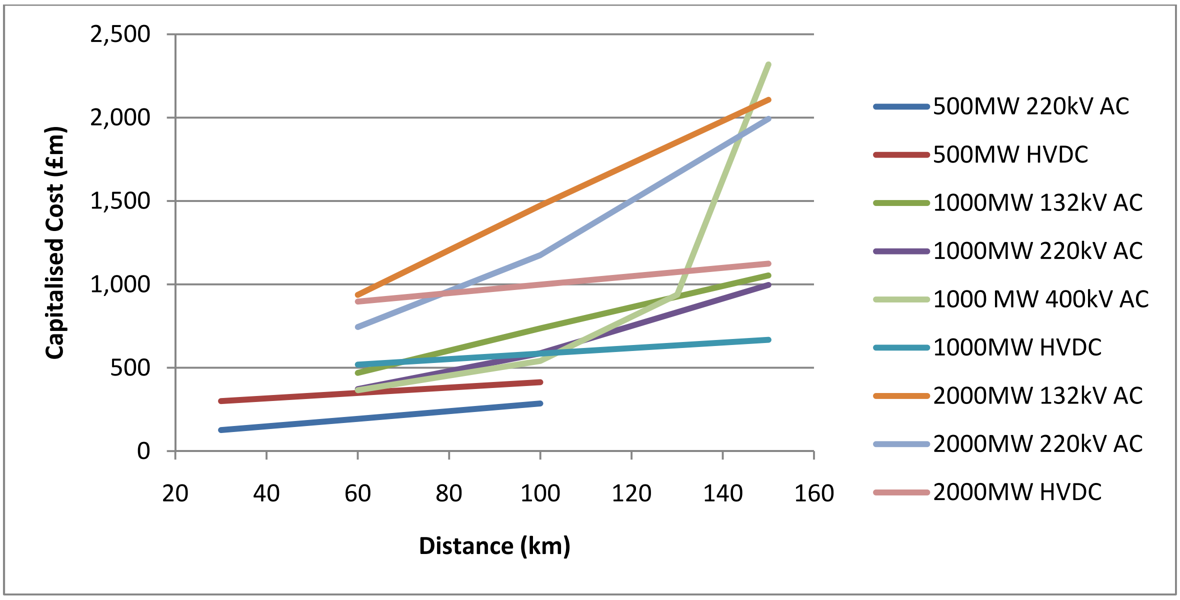


Figure 34 has been produced comparing the least cost connection options for 132kV, 220kV and DC for 500MW, 1000MW and 2000MW developments at a range of distances.

B.5 Analysis

By applying 220kV AC export the 1000MW 70km break point identified for 132kV AC could be pushed closer to around 1000MW 100km. 220kV AC XLPE submarine cables have been developed and tested making their wider application in the future likely given the above results. The cost difference is relatively small over 90km and there is potential for HVDC to be chosen in preference to AC due to the operational benefits such as complete control over converter output despite the additional cost.

Over the distances considered AC is always the cheapest option for 500MW developments. For windfarms of 2000MW or larger the export is most likely to consist of multiple 1000MW connections given the combination technical, economic, and regulatory issues talked about previously and so the break point remains the same.

A 3-core 400kV export cable could increase the break point; however the reactive compensation requirement above 100km ensures that the increase in break point will be limited only around 105km.

In the near future the break point whereby HVDC export technology will be preferred over AC will be around 1000MW and 90km.

B.6 Analysis Sensitivity

- **Figure 35 Breakdown of Cost for 1000MW Architecture Comparison**

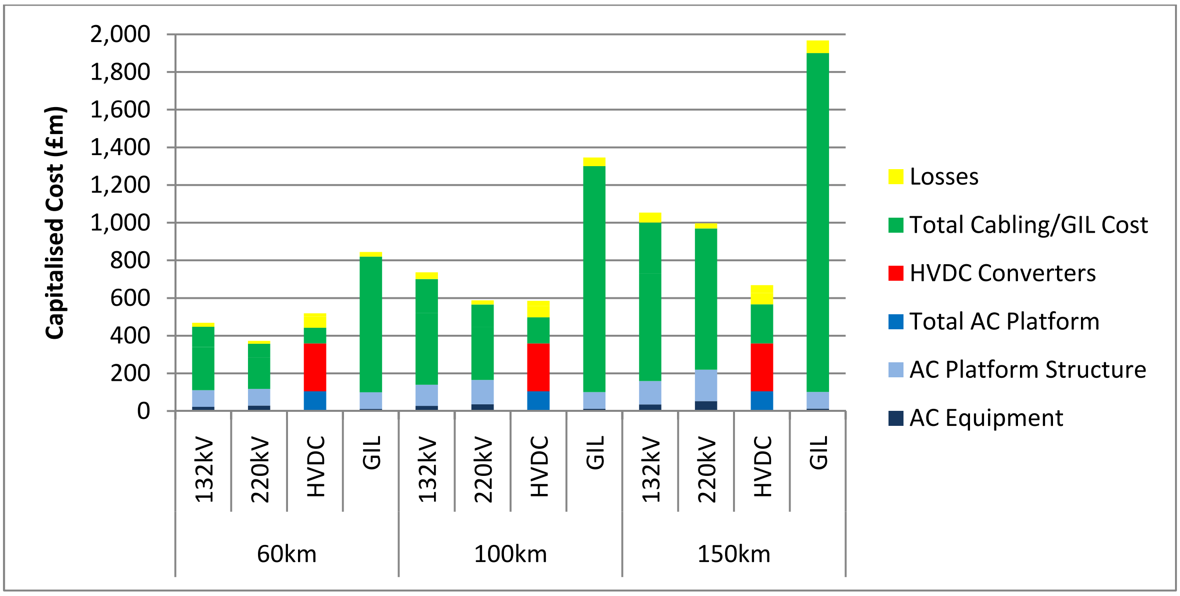


Figure 35 presents a breakdown of costs for the alternative export connection technologies. The chart shows clearly the relative weighting of cost components of the connection. The most significant cost components are cabling/GIL costs as well as converter costs associated with the HVDC options.

Variance in AC equipment and platform costs will be reflected across all architectures making the overall conclusions insensitive to such changes. Electrical losses are too small a cost to influence the selection of one technology over another but would be expected to influence the final detailed design of the connection.

Very high cabling costs for AC architectures results in a strong sensitivity to variance in cabling costs. For example the AC/HVDC break point (1000MW 90km) shifts in inverse proportion to the % increase in AC cabling costs, i.e. a 20% increase in cabling costs results in an approximate 20% decrease in breakpoint distance.

HVDC cabling costs are less significant than converter costs. The break point increases and decreases proportionally with HVDC converter costs (capital and installation) however with a ratio of only ¼, i.e. a 20% increase in HVDC converter cost relates to only an approximate 5% increase in break point.

Appendix C Detailed Studies on Optimised Architectures

C.1 Objective

To apply the results of the optimisation studies to the Development Cases from the Scenarios Report to enable a full range of studies to be completed including potential impact on the onshore Grid.

Table 9 shows how the optimisation study results have been applied to each Development Case.

C.2 Model

The detailed studies relate to harmonic and Fault Ride-Through which ultimately make up a basic assessment of the offshore systems impact on the onshore grid. The full system models have been created in DIgSILENT with the harmonic load flow and dynamic stability modules utilised to produce the respective studies. As the turbine is the primary factor in these studies a complete 3.6MW turbine model representing a leading turbine supplier has been used and scaled accordingly for other studies.

Appendix D illustrates the models used to assess the harmonic impact of each of the Development Cases stated below.

C.3 Methodology

Following the studies carried out into new and innovative collection and export designs there have been a number of optimisations recommended for further assessment. These follow the Development Cases outlined in the Scenarios Report and are a recommendation based on energy park size, distance from shore, turbine size and potential development time. The following optimisations have therefore been made.

- **Table 9 Optimised Designs for Development Cases**

Case Number	Development Case	Collector Technology	Export Technology	Turbine Size MW	Farm Size MW	Distance from Shore km	Development Time
Base	Base Case	33kV AC	132kV AC	3.6	500	60	Present
Case 1	Distributed Smaller Windfarms	33kV AC	220kV AC	3.6	500	60	Short
Case 2	Large Windfarms	33kV AC (100Hz)	HVDC	5	2000	100	Medium
Case 3	Very Large Windfarms	Series DC	Series DC	7.5	5000	150	Long
Case 4	Small Marine	Series DC	Series DC	1	20	30	Short
Case 5	Medium Wave	33kV AC	132kV AC	1	200	60	Medium

Case Number	Development Case	Collector Technology	Export Technology	Turbine Size MW	Farm Size MW	Distance from Shore km	Development Time
Case 6	Large Tidal	33kV AC	220kV AC	1	500	60	Long
Case 7	Combined Tidal and Wind	33kV AC	220kV AC	3.6 Wind 1 Tidal	500 Wind 500 Tidal	60	Long

The base case has been used to provide a benchmark on the relative advantages or disadvantages of new connection architectures which have been produced. This case is aimed at a present state of the art offshore wind development and has been used to verify the DIgSILENT model which will then be modified for the further Development Cases.

The following studies are performed to ascertain the comparative benefits of the alternate architectures against a present state of the art 'base case' and are not designed to quantify in detail whether or not a proposed architecture would comply with all current GB Grid Code and Technical requirements.

C.4 Results

C.4.1 Harmonics

The harmonic analysis undertaken in this project and reported on here has been conducted to provide a comparative assessment of the merits of one architecture over another and to inform the conclusions and recommendations on architecture and technology opportunities. It is important to recognise that this is the aim, rather than to attempt to develop detailed designs for individual energy farm connections, which because of the generic nature of the work and the non-location specific aspects considered, would not be feasible. Consequently, in conducting the harmonic studies there is no consideration of any background distortion at the onshore connection point within each study architecture. Such background information is highly location specific and whilst will undoubtedly be a significant influence on whether or not a particular energy farm connection will comply with the total harmonic distortion (THD) and individual harmonic limits dictated in Engineering Recommendation G5/4, it is not possible to consider background distortion levels in a generic fashion. This does not compromise the aims or outcomes of the harmonic studies conducted, as the purpose is to ascertain the relative merits of one architecture against another, which the approach adopted demonstrates.

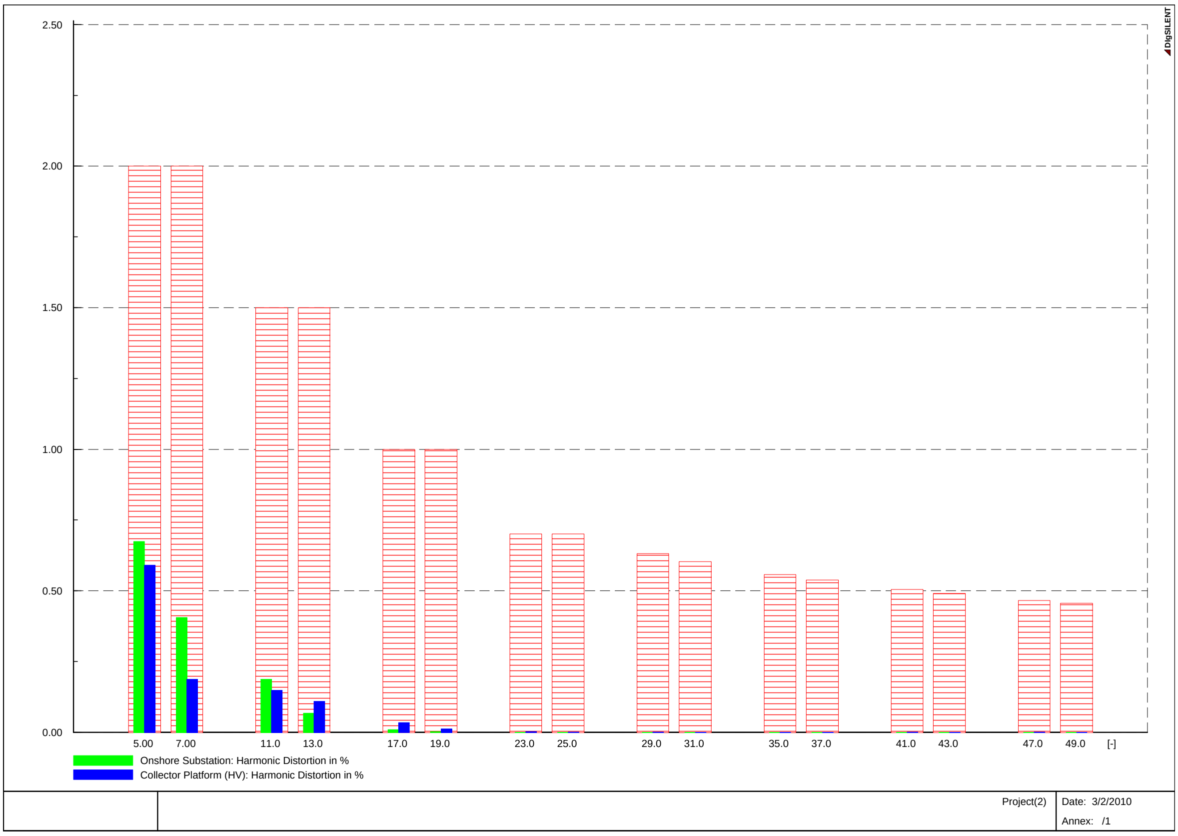
The harmonic load flow results for each of the development cases are shown in Table 10 in Appendix C.4.2 with a short description of the models construction and reason for selecting an optimised design. Figure 36 and Figure 37 illustrate in a graphical sense the harmonic distortion impact whereby the red trace represents the grid compliance values as stated in Engineering

Recommendation G5/4-1[23]. In addition the green trace illustrates the harmonic contribution at the offshore collector platform whilst the red trace represents the harmonic contribution at the Supergrid connection point.

Base Case

The base case provides a benchmark on which the performance of the Development Cases is compared and is representative of a present day, state of the art windfarm on which the models can be verified. The design of this case is described in Table 9.

▪ **Figure 36 Base Case Harmonic Load Flow**



Distributed Smaller Windfarms

The distributed smaller windfarm is indicative of short term offshore wind developments similar to that noted in the base case. Export cable optimisation has shown that in the near future 220kV AC technology could be the preferred design for connections of this size less than 100km from shore.

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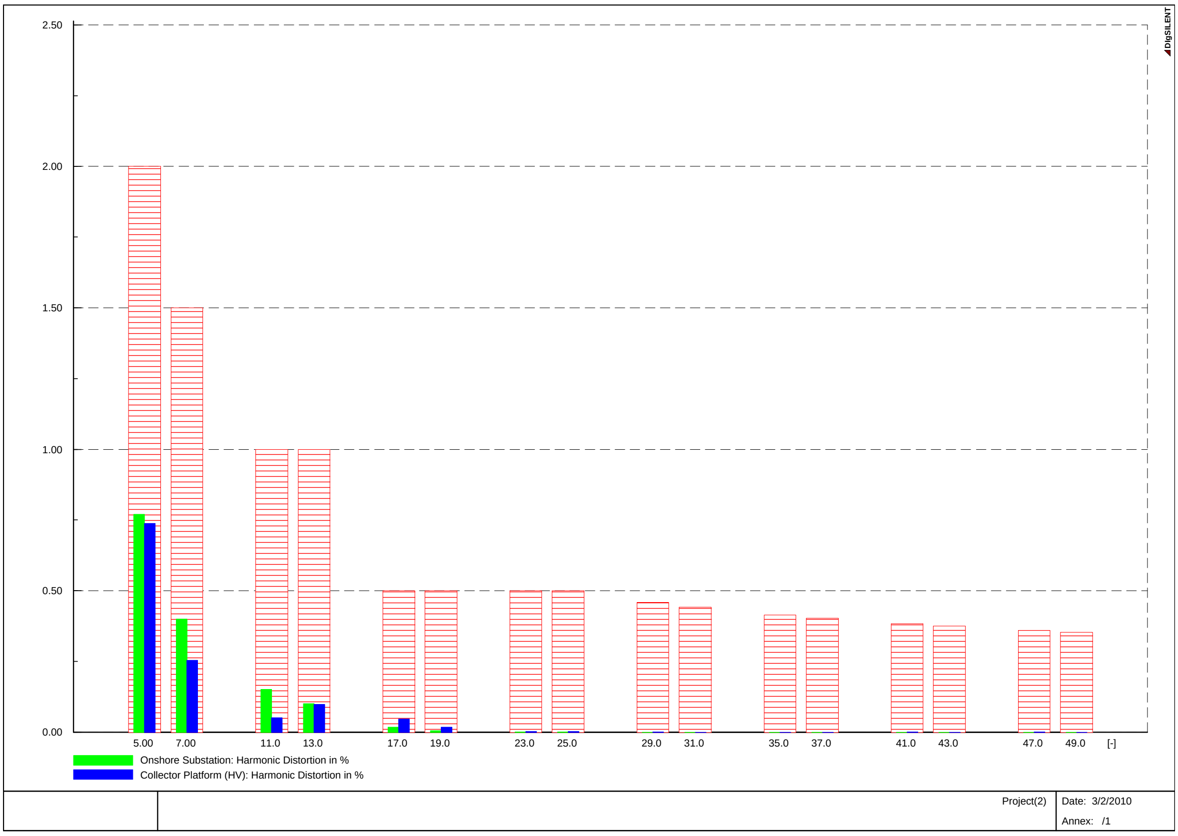
[23] Energy Networks Association, ‘Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the UK’, Engineering Recommendation G5/4-1, October 2005

For this reason the architecture selected for further studies is a 33kV AC collection design with 220kV AC export.

- **Figure 37 Distributed Smaller Windfarm Harmonic Load flow**



Large Windfarm

The large windfarm relates to potential Round 3 developments and puts emphasis on HVDC export technology with a distance from shore of 100km and total capacity of 2000MW. As has been noted previously, such a large design will more likely be split into multiple 1000MW modules. At 100km and 1000MW the results of the export optimisation studies show that a HVDC link is the preferred design for this case utilising a 33kV AC collection system. In addition as an AC/HVDC hybrid design is being employed it allows the use of the optimised intra-array frequency of 100Hz.

Very Large Windfarm

The very large windfarm indicates a long term future development some 150km from shore. At this distance the export technology used must be DC as the costs associated with AC at this distance are prohibitive. Again it is assumed that such a large development would be made up of a number of smaller modules assumed to be in the region of 1000MW. Due to the long term focus of this design it is possible to envisage the series DC system could be used following extensive research and developments.

Small Marine

The small marine case is aimed at the short term and relates both tidal and wave generation developments. The aim of this case is to illustrate any commonalities between this and the more significant medium and long term cases and could justify investment in an early stage that would benefit the short term capacity developments but continue to give benefits to the larger developments that will come in the future. For this reason the series DC design has been selected as this architecture could become very popular in the distant future for large scale developments. An application on a small scale short term development would allow assessment of the potential for such a design.

Due to the short term nature of the Development Case the generator output voltage has been limited to 12kV, the maximum available at present. This relates to a DC voltage of ±7.5kV. As the case is short distance and low capacity it was deemed unnecessary to have an exceptionally high export voltage so in order to allow two strings of 10 turbines to be connected an export voltage of ±75kV was selected.

Medium Wave

The medium wave case is a 200MW development some 60km from shore and using the breakpoints identified in the optimisation studies would indicate an architecture similar to that of the base case with 33kV AC collection and 132kV AC export.

Large Tidal

The large tidal case is similar to that of the smaller distributed wind case but utilises smaller turbine sizes. As the optimisation studies have shown that 33kV AC voltage is preferred for AC intra-array systems then the optimised architecture is based on that of the smaller distributed wind case.

Combined Tidal and Wind

This study will be looked at as two separate connections relating therefore to the large tidal and smaller distributed wind cases. The potential for connecting these architectures offshore with a single connection to shore will be assessed in the multiple connection architectures report following this.

C.4.2 Results

Engineering Recommendation G5/4-1 specifies harmonic voltage compatibility for varying connection voltages. As the Base Case and Case 5 are connected to the Supergrid at 132kV, the respective G5/4-1 standard will be utilised. For all other cases the harmonic compatibility for connections at 275 and 400kV are used. Table 10 shows the total harmonic distortion results for each case and reference to the G5/4-1 standard which must be met to allow grid code compliance in terms of harmonics.

- **Table 10 Total Harmonic Distortion Grid Compliance Results**

G5/4-1	Base Case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
3%	0.81%	0.89%	0%	0%	0%	0.57%	1%

The results show that for all Development Cases there is substantial compliance with grid code standards. This is especially seen with HVDC connections whereby the filters in the converters can dramatically reduce the harmonic distortion. The level to which the filters can reduce the distortion will be project specific; however for the studies carried out here the filters applied at the converter stations have had a dramatic impact at reducing total harmonic distortion at the grid connection point.

It can be seen that the most significant harmonic voltages are located at the low order harmonics which is indicative of an unsophisticated PWM converter. The model utilised for this section of analysis is developed around the time of 2005 and represents a basic single level PWM converter which introduces high values of low order harmonics. State of the art PWM designs, such as multi-level converters, can significantly reduce low order harmonic, restricting voltages to those located around the switching frequency which at present is in the region of 2kHz or the 40th harmonic[24].

Future PWM advances will therefore reduce harmonic distortion further; however basic technologies are also within grid code requirements as seen by this study.

C.5 Fault Ride-Through Capability

Fault Ride Through capability of an offshore wind farm and associated transmission system connection is largely determined by the generators and their control functionality and capability. In depth generator analysis is not however part of this work stream and consequently the Fault Ride Through assessment outlined here was designed to illustrate whether different network architectures can aid or be detrimental to this Grid Code performance characteristic.

The base case architecture was adopted in this study and was modelled using a low fault level at the super grid connection point (as indicated in the guidance provided by National Grid in 2008[25] with respect to conducting Fault Ride Through studies), with data on this aspect obtained from National Grid's Seven Year Statement for year 2009. Individual three phase faults were applied at the Supergrid connection with a variable fault impedance to create a Supergrid voltage drop and duration meeting voltage profile outlined in CC 6.3.15.1 (Figure 5) of the GB Grid Code and is shown here in Figure 38 for reference. The wind farm modelled was found to successfully comply

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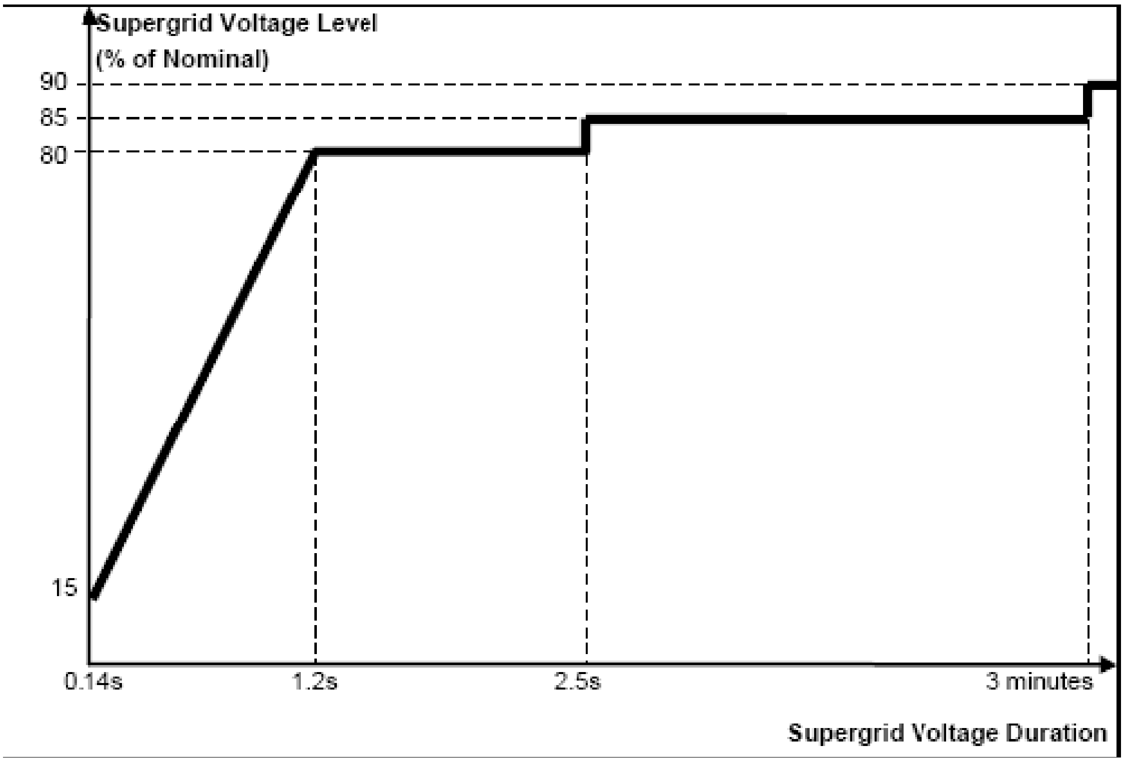
[24] Maibach et al, 'Full-Scale Medium-Voltage Converters for Wind Power Generators up to 7MVA', ABB Switzerland, Feb 2007

[25] Guidance Notes For Power Park Developers September 2008 Issue 2

with the Fault Ride Through requirements. This is to be expected as the base case is modelled upon a state of the art wind farm architecture which is already in operation.

- **Figure 38 Supergrid Voltage dips greater than 140ms in duration**



From this base case study it was possible to predict the relative advantages available from new architectures. For instance, for distances over 60km (that used in the base case) and connected via an AC export cable the impedance of the transmission circuits will be greater. With increased impedance the impact of a fault at the onshore grid is effectively reduced at the offshore turbine terminals and effectively allows improved fault ride through capability.

For HVDC links or a series DC connection design there is an element of isolation from the onshore grid with the use of converter stations, and consequently of onshore Supergrid faults. When an onshore Supergrid fault occurs, the power input to the AC system from the DC transmission system will be expected to reduce in proportion to the level of the retained AC voltage at the onshore DC converter station. It would be expected that a reduction in the power input to the AC system would require the wind turbines to reduce their power output to prevent a significant overvoltage at the turbine. However, if the DC converters have the facility to dissipate the excess energy (i.e. through the use of a chopper circuit[26]) then the wind turbines may be largely unaffected by the onshore Supergrid fault, and consequently Fault Ride Through performance would be expected to improve over that presented with an AC transmission connection.

A number of in depth studies have been carried out by numerous bodies on this topic to illustrate the control methods that can be used by a VSC converter station to meet the Fault Ride Through requirements of European and other Grid Codes.[26,27] These studies and others have concluded that although there are issues with power electronic converters having no current over-loading capability which can lead to the direct voltage becoming uncontrollable during a fault; there are a number of strategies to overcome this and have been employed. Following the implementation of these strategies the windfarm becomes effectively isolated from the grid and results in the windfarm not being significantly affected in abnormal conditions. This allows the windfarm to stay connected to the grid during and after grid short circuit fault and contribute to improve transient stability of the power system.

C.6 Analysis

The analysis of harmonic distortion studies has illustrated quite conclusively that the introduction of DC systems which incorporate converter stations significantly reduce the level of harmonic contribution to the grid. With fully DC systems the harmonic contribution is minimal throughout the system whilst with AC/HVDC hybrid systems the harmonic contribution in the AC collection system is removed by the DC link. Although the HVDC converter stations will produce a number of harmonics, the filters included in the construction of this equipment can greatly reduce this. One area where harmonic distortion has been seen to increase in magnitude compared to the base case is the introduction of 220kV AC as an export technology, however the impact is still very minor at the onshore grid and the model used is that of a pessimistic PWM converter.

In terms of Fault Ride-Through capability it can be seen that this can be improved in comparison to the base case in all future architectures. The increase in distance to shore introduces higher impedance to the Supergrid fault which will aid in reducing the impact on turbines in AC export cases. All DC connection cases utilise a converter station at the Supergrid which effectively isolates the offshore system resulting in turbines being largely unaffected by a Supergrid fault and improving Fault Ride-Through ability considerably.

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[26] R.L.Hendriks et al, ‘Fault Ride-Through Strategies for VSC-Connected Wind Parks’, EWEC, 2009

[27] H.Livani et al, ‘Improvement of Fault Ride-Through Capability in Wind Farms Using VSC-HVDC’, European Journal of Scientific Research, Vol.28 No.3, 2009, pp.328-337

Appendix D DIgSILENT Development Case Models

The following diagrams show the detailed windfarm models referred to within this report as arrived at in the conclusions and further studied in Appendix C with harmonic and fault ride through analysis.

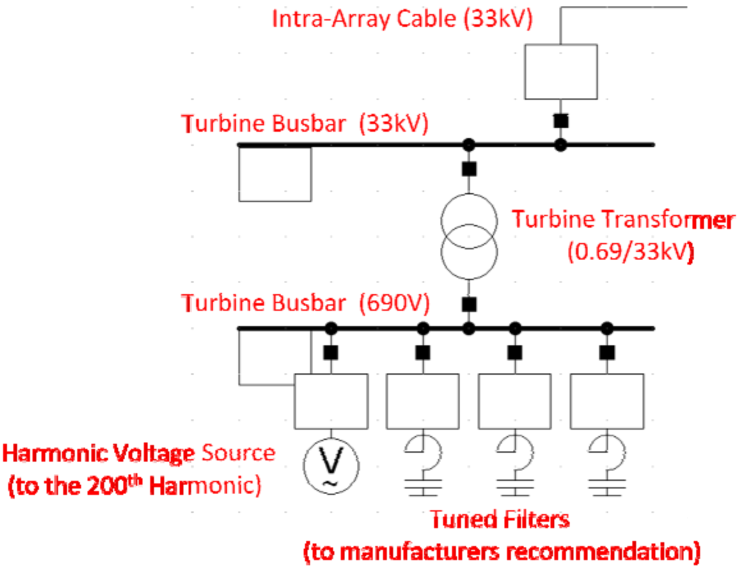
The following diagrams are colour coded by voltage level, blue represents generator voltage in all diagrams with the remaining coloured as follows;

- **Table 11 Optimised Designs for Development Cases**

Case Number	Development Case	Red	Green	Dark Red	Black	Turbine Size MW	Farm Size MW	Development Time
Base	Base Case	33kV AC Intra-array			132kV AC Export and Supergrid	3.6	500	Present
Case 1	Distributed Smaller Windfarms	33kV AC Intra-array			220kV AC Export and Supergrid	3.6	500	Short
Case 2	Large Windfarms	33kV AC (100Hz)	Intermediate AC	±320kV HVDC	Supergrid	5	2000	Medium
Case 3	Very Large Windfarms	Series DC ± 320kV Export?			Onshore Converter and Supergrid	7.5	5000	Long
Case 4	Small Marine	Series DC ± 150kV Export?			Onshore Converter and Supergrid	1	20	Short
Case 5	Medium Wave	33kV AC Intra-array			132kV AC Export and Supergrid	1	200	Medium
Case 6	Large Tidal	33kV AC Intra-array			220kV AC Export and Supergrid	1	500	Long

A legend of the major components used in the DIgSILENT models is shown in Figure 39 and Figure 40. These models were that used for harmonic distortion analysis with components and values being in line with a state of the art offshore wind turbine from a major manufacturer.

- **Figure 39 DIgSILENT Models Legend (AC Connection)**



- **Figure 40 DIgSILENT Models Legend (DC Connection)**