A comparison of AC and HVDC options for the connection of offshore wind generation in Great Britain

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***Abstract*-- This paper presents a comparison of two forms of cable connection of a distant offshore wind farm to a transmission system: AC and HVDC. The requirements of relevant industry standards in Great Britain (GB) that drive a connection design and, hence, its cost are highlighted along with an analysis of the ways in which AC cable connections might be made to comply while facilitating export of active power. Dynamic studies investigating responses to grid-side short circuit faults show that, in the particular scenarios studied, an AC connection of a wind farm in the place of a large synchronous generator is marginally detrimental while an HVDC connection is beneficial. A comparison of costs shows that the cross-over distance at which HVDC is cheaper than AC for wind farms of different sizes occurs at longer distances than have hitherto commonly been assumed, and AC connections benefit from reactive compensation not only at the point of common coupling and wind farm end but also at the connection mid-point.**

***Index Terms*—wind energy, cables, HVDC, reactive power, voltage control, power system stability, power system economics.**

I. Introduction

A large proportion of new wind farms in Britain seeking transmission connections will be offshore [1] and so require use of undersea cables. Moreover, many of them will be quite distant from the nearest existing transmission route into which they might be connected. At long distances, a HVDC connection from the wind farm itself to the main interconnected transmission system (MITS) becomes a cost-competitive alternative to a conventional AC connection, though HVDC might also be considered for onshore connections that require the use of cables for local planning reasons. In [2], the distance at which HVDC connection of an offshore wind farm becomes cheaper than an AC cable solution is described as being conditional on a number of factors including average wind speed, discount rate and wind farm size with results ranging between around 83km (for a 400MW wind farm with an average wind speed of 8m/s) and around 95km (for a 1000MW with an average wind speed of 11m/s). In [3], dependency of the 'break-even' distance is explored in respect of whether investment in both the connection and the wind farm is undertaken by the same party, in which case the distance is reported as being 35km for a 300MW wind farm, or two different parties in which case it is 80km. Meanwhile, [4] and [5] highlight the importance of losses in the evaluation..

It has been commonly assumed that HVDC is the only practical option for cable connections above a certain distance [3] and a number of HVDC connections of offshore wind farms are reported as being planned for commissioning in 2014 or 2015 [6][7]. However, anecdotal evidence suggests that wind farm developers are now hesitant to invest in what they still regard as a relatively unproven technology, namely voltage source converters (VSC) employed in a challenging offshore environment and connected to an offshore AC hub that collects power only from wind turbines. They have therefore sought more comprehensive evaluation of the costs and benefits of HVDC compared with AC and are considering an AC solution at significantly longer distances than [2] or [3] suggested would be economic. Precedent for using long AC submarine transmission cables has been set by the oil industry and the construction of interconnections between different, otherwise islanded, power networks [8]-[10]. These include three-phase AC cables at line voltages of 145kV and up to 162 km in length. Moreover, consideration is being given to ways in which the problems associated with long AC cables might be overcome, including use of mid-point compensation to reduce voltages and losses [11]. Meanwhile, one of the first planned HVDC connections of an offshore wind farm, BorWin1, was originally expected to be operational in 2009 but is, as of November 2014, reported by ABB to be planned for commissioning in 2015 [6] with a number of problems having been reported including overcurrent in a filter, a fire and "'dirty electricity' affecting the substation" [12].

This paper presents a comparison of AC and HVDC transmission for the point-to-point connection of offshore wind farms to the transmission system in Great Britain (GB) in order to establish the most economic form of connection for different sizes of wind farm with different lengths of cable connection. This is firstly determined by the functional

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requirements for the connection and these are set by relevant industry codes that define minimum performance capabilities.

Not least because of the high capacitance of long AC cables, a particular focus of the study reported here is in respect of voltage control and reactive power. For example, while it is well known that AC cables tend to generate reactive power, the requirements of the STC can be satisfied at the point of connection to the MITS by installation of appropriate reactive compensation. For a valid comparison of the cost of the AC option with that of HVDC, the cost of this reactive compensation should be included along with that of power losses. However, other performance characteristics, while not required by any of the codes, might be inherently provided by certain classes of equipment and prove valuable to operation of the system, e.g. the flexibility of VSC, not least in responses to faults and provision of reactive power. These characteristics are also important and have been investigated in this study in respect of contributions to system stability.

The next section of this paper briefly reviews the main codes that set the functional requirements for connection of offshore wind farms in British waters to the GB MITS. Then, some case studies are outlined followed by presentation of results of steady state and dynamic analyses, the latter of which compares responses to system faults when an offshore wind farm is connected either via an AC cable or via HVDC VSC. Then, some comparisons of the economics of different connection options are presented for different sizes of wind farm at different distances from shore along with some relevant regulatory issues followed by conclusions.

II. Requirements Set by Relevant Codes

There are three documents that detail the connection requirements for wind farms in Britain: The Grid Code [13]; the System Operator, Transmission Owner Code (STC) [14] which manages the relationship between different transmission owners (TOs) and between a TO and the system operator; and the Security and Quality of Supply Standard (SQSS) [15]. Within these documents there are four particular areas of relevance to the connection of a wind farm via a long transmission link: power factor capability at the point of common coupling (PCC) between the transmission link and the MITS; voltage tolerance band at all points in the network; design requirements to comply with loss of in-feed risks; and the capability for the voltage at each node and the generation in the system to recover following the clearance of a fault.

The Grid Code governs the interface between the generator (wind farm) and the immediate transmission link. Under GB regulatory arrangements, the transmission link between an offshore wind farm and the MITS will be maintained by an Offshore Transmission Owner (OFTO). The interface between the latter's assets and the MITS is governed by the STC.

A. Power factor and voltage control requirements

In order to support the voltage at the interface point between the wind farm transmission link and the MITS there must be the capability for the power factor to be controlled over a minimum range of 0.95 lagging to 0.95 leading. This requirement is valid over a certain active power transfer range [14]. A functional performance specification is also set out dictating the required capability for "continuous changes to the reactive power supplied" at the interface point between an offshore network and the onshore network. The associated voltage control system is required to be able to start a response to interface point voltage step changes within 0.2s of the application of a step, be capable of operating between 95% and 105% of the nominal voltage and have a slope characteristic between reactive power and voltage of between 2% and 7% within the range of reactive power capability. It should also be possible for the set point to be changed within 2 minutes of receiving an instruction from the National Electricity Transmission System Operator (NETSO). If it is the view of the NETSO that additional voltage control facilities are required for system reasons at the interface point, these will be specified in the Offshore Transmission Owner Construction Agreement. (It may be noted in passing that no such voltage control requirements are defined in the STC at interfaces between onshore networks).

In addition to these requirements, the voltage at all points within the electrical network should be within limits during normal operation. Two sets of steady state voltage limits (applying to post-transient conditions) are defined in the SQSS: planning limits and operating limits (Table I). The former are those that should be adhered to when designing the system whereas the latter are the final values for system operation. The former are tighter than the latter in order to provide some flexibility against a range of possible operating conditions. Limits are also defined with respect to step changes that occur as a result of switching operations within the network.

TABLE I: Limits for steady state transmission system voltages in planning and operation timescales [15]

System nominal voltage	Planning timescale voltage minimum	Planning timescale voltage maximum	Operational timescale voltage minimum	Operational timescale voltage maximum
400kV	380kV (95%)	410kV (102.5%)	360kV (90%)	420kV (105%)
275kV	248kV (90%)	289kV (105%)	248kV (90%)	303kV (110%)
132kV	-	139kV (105%)	119kV (90%)	145kV (110%)

B. Fault ride-through capability

Following the occurrence of a fault on the MITS with a duration of up to 140ms, the wind farm transmission link is required to remain connected to the rest of the system without the tripping of any plant associated with it. This must be achieved for a close-up solid three phase fault or any unbalanced short circuit fault. During the fault period the transmission link should generate maximum reactive current without exceeding equipment current ratings and, following the clearance of the fault by the operation of protection within the MITS and the restoration of the interface point voltage, the transmission link is required to restore its active power transfer to within 90% of pre-fault levels within 0.5 seconds. In response to a voltage dip with a duration longer than 140ms the transmission link should remain connected and generate maximum reactive power capability while the interface point voltage is at least 15% at 140ms from fault inception, rising to 80% at 1.2s and 90% after 3 minutes, and restore its active power transfer to within 90% of pre-fault levels within 1 second of the interface voltage being restored [13].

C. Loss of in-feed requirements

The electrical design of a wind farm transmission link must comply with requirements set out in the SQSS with regard to limiting the loss of in-feed risks to the system [15]. There are two main design requirements which apply to different pre-fault operational requirements: 'normal' in-feed loss risk and 'infrequent' in-feed loss risk. In the former case, a single secured event should not result in a generation in-feed loss of more than 50% of the registered generation capacity or 1000MW, whichever is smaller. Infrequent in-feed loss risk refers to occasions where the transmission link is operating in a degraded state due to a previous fault or maintenance outage. In such a case, no more than 1320MW of in-feed should be lost in response to a fault. Both 'normal' and 'infrequent' requirements must be considered when determining the number of transformers or converters. However, due to the potential cost of an additional cable, the requirement for a cable circuit is less onerous: following an outage of a cable due to a fault or maintenance, no more than 1320MW of generation in-feed should be lost.

III. Case studies – Connection of offshore wind farms of different sizes and distances from shore

In order to focus on the comparison between AC and HVDC technology options, similar basic connection designs have been considered in each case, based on a single SQSS compliant connection design placed in the public domain by National Grid Electricity Transmission (NGET) [16]. From that common starting point of an offshore wind farm connection, steady state and dynamic analyses have been carried out to identify ways in which the requirements of the Grid Code and the STC might be satisfied in each case, and then to perform an economic analysis of those broadly compliant options.

The bases for both steady state and dynamic analyses were as shown in Figs. 1 and 2 in respect of AC and HVDC connections respectively. Studies have been undertaken for 250MW, 500MW, 1000MW and 1500MW wind farms with different cable connection lengths. In each AC case, the connection is based on a suitable number of 350MVA three-core cables, chosen for use as it is the three-core submarine cable with greatest capacity that is in production and available from a number of suppliers [16]. Furthermore, in the analyses, the following assumptions have been made:

- active power only is fed into the distant, wind farm, end of the transmission cable.
- the cable capacity is de-rated by 12% to account for thermal constraints around the entry of the cable to the j-tubes [16].

With 220kV, 350MVA cables derated to around 300MVA, the offshore connection requirements of the SQSS indicate the use of 1 cable for a 250MW wind farm, 2 for 500MW, 4 for 1000MW and 6 for 1500MW.

For the HVDC case, for studies of faults on the AC system, only the converter at the PCC needs to be represented.

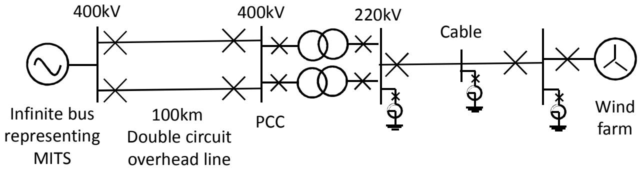

Fig. 1 Test network used to simulate close-up and distant faults with AC transmission and either DFIG or FRC wind turbines within the wind farm. Possible locations of shunt reactors are shown.

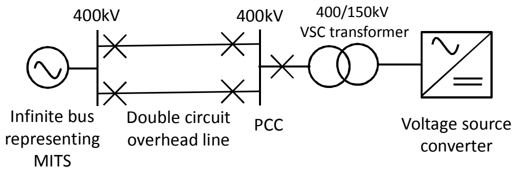

Fig. 2 Test network used to simulate close-up and distant fault with HVDC transmission (represented by the VSC terminal) for a wind farm connection

IV. Steady state analysis

In this section, the reactive power production characteristics of the AC cable connections are investigated over different lengths. By modelling the cable as four equal sections, denoted Subsea cable sections (SSC) 1-4 where SSC1 is that closest to the PCC, with three intermediary connection points, denoted Subsea buses (SSB) 1-3 and the cable parameters distributed equally, it can be ensured that the cable loading (both active and reactive power) does not exceed 100% of the continuous rating as its length is increased and that voltage rise is not excessive. The application of mechanically switched reactive compensation at various locations is investigated in order that Grid Code power factor requirements can be met at the interface point between the cable and the MITS (the PCC) and so that the voltage profile throughout the cable stays within its rating [13]. This will allow an indication of the required compensation capacity at each point to be given.

For the purpose of the steady state analysis, the grid end of the connection is directly connected to an infinite bus, fixing the voltage at this point at 1pu.

A. Single cable connection

To illustrate the issues, the case of a single cable is considered first. In Fig. 3, the amount of reactive power produced by the cable as its length is increased is measured at the PCC. It can be seen that, relative to the cable's continuous thermal rating, the amount of capacity available for export of active power from the wind farm decreases as the cable length increases and reaches zero at 120km. Fig. 4 shows the rise in voltage along the cable's length.

To meet the Grid Code connection requirements, there must be the capability to provide a minimum of 0.95 power factor leading and lagging at the PCC. Fig. 5 shows the quantities of required capacitive and inductive reactive compensation to meet the power factor requirements at the PCC. Although the cable produces reactive power, to ensure that 0.95 leading power factor can be achieved for short cable lengths, it can be seen from Fig. 5 that extra capacitance is required at the PCC for the shortest cable length. At longer distances, inductive compensation must also be added with sufficient capacity to absorb the maximum amount of reactive power produced by the cable plus enough extra to consume reactive power from the grid in compliance with the 0.95 lagging capability.

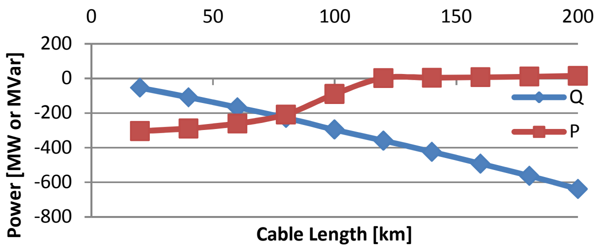

Fig. 3: Power export measured at the grid interface point for wind farm production of 308MW and unity power factor. (Negative values indicate export from wind farm to grid)

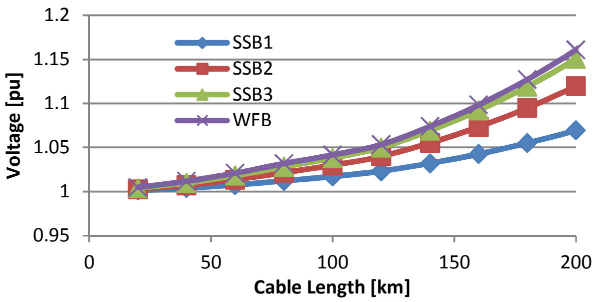

Fig. 4: Voltages at different points along the cable as overall length is increased, no reactive compensation installed

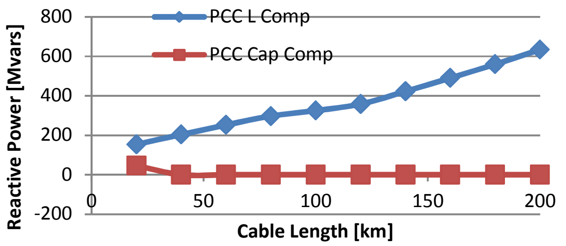

Fig. 5: Inductive and capacitive reactive compensation required at the PCC to comply with the Grid Code

B. Location of reactive compensation

In order to increase the amount of active power that can be transferred over longer cable lengths, reactive compensation can be added at the wind farm end of the cable in addition to the compensation at the grid end, provided the cable rating is not exceeded. Fig. 6 shows the loading of the different sections of cable as length increases, before compensation is added at the wind farm bus (WFB). It is clear that the first section of the subsea cable nearest the grid end, SSC1, has the highest loading and that SSC4 is the least loaded. This is because SSC1 is exporting the reactive power produced by the whole cable as well as the active power transfer. By adding reactive compensation at the wind farm end of the cable the vacant capacity of SSC4 can be used by some of the reactive power therefore freeing up capacity in SSC1, increasing the overall active power transfer capacity.

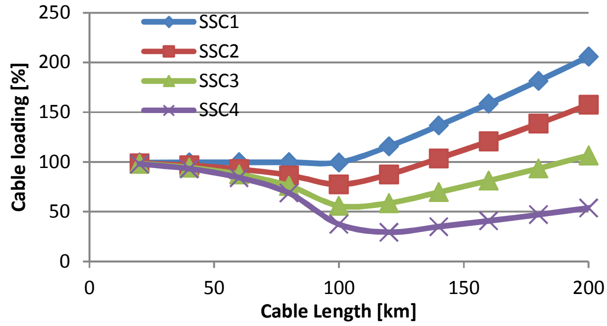

Fig. 6: Loading of the different cable sections as a percentage of the overall cable rating, where no reactive compensation is a present and the wind farm neither absorbs nor produces reactive power

It is demonstrated in Fig. 7 that adding reactive compensation at the wind farm end of the cable splits the reactive power produced by the cable between both ends, allowing greater quantities of active power to be transferred over longer distances, compared to Fig. 6. The limitation to the amount of reactive compensation that can be added at the wind farm end is the amount of vacant capacity in cable section 4. When the cable length becomes greater than 150km, the export of reactive power for compensation takes precedence over the transfer of active power. After 200km the whole cable capacity is taken up by the export of reactive power.

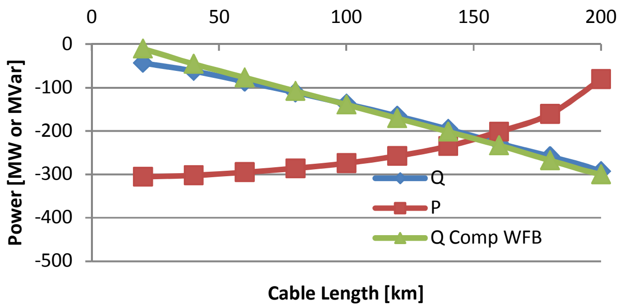

Fig. 7: Active and reactive power exported through the grid end of the cable and the reactive power absorbed by compensation at the wind farm bus (WFB) as cable length increases

A closer look at the results of adding compensation at the wind farm end reveals that when cable sections SSC1 and SSC4 are operating at maximum thermal capacity, SSC2 and SSC3 have spare capacity. To extend the active power transfer capability of the cable over longer distances, utilisation of this vacant capacity is critical. This can be achieved by adding reactive compensation at the cable mid-point. The authors' understanding is that such an action is actively being considered by a number of developers in the UK, e.g. the Smart Wind consortium which is developing the Hornsea zone in the North Sea has indicated that it is under consideration and the Crown Estate has suggested that it can be competitive [17][18]. The Horns Rev B wind farm in Denmark has also set a precedent for such an arrangement by employing a 100km AC cable connection with a compensating reactor near the cable mid-point [11] although the cable connection in this case consists of 42km of subsea cable and 58km of onshore cable and the mid-point compensating reactor is located onshore.

The addition of reactive compensation at SSB2, in equal quantity to that at the wind farm end of the cable, divides the cable reactive power production in three. The impact of this can be observed in Fig. 8 where the reactive power exported from the cable at the grid end is approximately equal to the reactive power absorbed by the compensation at the mid-point and wind farm end of the cable. Comparison of Fig. 8 with Figs. 3 and 7 shows the improvement of the active power transfer capability over long distances.

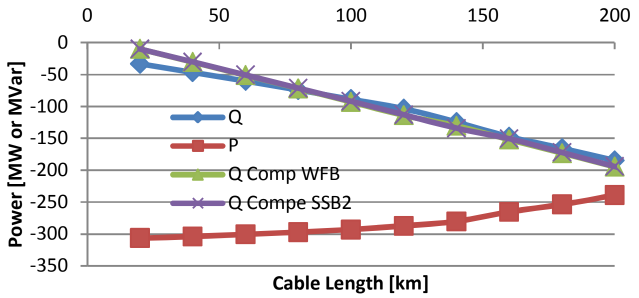

Fig. 8: Active and reactive power exported from the cable at the grid end, and the amounts of reactive power compensation included at the cable mid-point and at the wind farm bus

C. Other considerations for installation of reactive compensation

In addition to the power factor, voltage and cable rating requirements there are a number of other issues that must be considered. These include the maximum allowable voltage step change following a switching operation and the electrical location of reactive compensation.

1) Maximum allowable sizing of reactors

The SQSS maximum step change limit dictates the maximum size of single reactor used in the system. A planned maximum voltage deviation of 6% is allowable following a switching operation [13]. For example, in the network used in the above studies with 160km cable length, the maximum reactor size that can be switched at the distant end of the cable is approximately 100MVar, i.e. the required reactive compensation of 150MVar must be provided in at least two independent steps not larger than 100MVar.

2) Connection of reactive compensation

The connection of the reactive compensation is important when considering the voltage rise along the cable in the situation where the circuit breaker at the distant end of the cable is open. If the cable voltage does not remain within the limits when this circuit breaker is open, the reactive compensation must be directly coupled to the end of the cable before connection to the WFB so that it can be energised at the same time as the cable. Otherwise the reactive compensation could be connected to the wind farm busbar. For example, with a cable length of 160km the reactive compensation must be directly coupled to the cable, otherwise the voltage at the distant end of the cable will reach 1.09pu when the WFB cable circuit breaker is open.

V. Analysis of Dynamic Responses

An AC connection of an offshore wind farm and an HVDC connection will be materially different from each other in the way they respond to faults and, as a consequence, would be regarded by the system operator as more or less beneficial.

The purpose of the studies reported here is not to provide an exhaustive examination of the comparative performance but rather to illustrate some issues pertinent to the GB context and, in particular, the impact on voltage compliance and transient stability. The scenario used is one of exports of power from Scotland into England, a situation known to be limited by transient stability considerations.

A. Stability assessment scenario

A model of the GB transmission system has been implemented in DIgSILENT PowerFactory [19] and is based on the anticipated characteristics of the generation and transmission system in 2020. The generation is dispatched in such a way that the initial net power export from Scotland in the north to England in the south in 4300MW. This boundary is referred to in [1] as boundary B6 and features two double circuit overhead lines (Fig. 9). A permanent short circuit fault is applied to the west coast double circuit leading to its disconnection. This causes the power that was initially flowing down the western corridor to transfer to the east. The modelled initial condition is set-up so that when this contingency occurs, the system remains stable and settles to a new steady state with a voltage complying with the SQSS, though only just with the post-fault steady state voltage being close to the minimum of 0.95 defined in [15]. This scenario forms the base case used for comparison. In it, a 1200MW thermal power station is operating at the northern end of the eastern connector, referred to hereafter as location A.

Two further scenarios are introduced for comparison in which the thermal power station's output at A is replaced by an equivalent output from an offshore wind farm: 1. with the wind farm using an AC cable connection including minimum reactive compensation identified from steady state analysis to comply with the requirements of the SQSS, Grid Code and STC; 2. with the wind farm using an HVDC cable connection. These connections are illustrated in Figs. 1 and 2 respectively with, in both cases, the 100km double circuit overhead line and infinite bus replaced by a full model of the GB transmission system as it is expected to be in 2020 [1].

B. Dynamic modelling of HVDC link

In order to investigate the fault response when the thermal power station is replaced by a HVDC connected wind farm a model of the shore end VSC was developed. The response of a HVDC link to a grid fault is entirely dictated by the behaviour of the grid end VSC as it has the capability to control both its active and reactive power throughput with high bandwidth. Therefore it is not necessary to model the wind farm in detail; the wind farm power input to the HVDC link is represented in the transient stability assessment by a constant power input from the wind farm to the DC link capacitance.

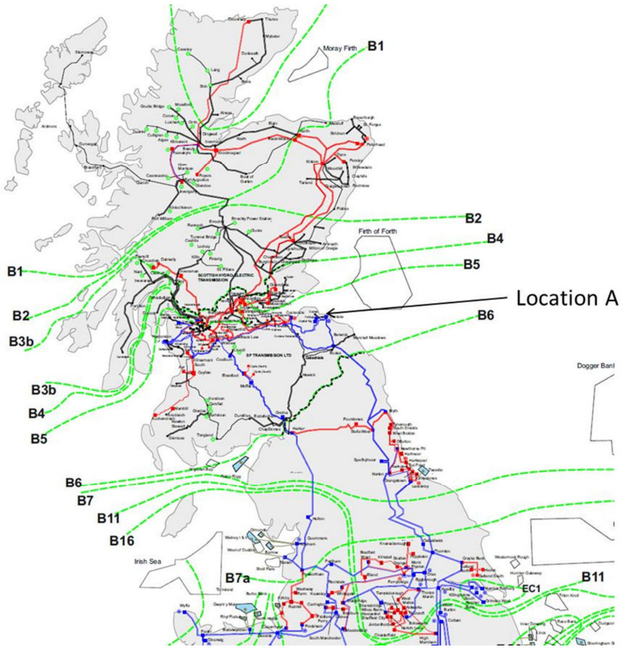

Fig. 9: test case for assessment of dynamic responses: Northern GB [1]

The VSC model developed is an average model and as such uses ideal controllable voltage sources to replicate the output voltage of the converter. Key to the dynamics of the VSC is the control algorithm. The algorithm that has been implemented uses DQ current control to regulate the output current of the converter by controlling its output voltage in relation to the voltage of the grid it is connected to. Included within this controller in addition to the current controller is a Phase Locked Loop to synchronise the converter output to the grid and two outer control loops which provide the references to the inner DQ current controller. These loops act to control the AC voltage at the terminals of the converter by regulating its reactive current output and the HVDC link voltage by regulating its active current output, both to a predefined constant reference. By controlling the DC link voltage to a particular reference the VSC active power output will track the power input from the wind farm.

Also included in the control algorithm is a current limit feature which primarily acts to ensure that the current rating of the converter is not exceeded, but in doing so gives precedence to outputting reactive current over active current. This means that in the event of a grid fault where the AC voltage control loop asks for an increased amount of reactive current to be fed into the grid to support the voltage, the active current will be curtailed and, if necessary, the full current rating can be output as reactive current. A further loop is also included which will curtail the input power to the HVDC link where the active power output of the converter is reduced therefore preventing the DC voltage from exceeding its rating.

C. Stability assessment results

For the western double circuit fault, angular stability is maintained for critical large synchronous generators in both wind farm cases. However, while both responses are acceptable (plots are omitted here simply due to space limitations), the HVDC connection case offers a moderate improvement in damping.

Aside from angular stability, it should also be verified that the post-fault steady state voltage is within limits throughout the system. It can be seen from Figs. 10 and 11 that the HVDC connection achieves this but the AC connection does not. Notwithstanding the STC's stipulation that a 'continuous' voltage regulation capability is required at the interface between the offshore network and the MITS, compliance with the steady state voltage limit could be achieved by, post-fault, switching out a bank of shunt reactance that had been installed to compensate the cable's gain. This is shown in Fig. 12 where the switching action takes place at 5s.

D. Other dynamic characteristics that should be considered

A basic requirement in respect of any generation connection is that the generation can 'ride through' any 'credible' transmission system fault. Using the models shown in Figs. 1 and 2, analyses conducted as part of this study but, for brevity, not reported here have shown that this can be achieved for a wind farm connected via HVDC and for both doubly fed induction generator (Type 3) and fully rated converter (Type 4) wind turbines at a wind farm connected via AC.

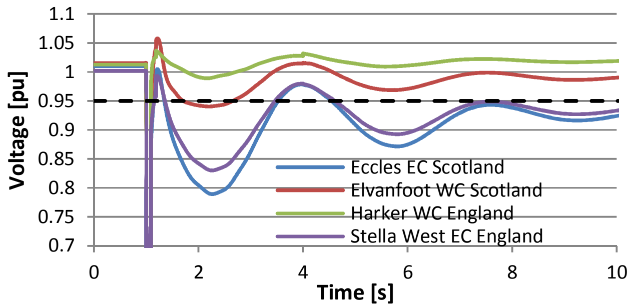

Fig. 10: AC connected wind farm at Location A: voltages at either end of the East Coast (EC) and West Coast (WC) circuits following a WC fault

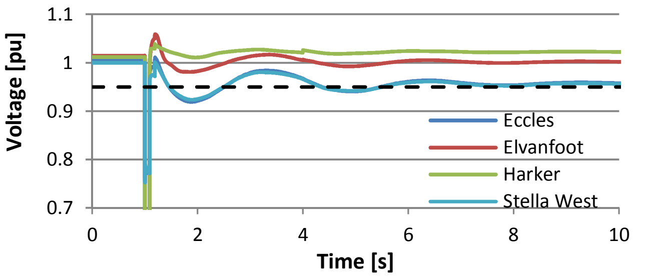

Fig. 11: HVDC VSC connected wind farm at Location A: voltages at either end of the EC and WC circuits following a WC fault

The presence of inductances and capacitances within a power system creates both series and parallel resonant frequency points. The number and frequency of each depends on the size of each lumped or distributed element and their placement with respect to each other [20]. The work reported in [20] suggests possible mitigation measures to low-order resonances in AC cable networks. Both AC and HVDC connections will have an impact on the resonances of the network whether due to the capacitance of the AC cable and the resonant circuit set up between it and the shunt reactors required to regulate the voltage profile over the cable length, or any filters required to attenuate switching harmonics produced by a VSC terminal. Switching operations and non-linear network elements can generate a wide range of high frequency voltage and current components which interact with system resonances to produce oscillations leading to excessive waveform distortion and over-voltages [21]. Damping of oscillations within a power system is often greater for higher frequencies due to the frequency dependence of impedance. The introduction of cables with high capacitance tends to lower the resonant frequencies to levels where damping may be considerably less than before making the occurrence of oscillations more likely [11][22]. Therefore, in addition to the factors that have been determined by both the steady state and dynamic parts of this study, the impacts of each transmission technology on system resonances and harmonic levels should also be taken into consideration when comparing the merits of each technology and mitigation measures taken where necessary, as described in [22].

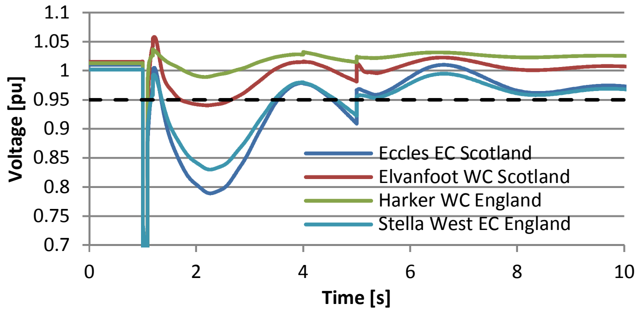

Fig. 12: AC connected wind farm at Location A: voltages at either end of the EC and WC circuits following a WC fault and a shunt reactor disconnected at the wind farm grid interface point after 5 seconds

In addition, the transient recovery voltage that appears across circuit breaker contacts when interrupting currents and the rate of rise of recovery of voltage should not exceed the capabilities of the circuit breaker, allowing it to successfully clear a fault. Both of these factors are influenced by the inductive and capacitive parameters on either side of the circuit breaker, the size of the fault current and type of fault. References [23][24] have shown that the highest overvoltage is at the onshore sending end of the cable in a load rejection study (where the wind farm is disconnected at the PCC and becomes islanded). As described in [23][24], investigations of the potential transient overvoltages due to faults within and without the wind farm transmission link, stochastic phased energisation of the export system and transformer inrush currents should be performed. This and the voltage step change limits noted in section II.A may result in the use of additional switchgear to allow energisation in stages, control-led switching (point on wave switching is commonly applied) or additional equipment to provide damping or current/voltage limitation. While this would entail additional cost, it would be small relative to, for example, the cable cost.

VI. Economic Appraisal

As has been noted above, a key part of the comparison of an AC connection option with an HVDC option is the assessment of the requirement for reactive compensation and its capital cost, including that of offshore platforms on which to install it. In addition to the capital cost of equipment, other key elements of cost are those of maintenance and of losses.

A. Capital costs

Estimates of the reactive compensation required for Grid Code compliance for different sizes of wind farm and different lengths of cable connection are given in Tables II-IV. Platform-based mid-point compensation has been added only where necessary to facilitate sufficient active power export. Capital cost assumptions are given in Tables V and VI in the Appendix and are based on the values published in [16]. Where a range of costs is given in [16], the mid-point value of the range has been used. However, it is also noted that the costs of equipment are impacted significantly by market conditions, in particular the price of copper and vessel charter rates; the sensitivity of costs to these and other factors is discussed in [25].

Table II: Inductive reactive compensation (MVAr) required at the GIP to ensure required reactive power capability

	250MW	500MW	1000MW	1500MW
80km	205	410	821	1231
120 km	250	500	100	1501
160km	235	470	939	1409
200km	263	527	1053	1580

Table III: Inductive reactive Compensation (MVAr) required at the mid-point of the cables to facilitate the necessary active power transfer

	250MW	500MW	1000MW	1500MW
80km	0	0	0	0
120 km	0	0	0	0
160km	151	301	602	903
200km	194	388	776	1165

Table IV: Inductive reactive Compensation (MVAr) required at the wind farm bus to facilitate the necessary active power transfer

	250MW	500MW	1000MW	1500MW
80km	108	216	431	647
120 km	171	342	682	1024
160km	152	304	608	912
200km	195	389	778	1168

The capital costs involved with HVDC transmission include the costs of the voltage source converters at either end of the link and the cables. There are two different ways in which a HVDC VSC based transmission system can be arranged: monopole and bipole. Monopole entails a single VSC at either end with two cables between: positive and negative conductors. A bipole commonly has three cables, two poles and a metallic earth return, and two VSCs at each end allowing the voltage difference between the positive and negative poles to be doubled, facilitating double the power transfer [26]**.** The choice between different arrangements is driven by the desired power transfer capacity, cable voltage rating and the ability of the link to operate in a degraded state following a cable fault. To connect the 1000MW wind farm a bi-pole arrangement has been chosen with cable voltages of ±300kV. The PCC end VSCs are rated so that no more than the minimum power factor capability, as required by STC, is provided.

B. *Operation and maintenance costs*

Operational costs have two primary sources: energy losses in the system and maintenance costs; together, these form a significant part of the lifetime cost of the transmission link. The primary source of losses in an AC transmission link is the cables although losses do also occur within the substations. The cost of compensating for the losses is treated as an operational cost to the transmission operator as extra generation must be dispatched to account for it in addition to the load to keep the system balanced.

Cable losses within the AC transmission link consist of two components: losses due to the reactive power production of the cable capacitance and losses due to the active power being transmitted. Both are a function of the cable resistance which itself comprises of components due to the conductor temperature, skin and proximity effects, armour and shield losses and cable length [25]. To calculate the losses in the cable the active and reactive components are each considered. It can be assumed that the capacitance of the transmission cable is evenly distributed along its length, and therefore it produces a certain amount of reactive power for every unit of length. However, the reactive power flow through each part of the cable is different. This is caused by the accumulation of the reactive power along the length of the cable which leads to it exporting reactive power to the MITS. Therefore the amount of reactive power flowing through the cable section closest to the MITS will be greatest and smallest at the wind farm end. The reactive power flow through different parts of the cable will be affected by the placement of reactive compensation at the wind farm end and at the cable mid-point, therefore this is also considered when determining the cable losses. The losses due to the active power transfer are calculated using the cable resistance and the current produced by the wind farm and are dependent on the wind speed. In addition, losses also occur within the transformers and reactive compensators; these comprise of no-load elements, 0.2% of nominal power flow, and load dependent elements, up to a maximum of 0.6% nominal power flow [27]. In this study 350MVA, 220kV three core AC cables with an 800mm^2 cross-section are used, which have a cable resistance of 0.06786ohm/km (taking into account conductor temperature, skin and proximity effects and armour and shield losses) and a capacitance of 0.17µF/km which produces a charging current of 6.9A/km [28].

The energy loss in the HVDC transmission link consists of two components: cable losses and conversion / substation losses. The cable losses are a function of the active power transfer and the cable resistance, whereas the conversion losses have a fixed no-load component as well as a component which is proportional to power flow. The HVDC cables used for the 1000MW and 500MW studies have the same diameter (1800mm^2) and therefore have a resistance of 0.0098ohm/km, whereas the cable used for the 250MW study has a diameter of 1200mm^2 with a resistance of 0.0151ohm/km [29]. The converter losses are taken to be 0.16% of nominal power flow under no load, rising to 1.6% at full load, based on performance reported in [25] and [30] for a two-level converter. Although new installations might use multi-level VSCs with lower losses, in this study converter loss represents between 27% and 42% of the total connection losses at full load for a 200km connection. A reduction would therefore have a notable effect on the overall losses of the system, but would translate to a minor impact – around 1% – in the context of overall system cost including capital expenditure.

To determine the annual volume of energy lost, a distribution of the wind farm output power is required to give an indication of the amount of time the wind farm is operating at full output and at part output (in incremental steps). This is obtained using the probability distribution of the wind speed experienced by the wind farm and a power curve relating the wind speed to the output power [31]. The Weibull distribution with a shape parameter of 2.1 and a mean wind speed of 10m/s is used [32]-[34]. The 10m/s mean wind speed is determined using the European Wind Atlas for a wind farm located more than 100km from shore, east of Scotland with a turbine hub height of more than 100m. The availability of the full wind farm capacity to produce power is also important. Operational experience with the first round of UK offshore wind farms indicates an availability of 80.2% [35].

The cost of compensating for the energy lost during transmission is calculated using an energy price of £45/MWh, which is an estimate of the average energy price at the time of the study [36]. Which party faces the cost of the losses depends on the location of the wind farm metering point. If it is at the WFB, the cost of transmission link losses is picked up by the transmission system operator. If it is at the PCC, the losses will represent lost revenue to the wind farm owner. The Offshore Transmission Owner (OFTO) regime in Britain requires the former [37]. However, if the latter were the case then the value of a Renewable Obligation Certificate (ROC), £43.99, must be added to the unit price of lost energy as the losses are effectively subtracted from the energy the wind farm supplies to the MITS [38]. The present ROC banding for an offshore wind farm is 1.5ROC/MWh generated [39].

In addition to the transmission losses, maintenance costs are a significant operational cost over the life-time of a transmission link. Submarine transmission cables, AC or HVDC, should require little maintenance so long as they are not damaged by a third party; however, the substation equipment requires regular maintenance. The nature of a substation situated on a platform potentially 200km from shore introduces significant extra access costs regardless of transmission technology. While it can be asserted with confidence that remote offshore substations will be costly to maintain, there is, as yet, little publicly available information on the level of those costs and where estimates are published, they differ significantly. For example, [40] gives a lifetime maintenance cost for AC offshore substation equipment of 15% of its capital cost whereas [3] gives an annual maintenance cost of 0.5% of the capital costs for an HVDC substation. For the present analysis, 15% of the AC substation capital costs has been taken as the maintenance cost and broken down into annual components. 0.5% of the annualised HVDC substation capital cost is used in the HVDC case.

C. Comparison of total costs

To allow comparisons to be drawn between the costs involved with each transmission technology, the lifetime costs are broken down over the expected life of the wind farm and transmission link (25 years) to give an annualised cost. To enable this, the effects of interest rates, perceived risk and depreciation of asset values are taken into account by calculating the capital recovery factor with a 25 year time frame and discount rate of 12%. This discount rate is the mid-point of a range given for offshore wind given in [41].

The level of annual costs, as with each of the factors described above, are a function of the wind farm capacity. Fig. 13 shows the annual costs of connecting 250MW, 500MW and 1000MW wind farms using either transmission technology. It can be observed from this that the cross-over distance at which HVDC connection is cheaper than AC for the 500MW case occurs at a greater transmission distance than for the 1000MW wind farm. This is primarily due to the proportionally larger capital costs involved with HVDC and the value of the losses in the AC cables being a lot less. For the 250MW case, the capital costs of the HVDC technology are sufficiently dominant to prevent it becoming the cheapest option at any of the transmission distances studied here.

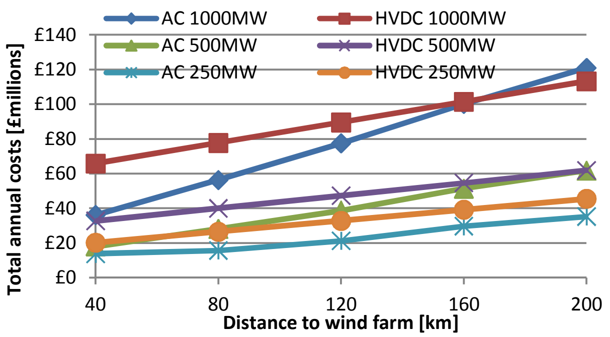

Fig. 13: Total annual costs of 250MW, 500MW and 1000MW transmission links using AC or HVDC technology over different transmission distances

The figures calculated here are highly dependent on system design assumptions and the arrangement of the renewable obligation incentive regime in the GB. To provide an insight into how sensitive the economic analysis is to these assumptions three sensitivity studies have been conducted: (1) where the opportunity cost of the ROCs that are lost due to transmission losses is included in the cost of energy (Fig. 14); (2) where the metallic earth return is removed from the 1000MW HVDC bipole system saving on both cable and installation cost (Fig. 15); (3) where a STATCOM is included at the PCC in the AC case to provide the continuous voltage control capability, which the STC implies is required. (For brevity, this result is not shown graphically). It can be observed from Fig. 14 that the cross-over between costs of the two technologies occurs at a shorter transmission distance for the 1000MW and 500MW cases, indicating that the AC transmission costs are more sensitive to the cost associated with losses than HVDC transmission. Also, in Fig. 15 a similar result is observed where the cross-over reduced to 120km, indicating that the omission of the metallic earth return could be preferable from an economic point of view, although the potential impact of the inability to still operate in the event of a fault on one cable is not considered in these calculations. Lastly, for a 1000MW wind farm with the meter at the WFB, the cross-over distance reduces from 160km to 120km if a STATCOM is used to provide the PCC reactive compensation.

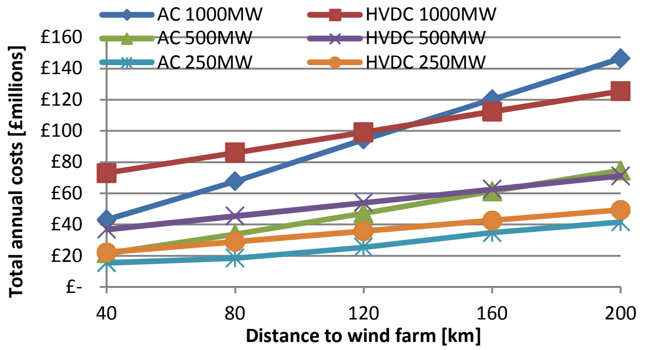

Fig. 14: Total annual costs of 250MW, 500MW and 1000MW transmission links using AC or HVDC technology over different transmission distances, where the cost of lost ROCs is included in the cost of lost energy.

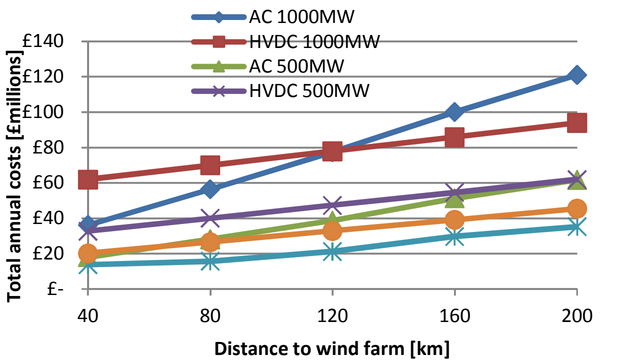

Fig. 15: Total annual costs of 250MW, 500MW and 1000MW transmission links using AC or HVDC technology over different distances, where the earth return cable has been omitted from the 1000MW HVDC option.

By way of comparison, for a 200MW-500MW offshore wind farm [2] with different lengths of cable connection, cross-over distances of 35km-80km are reported in different scenarios.

D. Developer incentives

To date in Britain, offshore wind farm developers have constructed the transmission link connecting their wind farm to the MITS and then sold it to an OFTO once it is operational. In such a situation and where the wind farm output metering point is at the wind farm bus, in evaluating different connection options, as far as the authors of this paper understand, there is little incentive for the wind farm developer to consider the potential volume of energy lost during transmission as this will not affect the revenue earned by the wind farm. As a consequence, the wind farm developer would likely be inclined to opt for the means of providing the transmission link between the wind farm and the MITS that has the lowest capital cost regardless of whether the overall lifetime cost – capital cost plus losses – was lower. This could result in the costs incurred by the system operator, to compensate for transmission losses, being higher than would otherwise be the case and a higher total cost.

VII. Conclusions

This study has investigated the technical and economic characteristics of two transmission technologies (AC and HVDC) that could be used for the connection of an offshore wind farm to the main interconnected transmission system (MITS) in Britain and described the influence of industry codes on a connection design and, hence, cost.

The analysis of the steady state characteristics of AC transmission has highlighted the importance of considering the reactive power production of a long AC submarine cable and how it affects active power carrying capability and voltage profile along the cable length. It has been shown that use of inductive reactive compensation at both ends of an AC cable connection and, where necessary, also the cable mid-point can release cable thermal capacity for the transfer of active power. An investigation of the dynamic characteristics of both the AC and HVDC transmission technologies in response to short circuit faults on the MITS has then been conducted using a model of the full GB transmission system. While the analysis presented here is limited, it does suggest that both approaches can comply with industry standards in a context that is known to be stability limited, albeit that further work may reveal benefits, e.g. in respect of system damping, arising from supplemental controls on an HVDC link or on an SVCs or STATCOM associated with an AC connection.

In addition to the technical investigations that have been conducted, an analysis of the economic characteristics of using either technology to connect the wind farm has been performed where it is noted that, as a minimum, the cost of equipment necessary to comply with relevant standards must be included. In respect of an AC connection, this includes reactive compensation. The analysis has determined the capital and operational costs of both technologies to give a comparison as the transmission distance is increased for different sizes of wind farm. For the HVDC option, capital costs associated with the VSCs are highly significant while the costs associated with the energy lost during transmission are substantially larger for the AC option deployed for a long distance than for the HVDC option. These two aspects combine to give a cross-over where the annual costs of using AC transmission becomes greater than those associated with using HVDC transmission at an approximate transmission distance of between 120km and 160km for a 1000MW wind farm, the shorter distance being for the case when reactive compensation in the AC case is provided by STATCOM or a metallic earth return is omitted from the HVDC design.

Wind farm capacity has a significant impact on the location of the cross-over between the annual costs of using AC and HVDC transmission technologies; indeed, it has been shown for a wind farm capacity of 250MW that, over the range of transmission distances studied, AC transmission has the lowest cost and for a 500MW wind farm the cross-over is approximately 200km. A trend therefore emerges between the wind farm capacity and the transmission distance at which HVDC becomes the cheaper transmission technology: the higher the wind farm capacity and therefore the required transmission capacity, the shorter the transmission distance where the cross-over occurs.

As a final remark, an AC option should be studied in more detail in respect of a number of technical considerations that have not been considered fully here. In particular, remedial measures may need to be introduced to limit transient over voltages during both controlled and uncontrolled operations. Furthermore, for both AC and HVDC options, the possibility of harmonic resonances having been introduced should be checked and damping circuits introduced if necessary.

VIII. Appendix

Table V: Assumed capital costs for AC connection [16]

Component	Cost	Notes, e.g. for 1000MW wind farm
350MVA 220kV 3-core, submarine cable	£470k / km	4 parallel cables with length increasing with distance to wind farm.
Cable installation of 2 cables in one trench at 1m depth	£675k/km / trench with 2 cables	4 cables require 2 trenches.
Onshore GIS switchgear (275kV and 400kV).	£2.1million / 275kV substation £2.6million / 400kV substation	Required for either side of GIP transformers.
220kV/400kV 275MVA transformer.	£2.34million / transformer	1053MVA capacity is required to transfer 1000MW at 0.95 pf, hence 4 transformers required.
500MW 220kV/33kV Offshore substation, including 500tonne platform, 220kV GIS switchgear, jacket foundation and installation in 20-30m water depth.	£39.1million / 500MW	A single platform would most likely be used; therefore the costs have been scaled linearly to give 1000MW capacity.
Mechanically switched shunt reactors 100MVar at 220kV.	£1.2million / 100Mvar	Required at GIP, cable mid-point and WFB, depending on cable length

Table VI: Assumed capital costs for HVDC connection [16]

Component	Cost	Notes, e.g. for 1000MW wind farm
500MW 300kV HVDC 1800mm^2 single core cable.*	£360k / km	3 parallel cables required for positive and negative poles and metallic earth return with length increasing with distance to wind farm. (earth return cable is assumed to be same as pole cables)
Installation of cables at 1m depth.	£675k/km / trench with 2 cables £400/km / trench with single cable	3 cables, 2 buried in a single trench and one cable in a second trench.
Shore end 550MVA 300kV Voltage Source Converter (VSC), inc.AC switchgear.	£68million / converter	2 VSCs are required giving +/- 300kV.
150kV/400kV 275MVA transformer, inc. 400kV GIS switchgear	£2.34million / transformer £2.6million / 400kV GIS substation	1053MVA capacity is required to transfer 1000MW at 0.95 pf, therefore 4 transformers are required.

Component	Cost	Notes, e.g. for 1000MW wind farm
Offshore VSC platform inc. 2x 500MW VSCs and 220kV GIS switchgear, including 8000tonne platform, jacket foundation and installation in 20-30m water depth.	£232million / platform	Single platform for bi-pole VSCs and AC switchgear.

IX. ACKNOWLEDGEMENTS

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XI. BIOGRAPHIES

Douglas Elliott gained his PhD from the University of Strathclyde in 2014 where he was part of the EPSRC funded Centre for Doctoral Training in Wind Energy Systems. His thesis focuses on investigating alternative electrical systems for offshore wind farms that provide cost savings and enhanced reliability, in particular looking at the application of DC inter-turbine collector networks. He is a member of the IET and also holds an MEng in Electrical Energy Systems from the University of Strathclyde. Douglas joined Siemens Wind Power in the spring of 2014 as a Development Engineer in the Frequency Converter Centre of Competency, based in the UK.

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