A Comparison of VSC-HVDC with Low Frequency AC for Offshore Wind Farm Design and Interconnection

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Abstract

In recent literature Low Frequency AC transmission has been suggested as a potential competitor to VSC-HVDC for offshore wind farms integration. This paper presents a techno-economic analysis and methodology for comparing both transmission methods in terms of power loss, reliability and capital investment costs. It is shown that LFAC when interfaced with an onshore cycloconverter can reduce loss, increase reliability and also decrease capital investment costs due in part to the absence of the offshore converter compared to VSC-HVDC. LFAC with a VSC replacing the cycloconverter is then included to determine its feasibility compared with the other transmission options presented.

Keywords: Low Frequency AC; VSC-HVDC; Offshore Wind; Power loss; Techno-economic comparison

1. Introduction

The research, development and implementation of efficient and cost effective interconnection possibilities for offshore wind are a key element in achieving ambitious European renewable targets. Current trends in research and commercial applications of offshore wind integration are towards Voltage Source Converter (VSC) High Voltage Direct Current (HVDC) transmission [1]. VSC-HVDC displays distinct control and design advantages over

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFAC</td>
<td>Low Frequency Alternating Current</td>
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<tr>
<td>VSC</td>
<td>Voltage Source Converter</td>
</tr>
<tr>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
</tr>
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</table>
traditional Line Commutated Converter (LCC) technology. For near shore (<50 km) wind farms, HVAC transmission is sufficient. At greater distances Low Frequency AC (LFAC) transmission, generally at a frequency of 16.7 Hz has been proposed as an alternative to conventional 50 Hz AC or VSC-HVDC [2]–[4].

LFAC is an interesting alternative primarily due to the extension of the maximum AC transmission distance at lower frequency, the elimination of the offshore converter station compared to VSC-HVDC and the reduced cost and complexity of the configurations [2], [5]. There are two main options for efficiently connecting LFAC to the grid in the literature; these are a Cycloconverter (thyristor based converter) or a VSC (IGBT based converter). The cycloconverter is the less expensive option alone, however the technical aspects of grid connection and compliance would require extra costs, in terms of extra filtering and reactive compensation [4]. Alternatively the VSC will alleviate the technical concerns when connecting to a mainland grid, with dynamic control over both active and reactive power, and a more sophisticated switching pattern reducing the need for lower order harmonic filters [6].

Previous works have studied VSC-HVDC [1] and LFAC [4] individually to understand their technical feasibility, however it is important a system level comparison is undertaken to fully understand the transmission options available to offshore wind farm developers in terms of their technical and economic characteristics.

This paper will perform a quantitative techno-economic comparison between VSC-HVDC and LFAC connected offshore wind farms, to provide a deeper insight into the potential advantages and disadvantages of LFAC as an alternative to VSC-HVDC in terms of losses, capital investment costs and reliability; taking into account the infrastructural requirements from offshore platform to the onshore grid. The analysis is based on actual wind speed data for 4 years from 2010-2013. Section 2 is provides an overview of the transmission options, Section 3 details the methodology behind the analysis, Section 4 presents the results, Section 5 analyses alternative transmission options and Section 6 discusses the results and challenges facing LFAC.

2. Overview of Transmission Options

This paper focuses on two configurations (see Figure 1), a 50 Hz collection grid with VSC-HVDC transmission, compared to a LFAC collection grid at 16.7 Hz with LFAC transmission. HVAC transmission is not considered here because the distance from the offshore wind farms to shore is assumed to be 100 km.

![VSC-HVDC and LFAC transmission options](image)

Offshore

Onshore

It is assumed here that the LFAC collection grid utilises the same 33 kV AC cables operated at a frequency of 16.7 Hz, and the same back to back converter as in the 50 Hz collection grid. Full converter wind turbines are used for this analysis and it is assumed that the full converter has the capability to produce AC at a frequency of 16.7 Hz for the LFAC grid [2]. The components required for the lower frequency system are similar to the 50 Hz system, however, the size and cost of the transformers and filtering will increase with reduced frequency [7]. Crucially there is no offshore converter, which reduces the capital investment cost. Onshore, the cycloconverter uses thyristor based technology compared to the VSC which uses IGBT’s. Cycloconverter connected LFAC configurations therefore require a strong AC grid onshore to enable reliable operation of the thyristors.

The operation of the VSC-HVDC system is a well understood technology for the connection of offshore wind [8], [9]. The cycloconverter in the LFAC system is a less common technology for transmission systems, although it is used regularly in mining operations and in large ships [10], [11]. The operation of a cycloconverter involves converting AC at a primary frequency to AC at a secondary frequency using the switching of thyristors. This is done here by using a 36 pulse cycloconverter. Each phase of the output wave has a positive and negative 6 pulse converter which converts the three phase input 16.7 Hz wave to each single phase 50 Hz output [4].
3. Methodology

3.1. Loss Evaluation

Table 1: System components of LFAC and VSC - HVDC

<table>
<thead>
<tr>
<th>LFAC</th>
<th>VSC-HVDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.7 Hz Wind Turbine Transformers</td>
<td>50 Hz Wind Turbine Transformers</td>
</tr>
<tr>
<td>16.7 Hz Collection Network</td>
<td>50 Hz Collection Network</td>
</tr>
<tr>
<td>16.7 Hz Transformer</td>
<td>50 Hz Transformer</td>
</tr>
<tr>
<td>-</td>
<td>Offshore Converter (VSC)</td>
</tr>
<tr>
<td>16.7 Hz Transmission Cable</td>
<td>HVDC Transmission Cable</td>
</tr>
<tr>
<td>Onshore Cycloconverter</td>
<td>Onshore Converter (VSC)</td>
</tr>
</tbody>
</table>

Analytical loss models for each component in Table 1 have been developed for each transmission system. Both the wind turbine transformer (0.69/33 kV) and the transformer at the offshore platform (33/220 kV) are modelled as in Meere et al. [12] to determine the winding and core losses at varying load. In the 16.7 Hz case it is assumed that the LFAC transformer is designed, such that the winding losses are the same as in the 50 Hz transformer. The core losses reduce from those in the 50 Hz transformer; this is due to the Steinmetz equation:

\[
P_{\text{Core, loss}} = A_c A_w k f^\alpha B_{pk}^\beta
\]

Where \( A_c \): Area of core, \( A_w \): Area of winding window, \( k \): constant, \( f \): frequency, \( B_{pk} \): peak flux density, \( \alpha \) and \( \beta \): material constants.

From Equation 1 it can be seen that assuming the flux density and the winding window area are kept constant; as the frequency reduces by a factor of 3 and subsequently the core area increases also by the same factor of 3, then the new core loss is dependent on the magnetic material used and the constant \( \alpha \), according to the following expressions:

\[
P_{\text{Core, loss}}_{\text{50 Hz}} : P_{\text{Core, loss}}_{\text{16.7 Hz}} = 50^\alpha : 3 \left( \frac{50}{3} \right)^\alpha
\]

Where \( \alpha =1.5 \) for M130-27S electrical steel [13].

The collection and transmission cables are a key component of the wind farm architecture. The 33 kV collection network cable is tapered with 3 different cross-sectional areas to transmit the power to the offshore substation; and the LFAC transmission cable is rated at 220 kV. The electrical behavior of these AC cables are modelled as in Meere et al. to determine the power losses. Equation 3 is used to calculate the dielectric losses, which are frequency dependent, thereby reducing with a reduction in frequency.

\[
W = 2\pi f CV^2 \tan \delta
\]

Where \( f \): frequency (Hz), \( C \): capacitance (F), \( V \): voltage (V), \( \tan \delta \): insulation loss factor (0.0004 - XLPE).

From previous literature comparing cycloconverters and VSCs for mining applications [10] the full load losses of a cycloconverter is 0.7%. The efficiency vs. load curve shown in Figure 2 is used to determine the cycloconverter losses at fractional loading. This curve is based on the typical efficiency vs. load for Line Commutated Inverters [14]. The evaluation of the efficiency of the VSC-HVDC converters, offshore and onshore is taken for a 2 level neutral point clamped design. Numerical equations for power loss are derived for the power switches in the converter, based on the average and root mean square of the converter current to estimate the conversion loss in the converter. The specific IGBT and free-wheeling diode device characteristics are taken from manufactures datasheets for both converters [15]. The conversion losses for VSCs are divided into conduction and switching loss. Conduction losses occur due to device on-state voltage drop across the device by averaging losses in each switch. The switching energy loss is a combination of on-state and turn-off switching loss and depends on the device characteristics, current and switching frequency [16].
3.2. Reliability

Reliability is an important aspect to consider when comparing technologies to transmit power onshore. Offshore locations can present difficulties for reliable operation. The repair time for offshore components can often be very high due to the difficulties in accessing offshore infrastructure [17]. The reliability analysis in this paper uses the failure rate (\(\lambda\)) and the Mean Time to Repair (MTTR) of the components to calculate the annual unavailability of the offshore wind farm (U) and calculate the Expected Energy Not Supplied (EENS).

Table 2 outlines the failure rates and MTTR of each of the components considered in the analysis which has been taken from various literature sources [17]–[19]. Cycloconverter failure rates were difficult to obtain, the failure rate used here is based on that of a thyristor based line-commutated converter [19]. On the assumption that the different transmission options have no impact on actual wind farm reliability, the wind farm availability is assumed here to be 100% to facilitate a comparison based only on the transmission systems. It is also assumed that for redundancy purposes there is a back-up transformer at each offshore substation.

Table 2: Failure rates and MTTR of Offshore Transmission System Components

<table>
<thead>
<tr>
<th>Component</th>
<th>(\lambda) (failures/yr.)</th>
<th>MTTR (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection network</td>
<td>0.008</td>
<td>2160</td>
</tr>
<tr>
<td>Circuit Breakers</td>
<td>0.032</td>
<td>720</td>
</tr>
<tr>
<td>Offshore Transformer</td>
<td>0.03</td>
<td>4320</td>
</tr>
<tr>
<td>Transmission Cable</td>
<td>0.08</td>
<td>720</td>
</tr>
<tr>
<td>VSC Onshore</td>
<td>0.05</td>
<td>720</td>
</tr>
<tr>
<td>VSC Offshore</td>
<td>0.05</td>
<td>50</td>
</tr>
<tr>
<td>Cycloconverter</td>
<td>0.101</td>
<td>50</td>
</tr>
<tr>
<td>Onshore Transformer</td>
<td>0.02</td>
<td>1440</td>
</tr>
</tbody>
</table>

3.3. Capital Investment Costs

Capital investment costs are calculated for each component of the HVDC and LFAC transmission options. It is important to note that capital costs are difficult to predict with any degree of certainty as they are location and vendor specific and generally difficult to obtain. Cost estimates for a VSC converter vary depending on the size and vendor. A cost of €150/kVA is estimated in [20], €111/kVA in [19] and €122/kVA in [21]. A Siemens report comparing cycloconverters and VSC’s for the application of grinding mills [10] (converters rated at 32 MW) states that the cost of a VSC is 140% the cost of a Cycloconverter. Capital costs for the AC and DC cables are estimated in [18] as €883/m for AC and €640/m for DC, in [21] as €750/m and €600/m and in [22] as €863/m and €518/m. Included in the cost of the offshore converter is reactor cost from [7]. The HVDC offshore platform cost is calculated by a fixed cost of €2.6m and a variable cost of €100,000 multiplied by the rated power of the converter [20]. HVAC platform cost is calculated from [18] with a fixed cost of 5 M€ and a variable cost of €20,000 multiplied by the rated power. Alternative HVDC and HVAC platform costs based on the volume of the substations are available in [21]. Transformer costs at 50 Hz and at alternative frequencies are calculated from [7]. Back to back converter costs are found to be €143/kVA [20]. The collection network costs are calculated from the costs of 33 kV AC cables in [7] and [20]. For each component the most expensive cost estimate is used in the analysis.

3.4. Energy Capture Analysis

An energy capture analysis is performed on a site in the Irish Sea which is approximately 100 km from the Point of common Coupling (PCC) onshore. Measured wind speed data is utilised to demonstrate the potential of the offshore wind resource in Ireland and also evaluate the performance, in terms of energy capture, of the LFAC system compared to the VSC – HVDC system. The wind data employed for the analysis is provided by the Irish
Marine Institute [23]. The wind speed measured at the buoy is taken just above the surface of the water and is converted to the correct hub height (90 m) wind speed for offshore turbines. Four years of measured wind data, with approximately 95% of the total annual data set are used in the energy capture analysis.

Figure 3 shows the 200 MW wind farm layout, consisting of 40, 5 MW, Type 4 wind turbines with full conversion capability connected in a radial network. The NREL reference 5 MW wind turbine [24] is used for this analysis. Alternative layouts will impact on the cable lengths required for the collection network and therefore the collection network losses; however the variation in the collection network losses from 50 Hz to 16.7 Hz will remain the same.

![Figure 3: Offshore Wind Farm layout](image)

3.5. Component Size

The reduction in operating frequency for LFAC has knock on effects on the size of some of the frequency dependent components. The wind turbine transformers are the main component impacted by the change in frequency. From Domínguez-García et al., [7] it is clear that a decrease in frequency by 3 increases the size of the transformer by approximately 3. This means that the space requirement for the transformer inside the nacelle of the wind turbine is 3 times as large as in the 50 Hz case, thus increasing costs and requiring potential re-design of the transformer and nacelle to allow for the increased weight of the wind turbine transformer.

4. Results

4.1. Energy Losses

The results presented here are from an energy capture analysis performed on the VSC-HVDC transmission system and on the LFAC system with a cycloconverter for 4 years, 2010-2013. Reviewing Table 3 it is clear that LFAC has a greater energy capture and fewer losses than the VSC-HVDC configuration due to the absence of the offshore converter and lower losses at lower frequencies of the collection network and the transformers.

<table>
<thead>
<tr>
<th>Year</th>
<th>VSC HVDC</th>
<th>LFAC</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Total Energy Capture (MWh)</td>
<td>Total losses (MWh)</td>
</tr>
<tr>
<td>2010</td>
<td>952.397</td>
<td>119.620</td>
</tr>
<tr>
<td>2011</td>
<td>981.249</td>
<td>124.732</td>
</tr>
<tr>
<td>2012</td>
<td>953.261</td>
<td>120.152</td>
</tr>
<tr>
<td>2013</td>
<td>994.655</td>
<td>119.879</td>
</tr>
</tbody>
</table>

Figure 4 displays the breakdown of the losses for LFAC and VSC-HVDC by component. The variations from LFAC to VSC-HVDC are due to both the frequency dependent nature of the losses of components and the different components necessary for each system. The error bars represent the standard deviation within each
component for each of the 4 years. The LFAC system has fewer losses, primarily due to only having one converter station but also due to the reduction in losses in the 16.7 Hz collection network from Equation 3 and the transformers because of the reduced core losses at lower frequency from Equation 2. The AC transmission cable has more losses than the DC cable as the DC resistance is the only factor causing a loss in the DC cable. Since the cycloconverter is a thyristor based device it is more efficient than the 2-level VSC and has 29% less losses per year.

4.2. Capital Investment Costs

Capital investment costs of the components are shown in Figure 5. The error bars display the variations in capital cost depending which of the costs from section 3.3 are used. In each case the most expensive cost has been selected for the components. The wind turbines and the associated components are not included in this comparison as they are the same for both farms.

The wind turbine transformer cost increases from 127 k€ (50 Hz) to 355 k€ (16.7 Hz) per transformer. The extra investment required for LV transformers in the LFAC connected 200 MW wind farm is 9.1 M€. The substation transformers (backup included) also increase in price from 2.6 M€ per transformer to 7.5 M€ per transformer at 16.7 Hz. The largest difference between the LFAC and the VSC-HVDC is the absence of the offshore converter in the LFAC case and the increased cost of AC cables compared to DC cables. It is assumed that 3-core AC cables are used, which have a larger cross sectional area compared to both the DC cables required for transferring 200 MW of power from the offshore wind farm. Cable installation costs are assumed the same for both AC and DC cables and therefore are not included in this analysis. In total LFAC with a cycloconverter costs 214.2 M€ and VSC_HVDC costs 237.3 M€, this is advantageous for LFAC, however the variation in the cost estimates are 47.9 M€ and 62.3 M€ respectively and the difference of 23.1 M€ is within the variation.
4.3. Component Sizing

The offshore substation contains a VSC in the HVDC system and a large transformer, the relevant switchgears and auxiliary equipment in the LFAC system, this reduces the size from 16000 m³ to 1000 m³ and the cost by 37.5 M€. At 16.7 Hz the transformers have to be re-designed in order to step up the voltage efficiently. In the wind turbine transformer this requires an increase in transformer volume from 1.15 m³ at 50 Hz to 3.45 m³ at 16.7 Hz, and an increase in weight from 2.75 to 8.23 tonnes. The increased size of this transformer has to be built onto the offshore wind turbine, requiring possible redesign of the transformer. The substation transformers also increase in size and volume from 52.52 m³ to 125 m³ and 157.24 to 374.26 tonnes. This redesign of the transformer produces an opportunity to utilise different materials and transformer structural designs.

5. Assessment of Alternative Transmission Options

The above comparison is based on the use of a cycloconverter for the conversion between 16.7 Hz AC and 50 Hz, however clearly this conversion could also be accomplished with a VSC. Moreover future VSC implementations are likely to be based on Modular Multi-level Converters (MMC) instead of 2-level VSC converters, which will reduce VSC losses further [25]. This section uses the same methodology to evaluate other possible connection strategies, namely the use of a 2 level or an MMC based VSC in the LFAC system instead of the onshore cycloconverter. Note for this analysis the only difference assumed between the 2 level converter and the MMC converter is in the efficiency, an assumption which merits deeper study.

Reviewing Table 4 it is clearly evident that the LFAC with a VSC is more expensive to implement than the LFAC with a cycloconverter. When the cycloconverter is replaced by a MMC based VSC there is an increase in reliability as the VSC is more reliable than the cycloconverter onshore and an improvement in efficiency due to the fact that at lower loads the MMC technology is more efficient than the cycloconverter. If a cost of losses of 100 €/MWh is applied then the cycloconverter configuration can save up to 1.08 M€ per year and the LFAC-VSC can save 1.36 M€ in losses per year compared to VSC-HVDC with MMC.

<table>
<thead>
<tr>
<th>Table 4: Comparison of alternative connection configurations</th>
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<tbody>
<tr>
<td><strong>Component</strong></td>
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<tr>
<td>---------------------</td>
</tr>
<tr>
<td>LFAC_Cycloconverter</td>
</tr>
<tr>
<td>VSC_HVDC</td>
</tr>
<tr>
<td>VSC_MMC_HVDC</td>
</tr>
<tr>
<td>LFAC_VSC</td>
</tr>
<tr>
<td>LFAC_VSC_MMC</td>
</tr>
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6. Discussion

The removal of the offshore converter station and the associated cost reduction would generally be considered one of the biggest motivations for utilising LFAC transmission. The results presented agree with this, however the cost differences may not be as large as first expected, largely due to the fact the cost reductions due to the elimination of the offshore station are partially offset by the cost of the AC cable and the extra cost of the transformers. When comparing the variation in costs between transmission options the range of costs in Figure 5 must be considered. The total variation in the LFAC and the VSC-HVDC costs are 47.9 M€ and 62.3 M€ respectively. While there is some merit in the fact that the LFAC system is cheaper as the most expensive case has been taken for each component, the difference in cost is still well within the variation for each of the transmission options and therefore the significance of the capital cost difference is questionable. Moreover external costs including filtering and reactive power compensation have not been considered in this analysis. The cycloconverter requirement for large filters and reactive compensation would make the LFAC configuration more expensive.

The improvement in reliability though the elimination of the offshore converter station is another positive for use of LFAC. This analysis suggests that LFAC is more reliable than VSC-HVDC due to the absence of the offshore converter, and that LFAC with a VSC connected is the most reliable configuration. However, it is
important to note the limitations in obtaining failure rates and MTTR data for VSCs - with a lack of available published data. The reliability of cycloconverters and VSC’s in particular requires further investigation.

The reduction in total losses is another encouraging aspect for LFAC over VSC-HVDC, it can be seen here that (assuming MMC technology) using LFAC with a cycloconverter reduces losses by 8.2% and using a VSC instead of a cycloconverter reduces losses further by 10.3%. The VSC with reduced power losses, increased reliability, independent control over active and reactive power and lesser requirement for filtering and reactive power compensation would be the preferred choice for connecting LFAC based on this analysis. Further research is needed to establish, from a grid connection perspective if a cycloconverter or a VSC connected LFAC offshore wind farm would be a more feasible solution.

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References


