Loss Evaluation of HVAC and HVDC Transmission Solutions for Large Offshore Wind Farms

N. Barberis Negra¹, J. Todorovic² and T. Ackermann³

Abstract - This paper presents a comparison of transmission system losses in percent for wind farm power production. Three technical solutions are analyzed, i.e. HVAC, HVDC Line Commutated Converter (LCC) and HVDC Voltage Source Converter (VSC). The losses for each technology are calculated for different size of the wind farm, various distances to shore. In addition, solutions with combinations of two and the three are analyzed and compared. From these analyses further analysis regarding reliability and economical issues can be considered in order to define best solutions for wind power transmission.

Index terms – Aggregated Model, HVAC, HVDC, LCC, “MW-km” Plane, Offshore Wind Farm, Percent Losses, VSC.

I. INTRODUCTION

Today’s installed offshore wind farms have relatively smaller rated powers and are placed at shorter distances from shore than future planned projects [1]. According to European Wind Energy Association (EWEA) predictions [2], in EU-15 by 2010, 10000 MW of offshore wind farms will be installed. On the one hand, offshore locations have better wind conditions than onshore ones: this means higher energy output. On the other hand, longer transmission distances lead to higher investment costs as well as higher energy losses [3].

All currently (early 2004) existing offshore wind farms are connected to shore by HVAC cables and only two of them have offshore substations [1]. For large wind farms, with hundreds MW of rated power, and long distances to shore, offshore substations would be necessary for either stepping up the voltage level (HVAC) or for converting the power to HVDC. [3].

Connection of such large offshore wind farms impose a challenging task for connection designers. Choice of a proper transmission system, either HVAC or HVDC, can be a decisive part of the overall project feasibility. Small differences in transmission losses between two solutions could cause large differences in energy output over a project time of 20 years.

In this paper system transmission losses for three different transmission systems, i.e. HVAC, HVDC Line Commutated Converter (LCC) and HVDC Voltage Source Converter (VSC) are compared for a 500 MW and a 1000 MW wind farm with different distance to shore (up to 200 km) at an average wind speed in the area of 9 m/s. The transmission system losses are calculated as percentage of losses of the annual wind farm production. It is assumed that the wind farm has a availability of 100 %.

Further analyses with different size of the wind farm (400 up to 1000 MW), different average wind speed in the area (8 up to 11 m/s) and different distances from shore (up to 300 km) are performed and presented in [5] and [6].

II. AGGREGATED WIND FARM MODEL

In order to evaluate losses in a transmission system for wind power, it is necessary to define the input power into the transmission system. Thus an aggregated model based on Holttinne and Norgaard ([7]) has been considered.

Input data for the model are:

- Wind farm size of 500 or 1000 MW;
- Standard 5 MW wind turbine;
- Wind speed in the area with average wind speed of 9 m/s represented by Rayleigh distribution;
- Dimension D of the wind farm equal to 25 for 500 MW and 50 km for 1000 MW (front side in respect to the direction of the wind) [3];
- Turbulence intensity I equal to 10 %;

![Figure 1. Comparison between a single wind turbine power curve and the wind farm power curve for a 1000 MW wind farm and an average wind speed in the area of 9 m/s.](image)

Figure 1. Comparison between a single wind turbine power curve and the wind farm power curve for a 1000 MW wind farm and an average wind speed in the area of 9 m/s.

Considering a variation of the wind in the site where the wind farm is installed of ± 5 m/s, it is possible to obtain the
power curve of the wind farm. In Figure 1 the power curve for the wind farm as well as for a single 5 MW wind turbine are compared.

In Figure 2 it is possible to observe the duration curve for the 1000 MW wind farm compared with durations curve for different average wind speed in the area (8, 10 and 11 m/s).

From Figure 2 it is possible to observe that increasing the average wind speed in the area, the rated power can be generated for longer period of time. At 11 m/s rated power is generated for almost 40% of the time and this value is almost the double than the time for 9 m/s.

III. HVAC TRANSMISSION SYSTEM

The production of large amounts of reactive power can be considered the main limiting factor of HVAC cable utilization in transmission systems for long distances. A comparison of the transmission capacity of cables with different voltage levels (132 kV, 220 kV and 400 kV) and different compensation solutions (only onshore or at both ends) is presented in Figure 3. Cables’ limits, as maximal permissible current, voltage swing of receiving end between no-load and full load (< 10%) and phase variation (< 30°) should not be exceeded, according to Brakelmann in [8]. For these cables, the maximal current is the only limit that is reached, while the other two are not critical constraints.

The critical distance is achieved when half of the reactive current produced by the cable reaches nominal current at the end of one cable. In that case, there is not any transmission capacity left for active power flow. For the considered cables, the critical distances are:

- \( L_{\text{max,132kV}} = 370 \) km
- \( L_{\text{max,220kV}} = 281 \) km
- \( L_{\text{max,400kV}} = 202 \) km

Figure 3. Limits of cables transmission capacity for three voltage levels, 132 kV, 220 kV and 400 kV

A. Components of the transmission system

Since, the voltage level within an offshore wind farm grid is typically in the range of 30 kV – 36 kV, an offshore substation is necessary to step up the voltage to the transmission level.

A HVAC transmission system used for connection of large offshore wind farms to the onshore grid contains:

- HVAC submarine transmission cable(s)
- Offshore transformer(s)
- Compensation units, TCR (Thyristor Controlled Reactors), both onshore and offshore
- Onshore transformer(s), depending on a grid voltage

These components provide the transmission from an offshore collection point of the wind turbines’ power (offshore substation) to a grid connection point placed onshore.

B. Loss calculations

3.2.1) Models and assumptions

Cable loss calculations are performed based on Brakelmann [9]. Loss calculations take into account the current distribution along cable line and temperature dependence.

For 132 KV and 220 KV voltage transmission levels, three core XLPE insulated submarine cables are used while for 400 KV level three single core XLPE submarine cables are considered in trefoil formation. Cable characteristics are tabulated in Table I.

According to Brakelmann in [9], the cable losses per unit length are calculated as

\[
P' = \left( P'_{\text{max}} - P'_D \right) \cdot \left( \frac{I}{I_N} \right)^2 \cdot \nu_\theta + P'_D
\]  

(1)
where \( P'_{\text{max}} \) are the nominal total cable losses, \( P'_{\text{D}} \) are the dielectric losses, per core, \( I \) is load current, \( I_N \) is the nominal current, \( \nu_0 \) is the temperature correction coefficient that is calculated as:

\[
\nu_0 = \frac{c_a}{c_a + \alpha_t \cdot \Delta \theta_{\text{max}}} \left[ 1 - \left( \frac{l}{l_N} \right)^2 \right]
\]

where \( \alpha_t \) is the temperature coefficient of the conductor resistivity [1\(^8\)K], \( c_a \) is the constant, i.e. \( c_a = 1 - \alpha_t (20 \, ^{\circ}\text{C} - \theta_{\text{amb}}) \), \( \Delta \theta_{\text{max}} \) is the maximal temperature rise, i.e. 90-15=75 \(^{\circ}\text{C}\), the ambient temperature is supposed to be \( \theta_{\text{amb}}=15 \, ^{\circ}\text{C} \).

### TABLE I
CABLES’ PARAMETERS AND MAIN CHARACTERISTICS

<table>
<thead>
<tr>
<th>Cable</th>
<th>132 KV</th>
<th>220 KV</th>
<th>400 KV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance (Ω/km)</td>
<td>48*10^-6</td>
<td>48*10^-6</td>
<td>45*10^-6</td>
</tr>
<tr>
<td>Inductance (μH/km)</td>
<td>0,34</td>
<td>0,37</td>
<td>0,39</td>
</tr>
<tr>
<td>Capacitance (μF/km)</td>
<td>0,23*10^-3</td>
<td>0,19*10^-3</td>
<td>0,18*10^-3</td>
</tr>
<tr>
<td>Nominal current (A)</td>
<td>1055</td>
<td>1055</td>
<td>1323</td>
</tr>
<tr>
<td>Cable section (mm(^2))</td>
<td>1000</td>
<td>1000</td>
<td>1200</td>
</tr>
<tr>
<td>Max. operating temperature [°C]</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

Since the cable current along the cable route is not constant for a specific load but depends on its position along a route, i.e. \( I=I(x) \), in order to calculate cable losses the following integral has to be solved:

\[
P'_{\text{lo}} = \frac{P'_{\text{max}}}{I_0 \cdot I_N^2} \cdot \int_0^{l_n} I^2(x) \cdot \nu_0(x) \cdot dx + P'_{\text{D}}
\]

Solving integral (3) for length \( l_n \), the cable losses per unit length are obtained. Multiplying the integral with actual cable length \( l_n \), the cable losses in W are achieved. This method provides accurate calculation of cables losses [9].

In order to calculate transformer losses, equivalent parameters like \( R_{\text{eqr}} \), representing iron losses, and \( R_{\text{eqc}} \), representing copper losses, are defined. These data are obtained from nominal transformer losses data ([12], [13] and [14]). Since, TCRs are used as compensation units, it is assumed that they have the same no load losses as an equivalent transformer with the same VA rating and half of load losses of an equivalent transformer with the same VA rating [10].

#### 3.2.2) Results

System losses for average wind speed of 9 m/s, for three transmission voltage levels (132 KV, 220 KV and 400 KV) and for two wind farm configurations of 500 MW and 1000 MW are presented in Table II and Table III, respectively.

Transmission system losses \( l_{\text{sys}} \) have been calculated as

\[
l_{\text{sys}} = \sum_{i}^{N} P_{\text{lo},i} \cdot p_i \cdot h \cdot a
\]

where \( P_{\text{lo},i} \) is the power lost by the transmission system at wind speed \( i \), \( P_{\text{gen},i} \) is the power generated by the wind farm at wind speed \( i \), \( N \) is the number of wind speed class considered for the model, \( p_i \) is the probability to have a certain wind speed \( i \) and it is obtained by the Rayleigh distribution, \( h \) is the number of hours in a year, \( a \) is the availability of the wind park.

### TABLE II
TRANSMISSION LOSSES OF A 500 MW WIND FARM, WITH 9 M/S OF AVERAGE WIND SPEED IN THE AREA IN % OF ANNUAL WIND FARM PRODUCTION.

<table>
<thead>
<tr>
<th>%</th>
<th>500 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 km</td>
<td>2.78</td>
</tr>
<tr>
<td>100 km</td>
<td>4.77</td>
</tr>
<tr>
<td>150 km</td>
<td>7.53</td>
</tr>
<tr>
<td>200 km</td>
<td>11.69</td>
</tr>
</tbody>
</table>

Shaded cells in Table II represents the best transmission solutions with the lowest losses, while number of cables indicates number of cables required for that chosen solution. In the 132 KV column, number of cables presents the number of cables required for the 200 km.

Within the loss calculations, a new cable is added to the wind farm when the transmission system requires more capacity (depending on the wind speed). The same approach applies for the Table III.

### TABLE III
TRANSMISSION LOSSES OF A 1000 MW WIND FARM, WITH 9 M/S OF AVERAGE WIND SPEED IN THE AREA IN % OF ANNUAL WIND FARM PRODUCTION.

<table>
<thead>
<tr>
<th>%</th>
<th>1000 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 km</td>
<td>3.15</td>
</tr>
<tr>
<td>100 km</td>
<td>5.7</td>
</tr>
<tr>
<td>150 km</td>
<td>8.75</td>
</tr>
<tr>
<td>200 km</td>
<td>12.36</td>
</tr>
</tbody>
</table>

Figure 4 shows the participation of each transmission component in the total transmission losses for a 500 MW wind farm at 100 km from the shore using a 132 kV cable. It can be seen that cable losses represent by far the largest share of the total transmission losses. Thus, in order to decrease the total transmission losses, the transmission designers should pay special attention on cable selection.

From Table II and Table III, it can be seen that only 220 KV and 400 KV solutions are considered. However, these two submarine XLPE cable designs are still under development [11]. Especially the 400 KV XLPE submarine cable is available for short lengths without appropriate joint and splices for longer lengths. Considering distances longer than
200 km, 132 KV solutions prevail [5], since at such long distances, 220 KV and 400 KV cables generate large amounts of reactive power.

![Diagram](image)

Figure 4. Participation of each transmission component in total transmission losses for 500 MW wind farm, 9 m/s of average wind speed, at 100 km transmission distance, 3 three-core 132 KV submarine cables [5]

IV. HVDC SYSTEM WITH LINE COMMUTATED CONVERTER

Line Commutated Converter (LCC) devices have been installed in many bulk power transmission systems over long distances both on land and submarine all around the world, see [16] and [17]. A drawback of this transmission solution is the required reactive power to the thyristor valves in the converter and may be the generation of harmonics in the circuit [16].

A. Components of the transmission system

Main components of the transmission system based on LCC devices are:

- AC and DC filters;
- Converter transformer;
- Converter based on thyristor valves;
- Smoothing reactor
- Capacitor banks or STATCOM;
- DC cable and return path;
- Auxiliary power set
- Protection and control devices (i.e.: cooling devices, surge arrester).

All these components are considered in the following loss calculations, except the STATCOM: The influence of the STATCOM on total losses we would like to refer to [15].

B. Loss calculations

4.2.1) Models and assumptions

In order to calculate transmission losses for different wind farm sizes, data from existing HVDC LCC installations are considered, see also [16] and [17].

Converter stations have been built in sizes of 250 MW, 440 MW, 500 MW and 600 MW. Losses vary typically with a linear trend between 0,11% (no load) and 0,7% (rated power) of the rated power [16]. Both monopolar and bipolar solutions are considered depending on the number of converter stations and on the size of the wind farm.

Cable models are based on Brakelmann’s theory [8] and models take into account variations of temperature in the cable in order to obtain more realistic results. In Table IV, solutions chosen for cables are presented: all the configurations are based on mass impregnated solution with conductors made of copper.

Lost power \( P_{\text{cab}} \) in the cable is calculated with formulae:

\[
P_{\text{cab}} = P_{L_{\text{max}}} \cdot \left( \frac{I}{I_N} \right)^2 \cdot \theta 
\]

\[
P_{L_{\text{max}}} = R_0 \cdot c_n \cdot I_N \cdot l_{\text{cable}}
\]

\[
c_n = 1 + \alpha_{20} \cdot (\Delta \theta_{L_{\text{max}}} + \theta_U - 20)
\]

\[
c_n = 1 - \alpha_{20} \cdot (20 - \theta_U)
\]

\[
\theta = \frac{c_n + \alpha_{20} \cdot \Delta \theta_{L_{\text{max}}} \left( 1 - \left( \frac{I}{I_N} \right)^2 \right)}{c_n}
\]

where \( R_0 \) is the DC resistance of the conductor at 20 °C per unit length ([18] and [19]), \( \alpha_{20} \) is the constant mass temperature coefficient at 20 °C ([18] and [19]), \( P_{L_{\text{max}}} \), is the lost power in the cable at its maximum operating temperature, \( \Delta \theta_{L_{\text{max}}} = 55 \degree C \) is the maximum operating temperature of the insulator, \( \theta_U = 15 \degree C \) is the ambient temperature, \( I_N \) is the nominal current of the cable, \( I \) is the current flowing into the cable and \( l_{\text{cable}} \) is the length of the cable used for the transmission.

| TABLE IV |
|-----------------|---|---|---|---|
| Rated power [MW] | 250 | 440 | 500 | 600 |
| Voltage level [kV] | 250 | 350 | 400 | 450 |
| Nominal current [kA] | 1 | 1.25 | 1.25 | 1.33 |
| Cable section [mm²] | 1000 | 1400 | 1200 | 1600 |
| Resistance [Ω/km] | 0.0177 | 0.0129 | 0.0151 | 0.0113 |
| Max operating temperature [°C] | 55 | 55 | 55 | 55 |

When more than one converter station is used for the transmission, the total power is split between the different converter station depending on the configuration that gives the lowest total losses.

Converter stations are shut down when low power is generated in the wind farm: in these conditions, only the losses of protection and control devices are considered and these devices are supplied by the auxiliary power set.

4.2.2) Results

Three different layouts are considered for 500 MW wind farm and four for 1000 MW wind farm: these configurations are shown in Table V with the system losses of each system.
Transmission system losses \( l_{\text{sys}} \) have been calculated with (4) and data from Table IV.

### Table V

**TRANSMISSION LOSSES FOR DIFFERENT CONVERTER STATION LAYOUTS WITH 9 M/S OF AVERAGE WIND SPEED IN THE AREA IN % OF ANNUAL WIND FARM PRODUCTION.**

<table>
<thead>
<tr>
<th>Length</th>
<th>500 CS</th>
<th>2 x 250 CS</th>
<th>600 CS</th>
<th>2 x 500 CS</th>
<th>600 CS + 440 CS</th>
<th>500 CS + 600 CS</th>
<th>2 x 600 CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 km</td>
<td>1.77</td>
<td>1.81</td>
<td>1.75</td>
<td>1.69</td>
<td>1.60</td>
<td>1.66</td>
<td>1.65</td>
</tr>
<tr>
<td>100 km</td>
<td>1.98</td>
<td>2.14</td>
<td>1.87</td>
<td>1.92</td>
<td>1.77</td>
<td>1.84</td>
<td>1.78</td>
</tr>
<tr>
<td>150 km</td>
<td>2.19</td>
<td>2.48</td>
<td>1.99</td>
<td>2.14</td>
<td>1.95</td>
<td>2.01</td>
<td>1.90</td>
</tr>
<tr>
<td>200 km</td>
<td>2.39</td>
<td>2.82</td>
<td>2.11</td>
<td>2.37</td>
<td>2.13</td>
<td>2.19</td>
<td>2.03</td>
</tr>
</tbody>
</table>

The grey marked cells in Table V, represent the configuration with the lowest losses.

For some configurations, participation of each component in the system losses of the system is shown in Figure 5.

![Figure 5](image)

Converter stations are responsible for the highest share of the overall system losses; participation of the cable increases with lengths.

### V. HVDC SYSTEM WITH VOLTAGE SOURCE CONVERTER

Voltage Source Converter (VSC) devices have been installed until today in some bulk power transmission systems over long distances both on land and submarine all around the world. This solution is newer than the previous one and relevant projects have been installed only from 1997 [17]. On the one hand, these solutions might supply and absorb reactive power to the system and help to may help to support power system stability; on the other hand losses are higher and line to ground faults can be problematic.

### A. Components of the transmission system

Main components of the transmission system based on VSC devices are:
- VSC converter station circuit breaker
- System side harmonic filter
- Interface transformer
- Converter side harmonic filter
- VSC unit
- VSC dc capacitor
- DC harmonic filter
- DC reactor
- DC cable or overhead transmission line
- Auxiliary power set

All these components are considered in the following loss calculation, except the auxiliary power set due to lack of information about its losses.

### B. Loss calculations

#### 5.2.1) Models and assumptions

In order to calculate system losses for different wind farm sizes, and due to lack of data from manufactures, data are mainly used from installed projects. For instance, system loss data are extracted from installed projects such as the Cross Sound Cable [21] and the Murray Link Project [22]. By calculating the transmission losses of those projects, see [9], it is possible to calculate the losses for the total converter station (350 MW and 220 MW). In general, the idea is to divide the total system losses into three components (2 stations + the cable) in order to use the data for further calculations.

Considering the system represented in Figure 6, that is valid for both HVDC transmission solutions,

\[
\begin{align*}
\text{P}_{\text{in}} & = \text{P}_{\text{s1}} + \text{P}_{\text{s2}} + \text{P}_{\text{c}} + \text{P}_{\text{out}} \\
\text{P}_{\text{s1}} & = (1-x_s) \cdot P_{\text{is}} \\
\text{P}_{\text{c}} & = P_{\text{s1}} - P_{\text{s2}} = R \cdot I^2 = R \left( \frac{P_{\text{i}}}{V_C} \right)^2 \\
\text{P}_{\text{out}} & = (1-x_s)P_{\text{s2}}
\end{align*}
\]

where \( V_C \) is the rated voltage of the cable and \( I \) is the current flowing in it. Defining then equation
\[ \frac{R}{V_s^2} \left( 1 - x_s \right)^2 P^2 - \left( 1 - x_s \right)^2 P_m + P_{out} = 0 \]  

(13)

it is possible to calculate the value of \( x_s \) since all the other parameters are known.

In order to consider the temperature dependence of the resistance, it is possible to follow the procedure shown by Brakelmann ([9]) for an AC cable, taking into account the DC nature of our system (equations (6)-(9)). It is thus possible to calculate the resistance of the cable as

\[ R = \frac{P_{\text{loss}}}{\min} \frac{V_s}{I_s} \]  

(14)

Since the data for the cable provide only the input and the output power for the whole transmission system, it is necessary to solve the calculations in a loop with (6) – (9), (13) and (14) in order to obtain the value of the current that flows into the cable and thus calculate the resistance. In each step the values for \( I \) and \( R \) are improved and the loop stops when the difference between \( R \)'s at (k-1) and (k) is lower than 0.0001.

Manufacturers are working on larger converter station ratings; however, no detailed data are publicly available for those new converter stations. Hence, the losses for a 500 MW converter station are estimated from the losses of a 350 MW converter station.

Again, for the loss calculations of the cable Brakelmann’s theory [9] is used and the model takes into account variations of temperature in the cable in order to obtain more realistic results. In Table VI, solutions chosen for cables are presented: all the configurations are based on PE solution, conductors are made of copper and rated voltage is 150 kV. The same approach described with (5) – (9) is used in the calculations for this transmission system.

When more than one converter station system is considered for the transmission, the division of the power into each station depends on the configuration that gives lowest overall transmission system losses.

| TABLE VI |
| CABLES DATA FOR THE VSC MODEL COMPILLED AND CALCULATED FROM [9], [17], [18] AND [19]. |

<table>
<thead>
<tr>
<th>Rated power [MW]</th>
<th>220</th>
<th>350</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal current [kA]</td>
<td>0.793</td>
<td>1.2</td>
<td>1.677</td>
</tr>
<tr>
<td>Cable section [mm²]</td>
<td>1300</td>
<td>1300</td>
<td>2000</td>
</tr>
<tr>
<td>Resistance [μΩ/km] @ 20 °C</td>
<td>0.0138</td>
<td>0.0138</td>
<td>0.008</td>
</tr>
<tr>
<td>Max operating temperature [°C]</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
</tbody>
</table>

Converter stations are shut down when power production in the wind farm is lower than transmission system losses: in these conditions, only the losses of protection and control systems are considered and these devices are supplied by the auxiliary power set. However, due to lack of information, these losses are neglected.

5.2.2) Results

Three different layouts are considered for 500 MW wind farm and four for 1000 MW wind farm: these configurations are shown in Table VII with the percent losses of each system.

| TABLE VII |
| TRANSMISSION LOSSES FOR DIFFERENT CONVERTER STATION LAYOUTS WITH 9 M/S OF AVERAGE WIND SPEED IN THE AREA IN % OF ANNUAL WIND FARM PRODUCTION |

<table>
<thead>
<tr>
<th>Length Cable</th>
<th>500 MW, 9 m/s</th>
<th>1000 MW, 9 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 km 350 + 220 CS</td>
<td>4.05 4.21 4.43</td>
<td>4.02 4.0893</td>
</tr>
<tr>
<td>100 km 4.43 4.58 4.87</td>
<td>4.52 4.5697</td>
<td></td>
</tr>
<tr>
<td>150 km 4.82 4.94 5.31</td>
<td>5.02 5.0317</td>
<td></td>
</tr>
<tr>
<td>200 km 5.20 5.30 5.75</td>
<td>5.52 5.505</td>
<td></td>
</tr>
</tbody>
</table>

Transmission system losses \( I_s \) have been calculated with (4) and data from Table VI.

![Figure 7. Loss Participation to the overall system from data in Table VII, VSC system.](image)

The grey cells in Table VII represent the configuration with the lowest losses. For some configurations, participation of each component in the system losses of the system is shown in Figure 7. It can be seen that converter stations contribute most to the overall system losses; participation of the cable increases with lengths.

VI. COMPARISON OF DIFFERENT SOLUTIONS

In this section a comparison of the different transmission system is presented. Table VIII shows a comparison of the three transmission systems considering current installed technology and main components.
### Table VIII: Comparison HVAC-HVDC Transmission System ([1]-[6],[23])

<table>
<thead>
<tr>
<th></th>
<th>HVAC</th>
<th>HVDC LCC</th>
<th>HVDC VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum available capacity per system</td>
<td>800 MW at 400 kV [380 MW at 220 kV [220 MW at 132 kV all up to 100 km ]</td>
<td>Up to 600 MW (submarine transmission)</td>
<td>Up to 350 MW installed 500 MW announced</td>
</tr>
<tr>
<td>Voltage level</td>
<td>132 kV installed 220 and 400 kV under development</td>
<td>Up to ± 500 kV</td>
<td>Up to ± 150 kV</td>
</tr>
<tr>
<td>Offshore Installed Projects</td>
<td>Many small installation (Table 1.5 in [6])</td>
<td>Not yet installed</td>
<td>Only test projects</td>
</tr>
<tr>
<td>Black start capability</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Technical capability for network support</td>
<td>No, SVC are required to supply reactive power</td>
<td>No, capacitor banks or Statcom are required to supply reactive power to the valves</td>
<td>Yes, reactive power can be generated or absorbed by the VSC devices</td>
</tr>
<tr>
<td>Offshore station in operation</td>
<td>Yes</td>
<td>No</td>
<td>No, but announced</td>
</tr>
<tr>
<td>Decoupling of connected networks</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Cable model</td>
<td>Resistances, capacitance and inductance</td>
<td>Resistance</td>
<td>Resistance</td>
</tr>
<tr>
<td>Requirements for ancillary service</td>
<td>Not necessary Yes for low wind speeds conditions</td>
<td>Yes for low wind speeds conditions</td>
<td></td>
</tr>
<tr>
<td>Space requirements offshore substation</td>
<td>Smallest size Biggest size Medium size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation costs</td>
<td>Small for station (only transformer) High cost for cable</td>
<td>High cost for station (transformer, filters, capacitors banks, thyristor valves...) Low costs for cable</td>
<td>Station 30-40 % more expensive than LCC solution (IGBT more expensive than thyristor valves) Cable more expensive than LCC</td>
</tr>
</tbody>
</table>

From results in sections III, IV and V, the AC solution provides the lowest losses for a distance of 50 km from shore, while for 100, 150 and 200 km from the shore the HVDC LCC solution has lowest transmission losses (Table IX and Table X). In the tables, ‘Config.’ stands for the rated power and the voltage level (between breakers) of the transmission for the HVAC system and the rated power of the converter station for the two HVDC solutions and ‘Nr Cables’ the number of cable requires for the transmission.

In Figure 8 it is possible to observe loss comparison results of all three transmission systems (HVAC, HVDC LCC and HVDC VSC) for 400 up to 1000 MW wind farm at 0 up to 300 km from the shore.

### Table IX: Loss Comparison for 500 MW Wind Farm at 9 m/s Average Wind Speed in the Area (CS = Converter Station)

<table>
<thead>
<tr>
<th></th>
<th>HVAC</th>
<th>HVDC LCC</th>
<th>HVDC VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Config.</td>
<td>500 MW (400 kV)</td>
<td>600 MW CS</td>
<td>(350 + 220) MW CS</td>
</tr>
<tr>
<td>Nr Cables</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>at 50 km</td>
<td>1.13</td>
<td>1.75</td>
<td>4.05</td>
</tr>
<tr>
<td>at 100 km</td>
<td>2.54</td>
<td>1.87</td>
<td>4.43</td>
</tr>
<tr>
<td>Config.</td>
<td>500 MW (400 kV)</td>
<td>600 MW CS</td>
<td>(350 + 220) MW CS</td>
</tr>
<tr>
<td>Nr Cables</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>at 150 km</td>
<td>4.98</td>
<td>1.99</td>
<td>4.82</td>
</tr>
<tr>
<td>Config.</td>
<td>500 MW (220 kV)</td>
<td>600 MW CS</td>
<td>(350 + 220) MW CS</td>
</tr>
<tr>
<td>Nr Cables</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>at 200 km</td>
<td>7.76</td>
<td>2.11</td>
<td>5.20</td>
</tr>
</tbody>
</table>

### Table X: Loss Comparison for 1000 MW Wind Farm at 9 m/s Average Wind Speed in the Area (CS = Converter Station)

<table>
<thead>
<tr>
<th></th>
<th>HVAC</th>
<th>HVDC LCC</th>
<th>HVDC VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Config.</td>
<td>1000 MW (400 kV)</td>
<td>440 + 600 MW CS</td>
<td>3 x 350 MW CS</td>
</tr>
<tr>
<td>Nr Cables</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>at 50 km</td>
<td>1.14</td>
<td>1.60</td>
<td>4.02</td>
</tr>
<tr>
<td>at 100 km</td>
<td>2.32</td>
<td>1.77</td>
<td>4.52</td>
</tr>
<tr>
<td>Config.</td>
<td>1000 MW (220 kV)</td>
<td>2 x 600 MW CS</td>
<td>2 x 500 MW CS</td>
</tr>
<tr>
<td>Nr Cables</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>at 150 km</td>
<td>4.30</td>
<td>1.91</td>
<td>5.02</td>
</tr>
<tr>
<td>Config.</td>
<td>1000 MW (220 kV)</td>
<td>2 x 600 MW CS</td>
<td>2 x 500 MW CS</td>
</tr>
<tr>
<td>Nr Cables</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>at 200 km</td>
<td>7.58</td>
<td>2.04</td>
<td>5.51</td>
</tr>
</tbody>
</table>

Figure 8. “MW-km” plane, comparison HVAC-HVDC LCC for different wind farm size (400-1000 MW) and different distances to shore (0-300 km) for average wind speed of 9 m/s.

Figure 8 shows that an HVAC system leads to the lowest transmission system losses for a distance of up to 55-70 km (depending on the size of the wind farm). For a longer distances HVDC LCC becomes the solution with lowest losses. Dash-dotted lines in Figure 8 shows the 1, 1.6 and 2 %...
loss line depending on wind farm sizes and distances. Observing these lines it can be seen that in the AC-area, losses do not vary so much and they remain nearly constant for increasing wind farm capacity and almost constant distances to shore. In the LCC-area instead loss vary much more with changing wind farm size and distance: this behaviour is caused by the configuration chosen for the transmission of the power with the LCC system. In fact for each wind farm size a different combination of converter stations is considered and thus losses are only partly correlated between each other.

A. Combination of two transmission systems.

In some cases it might be beneficial to combine different transmission solutions in order to obtain a wider overview of possible solution and to improve some features of the system (reliability, stability, etc.). For example a HVDC VSC transmission system, might be useful to improve the stability of the system since it can control the generation and absorption of reactive power in the system.

Configurations are defined according to the current technology and data for the components are taken from the previous sections. When a combination is chosen, it is assumed that the system with highest losses is the main transmission component and the lowest one is installed with lower transmitted power in order to decrease the total system losses. When instead system losses of both systems are close, it is assumed that both transmission systems transmit the same amount of power. When HVDC VSC solution is considered, some limitations in the possible combinations must be considered due to the small range of rated power of the converter station (on the market are only available a 220 and a 350 MW converter station).

Results are presented in Table XII and Table XIII: in row ‘Config’ the rated power of the relative transmission system is pointed (in brackets: the voltage level of the HVAC system), in ‘Nr Cables’ the number of cables necessary for each transmission system and ‘at x km’ system losses are shown. In the tables, symbol ‘+’ divides the kind of system used for the transmission.

From the tables it can be seen that the combination of two different transmission systems never improves the system losses compared to configurations with a single transmission system. However system losses of the system with highest losses decrease with the combination with another system. For example a HVDC VSC system has losses of 4.05% (Table IX) if it operates alone at 50 km from the shore, but its losses could be decrease up to 2% if it is combined with a HVAC transmission system.

B. Combination of three transmission systems

Large wind farms (up to 1000 MW) are supposed to be installed in a wide offshore area. Large offshore wind turbines (5 MW) could be placed at distance of 1 km from each other.

Such large wind farms might have different distances to shore and different grid connection’s conditions. One example of such wind farm configuration is presented in Figure 9. From the considered 1000 MW wind farm, power can be transmitted by three different transmission systems, characterized by different distances from shore and different grid strengths at the onshore connection point.

The AC system might be used at short distances with small amount of transmitted power and connected to a weak grid. The HVDC VSC system might have the best stability possibilities and is might be connected to a medium-strong grid. HVDC LCC solution has lowest transmission losses and thus it is used for transmission of large amount of power at long distance from a strong grid connection point.

Three cases of power distributions among transmission systems, for 9 m/s of average wind speed, are considered:
1. 80 MW by AC, 220 MW by HVDC VSC and 700 MW by HVDC LCC
2. 50 MW by AC, 350 MW by HVDC VSC and 600 MW by HVDC LCC
3. 180 MW by AC, 220 MW by HVDC VSC and 600 MW by HVDC LCC

Figure 9. 1000 MW wind farm at different distances to shore, case 1

Depending on the wind farm generation, different transmission systems are considered. For example in case 1, if the wind farm produces less than 80 MW, AC transmission system is used. For the range 80 – 700 MW, only HVDC LCC solution is loaded, whereas between 700 – 780 MW, HVDC LCC operates at 700 MW and remaining power is transmitted by the AC system. For generated powers between 780 – 1000 MW, HVDC LCC and AC systems transmit their rated power and the rest is transmitted by the HVDC VSC system. This configuration is chosen in order to obtain the lowest value for the total losses of the transmission system. It must be mentioned that in reality the operation mode might be different, particularly in regards to the operation of the HVDC VSC which might be used to support the operation of the onshore grid during certain times

VII. CONCLUSIONS

Interest on large offshore wind farms has increased in the last years and many studies are under development. Design and specification of the transmission system to shore is of the critical parts for the development of very large (>>200 MW) offshore wind farms. This paper investigates the total transmission losses of three transmission solutions, i.e. HVAC, HVDC LCC and HVDC VSC.

In general, HVAC solution leads to the lowest losses for distances of up to 70 km from the shore, whereas after this distance, HVDC LCC solution has lower losses and is therefore preferable from the losses point of view. However, many other aspects will influence the final choice of the design, e.g. number of cables required, reliability, life cycle costs, integration into the onshore power system etc. Further studies are therefore needed to determine the preferred design of transmission system between the offshore wind farm and the shore.

TABLE XIV
PERCENT OF AVERAGE TRANSMISSION LOSSES OF SYSTEM IN FIG. 2., AND PARTICIPATION OF EACH TRANSMISSION SYSTEM IN TOTAL LOSSES

<table>
<thead>
<tr>
<th>Cases</th>
<th>Losses [%]</th>
<th>AC participation [%]</th>
<th>LCC participation [%]</th>
<th>VSC participation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>2.60</td>
<td>5.27</td>
<td>72.26</td>
<td>22.47</td>
</tr>
<tr>
<td>Case 2</td>
<td>2.71</td>
<td>4.58</td>
<td>56.8</td>
<td>39.19</td>
</tr>
<tr>
<td>Case 3</td>
<td>3.21</td>
<td>11.62</td>
<td>63.71</td>
<td>25.37</td>
</tr>
</tbody>
</table>

Losses for the wind farm are presented in Table XIV. HVDC LCC system causes the highest share in the in the total losses, as expected, due to the fact that it transmits the greatest amount of power. Besides the more the VSC system participates to the transmission, the more percent losses are: this is reasonable since VSC is the solution with higher losses. However increasing transmission by AC, total losses decrease, but this might create problems for the stability of the grid since in the grid at the connection point is weak.

VIII. REFERENCES

[17] List of projects found at www.abb.com (last visit January 2005).