Optimization of Offshore Wind Farms with HVAC and HVDC Transmission Networks

Asma Dabbabi, Salvy Bourguet, Rodica Loisel, and Mohamed Machmoum

Abstract Recently, offshore wind farms have attracted more and more attention because of their greater energy capacity. To get the best performances of a wind farm park, a technical and economic compromise between energy yields and overall investment must be established. In this paper, a study was done on Borssele I & II offshore wind farm with HVAC and HVDC transmission technologies to compare their performances with different transmission distances.

1 Introduction

The European Union has set targets to reduce the amount of CO_2 through the integration of renewable energy sources. By 2020, 20% of European energy supplied should come from renewable sources with a 20% reduction in CO_2 emissions compared to 1990 [1].

Offshore wind energy is one among renewable energies, which has several advantages over land-based wind, such as stronger and more regular wind at sea. The exploitation of offshore energy involves investments in energy transmission to the terrestrial network. Nevertheless, it is important to consider cheaper transmission solutions with less energy loss. There are two main transmission technologies: HVAC and HVDC. In the literature, studies have been done by P. Monjean [2] comparing several topologies of internal connections of offshore wind farms according to various criteria such as technological feasibility and availability. Thus, this comparison led to favor HVDC transport over HVAC or MVAC transport under certain conditions (significant distance from the coast). In addition, S. Gasnier [3] has developed a technical and economic evaluation tool for different connection architectures. His work has focused on the economic study of DC topologies by

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calculating the Levelized Cost of Energy (LCOE), which involves electrical losses and overall investment costs of the wind farm. Besides, O. Dahmani focused on the modeling and optimization of topologies of offshore wind farms with AC distribution and transmission networks, and studying their reliability [4].

The objective of this paper is to make a comparison between HVAC and HVDC technologies for a large offshore wind farm such as Borssele I & II. The paper is divided into five sections, the first presents the difference between the HVAC and HVDC architecture, the second and third parts respectively present the electric and economic models of an offshore wind farm, the fourth part presents the algorithm developed for offshore wind farms optimization, and the last part is dedicated to the study and comparison of the energy and economic performances between both technologies for Borssele I & II park.

2 Transmission Technologies

Figure 1 shows two different architectures of an offshore wind farm. The first topology consists of wind turbines exploiting wind energy, a MV distribution

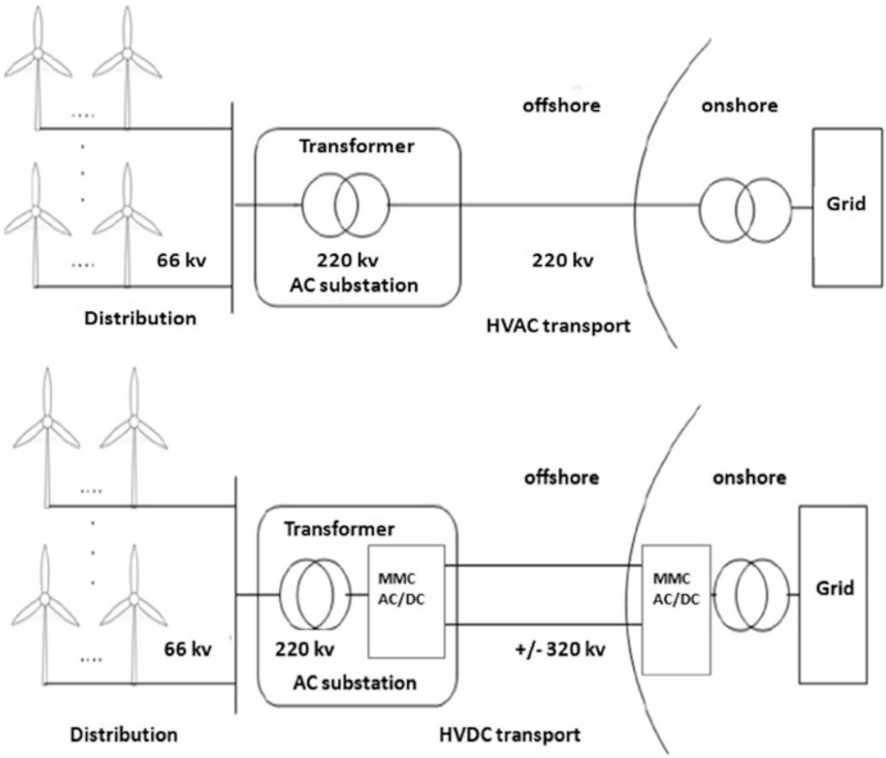

Fig. 1 Transmission technologies

network in which the wind turbines are connected and the AC offshore substations are founded under a medium voltage 66 kV and finally a 220 kV HVAC transmission network that is directly connected to the onshore point called the delivery point (DP). The second topology has the same distribution network as the first, but here the transport is in HVDC under a voltage of ± 320 kV; therefore, the DC offshore substations contain AC/DC converters and the DP must contain a DC/AC converter in order to inject the energy transmitted to the terrestrial network.

3 Offshore Wind Farm Electrical Models

3.1 Turbines

The study of the energy losses of the different topologies of offshore wind farms is carried out over a total operating life estimated between 20 and 30 years. Since the analysis is done for a long term, the modeling of the various components of the electrical network is made for a balanced, permanent, and sinusoidal operating regime.

Borssele park zone I & II is composed of 116 turbines with 6 MW each. The turbines used for this study are General Electric Haliade with a rotor diameter (RD) of 150 m and a hub height of 100 m [5]. Each turbine is modeled by an active power generation curve as a function of wind speed. The typical production curve of the Haliade wind turbine is shown in Fig. 2.

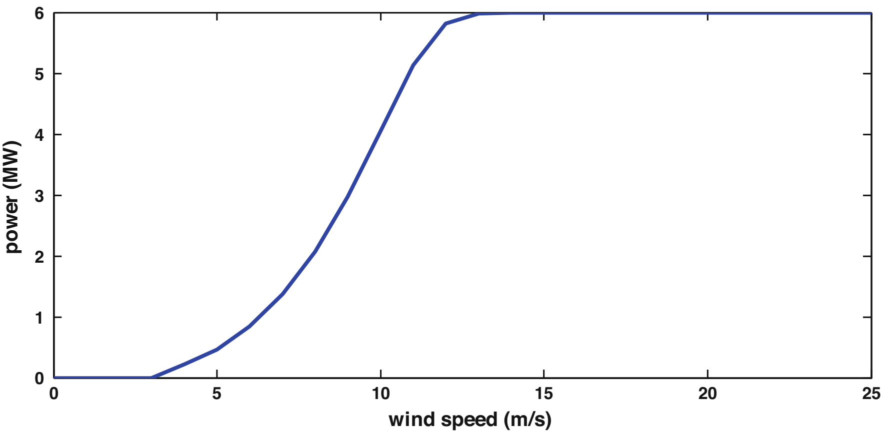

Fig. 2 Power curve of the Haliade 6 MW wind turbine

3.2 Submarine Cables

All cables are modeled using a π model that takes into account the type of soil surrounding cables and the cable geometric dimensions in accordance with IEC 60228 and 60287 [6]. Table 1 shows the properties of all the cables used for Borssele I & II.

3.3 Multilevel Modular Converters (MMCs)

In order to ensure the energy conversion in the case of HVDC transmission, a multilevel modular converter is chosen. This structure easily adapts to very high voltage and power levels. Figure 3a shows the VSC HVDC converter model, while Fig. 3b presents the equivalent single-phase power flow model of a converter connected to the AC network. The converter is represented as a controllable voltage source U_c behind the phase reactor, represented as a complex impedance Z_c. The

Table 1 Submarine cables parameters of Borssele park [7]

	MVAC		HVAC			HVDC			
Rated voltage (kV)	66		220			±320			
Section (mm^2)	240	630	500	800	1000	240	630	1200	2000
Rated power (MW)	54.9	81.7	250	295	330	446	797	1147	1540
Rated current (A)	480	715	655	775	866	697	1246	1791	2406
R at 20 °C (mΩ/km)	85	41.4	39.1	24	21	75	27.3	15.1	9
C (nF/km)	220	320	140	170	190	–	–	–	–
L (mH/km)	0.38	0.33	0.43	0.4	0.39	–	–	–	–

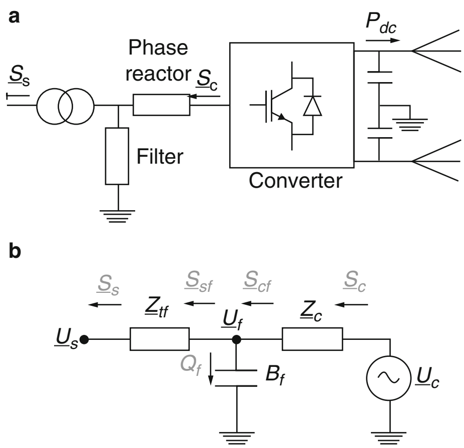

Fig. 3 (**a**) VSC HVDC converter model [8]. (**b**) Equivalent single-phase power flow model of a VSC HVDC converter [8]

Table 2 *a*, *b*, and *c* parameters values [9]

VSC	*a*	*b*	*c*
Rectifier	11.033e−3	3.464e−3	4.400e−3
Inverter	11.033e−3	3.464e−3	6.667e−3

filter is represented as a susceptance B_f at system frequencies and Z_{tf} is the complex impedance of the transformer.

In our case, the nominal power of the MMC is the sum of the nominal powers of the turbines that are interconnected. Concerning the calculation of the MMC losses, we used a generalized model of losses which is a model of ABB Corporate Research Sweden based on the data of the HVDC link Light of Södra Länken, evaluated with 600 MW and ±300 kV [9]. The VSC HVDC link is assumed to operate at a power factor of about 1.

The losses of the converter are written according to the converter current I_c determined by the active and reactive power exchanged with the AC system. The overall converter losses P_{loss} can be divided into three loss components, discussed further in [9]: no load losses, linear losses, and quadratic losses as shown in Eq. (1).

$$P_{loss} = a + b\, I_c + c\, I_c^2 \tag{1}$$

With:

$$I_c = \frac{\sqrt{{P_c}^2 + {Q_c}^2}}{\sqrt{3}\, U_c} \tag{2}$$

P_c, Q_c: active and reactive power to be injected/absorbed by the converter and U_c: converter voltage.

Table 2 shows the per unit values of coefficients *a*, *b*, and *c* for the Södra Länken model.

a, *b*, and *c* values depend on the converter nominal power and its voltage level. So for different values of power and voltage other than those of the Södra Länken model, a calculation of *a*, *b*, and *c* must be made (more details are given in [10]). Note that the inverter losses are greater than rectifier losses because the inverter uses the IGBTs more frequently, while the rectifier uses the diodes more frequently.

3.4 Transformers

The transformers are modeled by a T-model presented in the Fig. 4.

The impedance of the transformer depends on its rated power. The per unit values of the transformer parameters are:

$R_{TS} = 0.007$ p.u, $X_{TS} = 0.1$ p.u, $R_F = +\infty$, and $X_m = 50$ p.u [6].

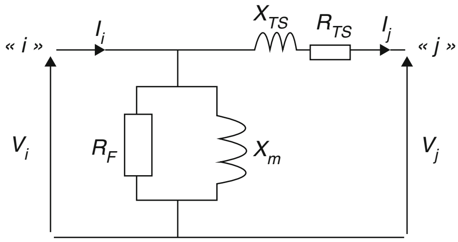

Fig. 4 Transformer model in per unit

Table 3 Cost of submarine DC cables [7]

	HVDC			
Rated voltage (kV)	±320	±320	±320	±320
Section (mm^2)	240	630	1200	2000
Rated power (MW)	446	797	1147	1540
Cost (k€/km)	502	677	1019	1405

4 Offshore Wind Farm Economic Models

4.1 Submarine Cables

The cost model for an AC cable is represented by the following equation:

$$C_{\mathrm{cable},ij} = C_{\mathrm{SI}} + \left(\alpha_{\mathrm{c}} + \beta_{\mathrm{c}} \exp\left(\gamma_{\mathrm{c}}.10^{-8} S_{\mathrm{C},n,ij}\left(C_{\mathrm{section}}\right)\right)\right) \tag{3}$$

This function depends on the initial investment cost, the transport, and installation cost C_{SI}, which are proportional to the cable length and the cable nominal power $S_{\mathrm{C}n,ij}$. The coefficients α_{c}, β_{c}, and γ_{c} are dependent on the cable voltage level. The reference model of S. Lundberg [4] was used for AC submarine cables costs. The DC cables cost is modeled with the following equation [11]:

$$C_{\text{cable pair HVDC}} = 0.652 + 0.00098 P_{\text{ratedcabpair}} - 0.002363 U_{\text{HVDC}} \tag{4}$$

Table 3 presents the DC cable cost in k€/km in function of different sections and rated powers.

4.2 Offshore Substations

The AC offshore substations' AC cost is given by the following equation [11]:

$$C_{\mathrm{ss}}^{\mathrm{HVAC}} = 2.534 \text{ Me } + 0.0887\ P_{\mathrm{ss}} \tag{5}$$

where P_{ss} is the sum of the nominal power of the turbines connected to the substation (MW) and C_{ss}^{HVAC} is the cost of the substation (M€). The same expression is used for DC substations, but with an increase of 85% to account for additional components [11].

4.3 Transformers

The expression of the transformer cost is presented by Eq. (6) [4]:

$$C_{\text{transfo}} = 0.03327 P_{\text{transfo}}^{0.7513} \quad (6)$$

where P_{transfo} is the transformer nominal power (MVA) and C_{transfo} is the cost (M€). The minimum transformer nominal capacity is estimated at 40 MW.

4.4 MMCs

The MMC cost [11] is given by the following expression:

$$C_{\text{MMC}} = 54.985 \text{ M€} + 0.0589 \ P_{\text{MMC}} \quad (7)$$

where P_{MMC} is the MMC rated power (MVA) and C_{MMC} is the MMC cost (M€).

4.5 Reactive Power Compensation

The reactive power compensation cost is the sum of the compensation equipment cost C_{ec} (€) and the increment of the platform cost C_{incremt} (€) [4].

$$C_{\text{comp}} = C_{\text{ec}} + C_{\text{incremt}} \quad (8)$$

The compensation equipment cost C_{ec} is proportional to the total reactive power of the network (consumed or produced) Q_{comp}.

$$C_{\text{ec}} = \alpha_{\text{ec}} + \beta_{\text{ec}} Q_{\text{comp}}^{\gamma_{\text{ec}}} \quad (9)$$

C_{incremt} is proportional to reactive power installed on each offshore substation $Q_{\text{comp,sub}}$.

$$C_{\text{incremt}} = 608. Q_{\text{comp,sub}}^{0.765} \quad (10)$$

G. Guidi's model is used to estimate both the parameters α_{ec}, β_{ec}, γ_{ec}, and the term $C_{\text{increment}}$ [4].

5 Offshore Wind Farm Optimization (Borssele I & II)

Optimal structure of an offshore wind farm is a structure that verifies certain constraints such as minimizing the cost of energy transmitted to the grid and minimizing power losses. Indeed, each electrical topology is characterized by a number of offshore substations as well as connections of wind turbines in the distribution network and a transmission network configuration HVDC or HVAC.

The genetic algorithm provides the first topologies of connections such as the connection between the wind turbines and the connection between offshore substations. Next, the Prim's algorithm is used to complete the connection between each group of wind turbines and the nearest substation as well as between each group of substations to DP (search for the shortest path) [4]. The optimization algorithm flowchart is depicted in Fig. 5.

5.1 Economic Functions

The Borssele I & II park is optimized according to an economic function (mono objective).

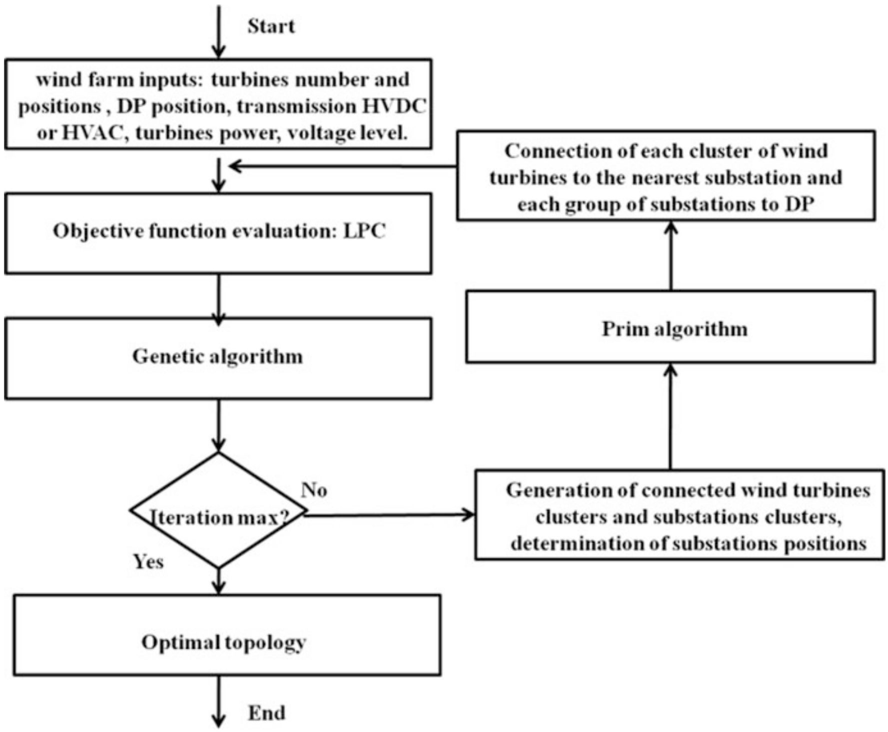

Fig. 5 The optimization algorithm flowchart

The objective function is the levelized production cost (LPC (€/kWh)), which is the ratio between the total investment cost and the average energy delivered to the grid.

$$\mathrm{LPC} = \frac{C_{\mathrm{invest}}}{E_{\mathrm{d}}} \tag{11}$$

With:

$$C_{\mathrm{invest}} = \frac{r\,(1+r)^{T}\;T}{(1+r)^{T}-1}\,\frac{1}{1-\mathrm{PR}}\,C_0 \tag{12}$$

$$E_{\mathrm{d}} = P_{\mathrm{sortie}}\;N_{\mathrm{t}}T = \left[(n_{\mathrm{eol}}P_{\mathrm{eol}}) - P_{\mathrm{pertes}} - P_{\mathrm{L}}\right]N_{\mathrm{t}}\;T \tag{13}$$

C_0: total initial investment, T: offshore wind farm lifetime set at 20 years, r: bank interest rate of 4%, PR: banks profit 2%, n_{eol}: number of wind turbines, P_{eol}: wind turbine power, P_{losses}: power losses, P_{L}: total active power consumed, $N_{\mathrm{t}} = 8760$ (number of hours of wind farm operation per year).

5.2 Power Flows

Power flows aim to calculate the nodal voltage modules and phases. The Mat AC/DC tool [12] implemented with Matlab® allows this calculation.

- Load flow AC

  In the AC wind farm case, the turbines and the transformers (66 kV/220 kV) are modeled as PQ nodes. In addition, in the terrestrial network, a last transformer (220 kV/380 kV) is added to increase the voltage and to inject it directly to the grid. Finally, the transformer output must be a reference node to balance the power flow.
- Load flow AC/DC

  In this case, the studied system is hybrid (AC distribution and HVDC transport), so the calculation of load flow must take into account the two regimes.

In fact, the turbines are considered as PQ nodes. The AC side of the MMCs and the terrestrial network node are defined as reference nodes. Therefore, the network is divided into different AC zones where each zone contains a reference node, and between these zones there are DC zones which present the HVDC transmission lines. Transformers are considered as PQ nodes.

For the calculation of the AC/DC load flow, the sequential method is used. It consists in calculating the state variables of the AC and DC systems and iterating

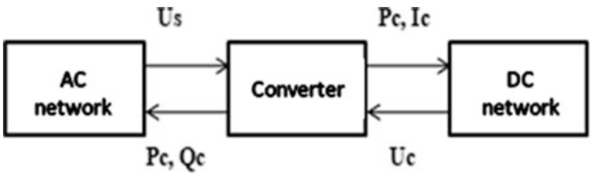

Fig. 6 The calculation interface of the AC/DC load flow

them one by one, until all state variables converge. During this process, the AC energy flow equations and the DC equations are solved separately.

To calculate the variables of the AC system, the converter can be considered as an equivalent PQ node connecting to an AC bus. Then, to solve the DC equations, the AC system is considered as a constant voltage of the converter bus. Figure 6 shows the calculation interface of the AC/DC load flow by the sequential method.

For converters control, there are two different modes:

1. Active power injection control which can be divided into three types:
   (a) Constant P: the converter injects a constant active power to the AC network.
   (b) Constant U_{DC}: the active power changes to keep the DC bus voltage constant.
   (c) DC droop: the active power changes linearly with its power.
2. Reactive power injection control which can be divided into two types:
   (a) Constant Q: the converter injects a constant reactive power to the AC network.
   (b) U_s constant: reactive power changes to maintain constant AC bus voltage.

In our case, each terminal of the AC zone (reference node) contains a converter, which must be controlled in constant active and reactive power "converter PQ," the last converter connecting all the transmission lines must be controlled by the imposition of a constant AC and DC voltage to keep the stability of HVDC lines, it is a "DC reference converter." Injections of active and reactive powers should be limited by a PQ diagram [8] defining the converter steady state operating points.

6 Results

6.1 *Performance Evaluation of Borssele I & II with Genetic Algorithm Optimization*

In this part, a comparison between the reference topology of Borssele I & II and the topology found with the optimization algorithm was done. For the genetic algorithm, four substations are fixed with variable positions. Figures 7 and 8 show, respectively, the basic architecture of Borssele I & II and the topology found after optimization.

The performances of reference topology with a transmission distance equal to 50 km are: LPC [c€/kWh] = 0.6893, active losses P_{ac} [MW] = 45.806, and reactive

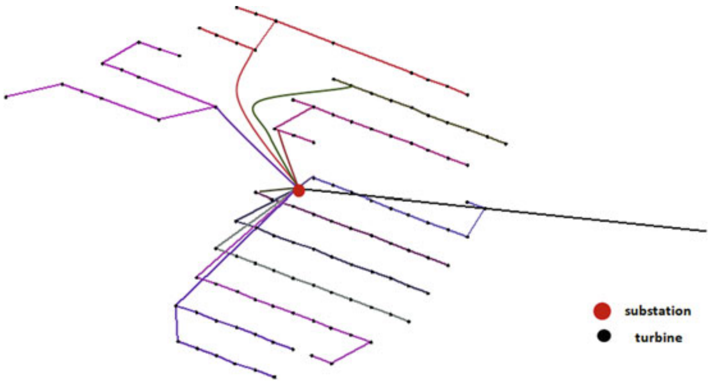

Fig. 7 The reference topology of Borssele I & II

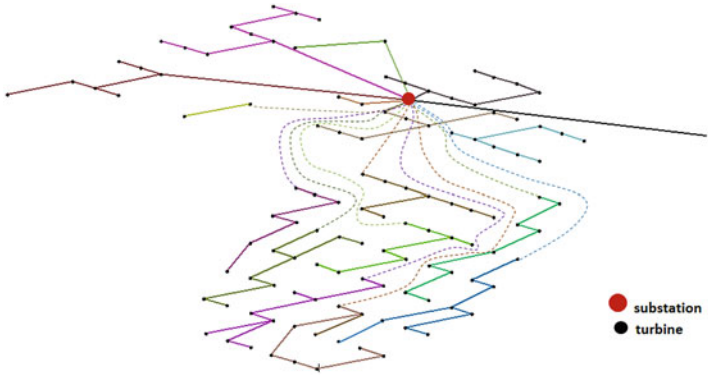

Fig. 8 Borssele I & II topology obtained by optimization

losses Q_{ac} [MVar] = 171.41. For the same transmission distance, the performances of the topology obtained by optimization algorithm are: LPC [c€/kWh] = 0.6889, active losses P_{ac} [MW] = 47.796, and reactive losses Q_{ac} [MVar] = 170.80.

The results found with the genetic algorithm are almost the same as the reference one, which validates that the reference topology is already optimized. In this case study, the minimization of the LPC is privileged than that of the losses. Furthermore, for other network topologies the optimization tool optimizes both the LPC and the losses.

6.2 Comparison Between HVAC and HVDC

In this part, Borssele park I & II is optimized for both transmission technologies. A comparison of the LPC is achieved depending on the transmission distance. Borssele I & II contains 116 turbines each producing 6 MW, one substation for both cases AC and DC is fixed, its position is determined by the genetic algorithm. For a DC network, the losses are divided into three categories: transmission losses (HV network), converters losses, and distribution losses (MV network). Q_{dc} are the reactive losses for the distribution network in DC case. Table 4 shows the comparison between transmission technologies for Borssele I & II for different transmission distances.

Between the distances 50 and 103 km, the HVAC technology presents more advantages than the HVDC regarding the LPC but the total DC losses remain less than the AC losses by a factor about 1/4. In fact, the DC transmission lines contain no reactive losses and the only losses are the resistive losses, which cause the reduction of the overall losses. From the distance 140 km, the HVDC is more efficient than the HVAC technology; it presents a lower LPC, and it is explained by the fact that for large transmission distances the total AC structure cost is greater than structure cost of wind farms in DC. The DC total losses are still lower than AC losses network for large transmission distances. Table 5 shows the detailed components costs in both cases of HVAC and HVDC at a distance 168 km.

Table 4 Comparison between HVAC and HVDC

Distance (km)	Losses HVAC MW MVA	Losses HVDC MW MVAR	LPC_{ac} (c€/kWh)	LPC_{dc} (c€/kWh)
50	$P_{ac} = 47.79$ $Q_{ac} = 170.80$	$P_{dc} = L_{transHV} + L_{conv} + L_{distrMV}$ $P_{dc} = 3.41 + 22.80 + 11.57 = 37.78$ $Q_{dc} = 110.27$	0.688	1.019
80	$P_{ac} = 63.450$ $Q_{ac} = 186.13$	$P_{dc} = 5.17 + 22.83 + 12.231 = 40.23$ $Q_{dc} = 111.34$	0.895	1.116
103	$P_{ac} = 75.535$ $Q_{ac} = 198.03$	$P_{dc} = 7.14 + 22.90 + 11.936 = 41.97$ $Q_{dc} = 111.39$	1.008	1.182
140	$P_{ac} = 96.260$ $Q_{ac} = 218.73$	$P_{dc} = 9.15 + 22.96 + 12.269 = 44.37$ $Q_{dc} = 112.15$	1.272	1.252
168	$P_{ac} = 109.98$ $Q_{ac} = 232.33$	$P_{dc} = 11 + 23.05 + 11.525 = 45.57$ $Q_{dc} = 112.68$	1.481	1.253
199	$P_{ac} = 126.26$ $Q_{ac} = 248.70$	$P_{dc} = 13.19 + 23.09 + 12.228 = 48.50$ $Q_{dc} = 112.89$	1.734	1.359

Table 5 Components costs for HVAC and HVDC cases

	HVAC		HVDC	
	M€	%	M€	%
MV cables	317.82	22.01	289.38	23.41
HV cables	998.79	69.16	270.55	21.88
Transformers	14.037	0.972	13.84	1.12
Platforms	99.97	6.92	363.49	29.40
MV switchgears	9.29	0.64	9.29	0.75
HV switchgears	3.67	0.25	1.22	0.099
Compensations	0.396	0.0274	–	–
Converters	–	–	288.25	23.32

According to Table 5, at a distance of 168 km, the cost of HV cables represents 69.16% of the total cost. However, the HVDC cables cost represents only 21.88% of the total cost. This cost evolves according to the transmission distance, which proves the increase of the LPC_{ac} compared to LPC_{dc} for large distances. The costs of converters and substations platforms in the DC case present the greatest costs, but it does not vary with the increase in transmission distance.

7 Conclusion

This research work highlights the comparison between two transmission technologies HVAC and HVDC. Investment costs and energy losses regarding different transmission distances are studied for an offshore wind farm topology Borssele I & II. HVDC has lower energy losses compared to HVAC, but AC network can be more efficient regarding LPC for distances lower than 103 km. As a result, imposing an optimization framework where needs and constraints are clarified is essential to find the best technology according to economical and energetic compromise. In future work, the maintenance cost (OPEX) will be integrated in the economic function for a better evaluation of offshore wind farm performances.

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