Techno-Economic Analysis of HVAC, HVDC and OFAC Offshore Wind Power Connections.

S. Hardy, K. Van Brusselen, S. Hendrix
CG Holdings Belgium NV - Systems Division
Mechelen, Belgium

Prof. D. Van Hertem, Dr H. Ergun
KU Leuven, Dept. Electr. Eng (ESAT)
Heverlee, Belgium

Abstract—This work performs an economic analysis of HVAC and HVDC transmission options for Offshore Wind Power Plants (OWPPs). The primary objective is to produce a range for each technology under which it is the most economic option. The economic model developed accounts for system losses and reliability. HVAC technological variations included are the use of a mid point compensation platform and Optimal Frequency AC (OFAC). The investigation found mid point compensation to be highly beneficial, significantly increasing the economic range of HVAC via smaller cable sizes and reduced Expected Energy Not Served (EENS). An opportunity for optimal offshore grid expansion requiring limited up front investment using mid point compensation is presented. The viable range of OFAC was found to be limited. Furthermore, a reduction in export cable size was found to frequently be economic and the use of 2 transformers over 1 for improved reliability; warranted.

Index Terms—Cost benefit analysis, offshore power plants, transmission systems, wind energy.

I. INTRODUCTION

In 2017, 3148 MW of new offshore wind capacity was added to the European grid. The average OWPP added was 493 MW at a distance of 41 km [1]. In 2013 these same statistics were 271 MW and 29 km respectively [2]. With a cumulative European offshore wind capacity expected to reach 25 GW by 2020 [1], the trend of larger OWPP further from shore is likely to continue making it essential to fully understand the applicability of the available transmission options.

As OWPP increase in size and move further from shore the economic technology for connection to shore changes. For small OWPP less than about 15 km from shore, Medium Voltage (MV) within the collection grid can be connected directly, avoiding the need for a costly Offshore Substation (OSS) [3]. As the transmission distance or power increases, transmission losses become unacceptably high and an OSS with an MV to High Voltage (HV) transformer is required. Underwater HVAC cables, however, suffer from high capacitance and therefore have a limited range [4]. Reactive compensation can increase the possible range but, eventually this investment exceeds that of using HVDC [5], [6]. Cost analyses of HVAC systems using compensation split between the OSS and shore have been studied extensively [7]–[10]. Another possibility to extend the range of HVAC is to include a intermediary compensation

platform. In this regard the literature is found to be lacking. An additional proposal for extending the range of AC systems is Low Frequency Alternating Current (LFAC) [11]. A commonly proposed LFAC system operates at 1/3 standard frequency, extending HVAC transmission by reducing cable capacitance and skin effect [11]. Building on this idea, OFAC has been suggested [12]. The economic feasibility of LFAC and OFAC has only been studied to a limited extent and requires a more thorough investigation [11], [13], [14].

In this paper the authors have expanded upon a model originally developed in [7] to quantize the full economic range of HVAC for offshore wind transmission by including both intermediary compensation and OFAC transmission. To the best of the authors knowledge no economic comparison including both these technologies has been performed to date. In the following section a detailed description of the developed economic model is presented. Any assumed values are summarized in table IV of Appendix A. Results are presented following the description of the model.

II. ECONOMIC MODEL

A. Wind Power Characteristics

The wind profile described in [7] with wind frequency distribution of the annual time series shown in Fig. 1 is used. A diversified profile is assumed to be more suitable for OWPP spread out over a geographical large area. A diversified input profile produces fewer variations in output and spends less time at the generating extremes of zero and 100 %. The profile has a load factor of 40 % and a load loss factor (δ) of 23 %.

Fig. 1. Wind Frequency Distributions

B. Cost Breakdown Methodology

The cost model is based on work by [7] using empirical data from commercial projects. The method breaks down the OWPP cost into component calculations of Capital Expenditures (CAPEXs) and Operating Expenditures (OPEXs).

CAPEX and OPEX are further divided into Terminal Costs (TCs) and Route Costs (RCs) as per fig. 2. TCs are distance independent quantities like a substation while RCs increase with distance from shore, the transmission cable is an example.

Fig. 2. Breakdown Of System Cost Model.

C. 50Hz HVAC

Fig. 3. Single line diagrams of HVAC transmission system.

1) *Terminal Capital Cost (TCC)*: Fig. 3 shows the single line diagram of the modeled HVAC transmission system. The TCC of an HVAC connected OWPP can be approximated by the sum of the Offshore Power plant and Platform Cost (OPPC) and the Onshore Plant Cost (OPC) (1). The OPPC is the sum of a fixed cost (FC) representing the foundation, float out and erection costs and a variable cost linearly dependent on the OWPP (S_T) rating [7]. Here, n_T and S_{ST} are the number and size of the transformers. f_{CT} and p_{CT} are the variable platform and plant costs respectively. dc is a cost factor for more than 1 transformer. The OPC is calculated using (3), developed for large transformers [15].

$$TCC = OPPC + OPC \quad (1)$$

$$OPPC_{hvac} = FC_{hvac} + [1 + dc \cdot (n_T - 2)] \cdot (f_{CT} + p_{CT}) \cdot n_T \cdot S_{ST} \quad (2)$$

$$OPC_{hvac} = 0.03327 \cdot S_T^{0.7513} \quad (3)$$

2) *Route Capital Cost (RCC)*: The RCCs can be approximated by the sum of the Compensation Cost (QC) and the Cable Cost (CBC) (4). QC (5) is the sum of the offshore (Q_{off}) and onshore (Q_{on}) compensation multiplied by their respective costs: (Q_{Coff}) and (Q_{Con}) [7]. (6) gives the total amount of compensation (Q) required to reach unity power factor (pf) as a function of frequency (f_n), cable capacitance (C_{qc}), length (l_c) and number of parallel cables (n_c) [13]. The cost per unit length (c_{cbl}) is found in [7]. Assuming a 50-50 split of onshore to offshore compensation the new line capacity (P_C) is then defined by (8) [13].

$$RCC = QC + CBC \quad (4)$$

$$QC = Q_{c_{off}} \cdot Q_{off} + Q_{c_{on}} \cdot Q_{on} \quad (5)$$

$$Q = V_n^2 \cdot 2\pi f_n C_{qc} \cdot l_c \cdot n_c \quad (6)$$

$$CBC = n_c \cdot c_{cbl} \cdot l_c \quad (7)$$

$$P_C = \sqrt{S_{cbl}^2 - Q_{on}^2} \quad (8)$$

3) *Terminal power Losses Cost (TLC)*: (9-11) define the offshore (TLC_{offt}) and onshore (TLC_{ont}) transformer losses. TLC is a cumulative function taken over the lifetime (T_{op}) of the OWPP [13]. Here, E_{op} is the cost of energy, V_n is nominal voltage, η is efficiency of a transformer, r_c the per unit resistance of the cable and δ is the load loss factor introduced in section II-A.

$$TLC = TLC_{offt} + TLC_{ont} \quad (9)$$

$$TLC_{offt} = S_T \cdot pf \cdot (1 - \eta_{offt}) \cdot T_{op} \cdot \delta \cdot E_{op} \quad (10)$$

$$TLC_{ont} = [S_T \cdot pf - \left(\frac{S_T \cdot pf \cdot \eta_{offt}}{n_c \cdot V_n} \right)^2 \cdot r_c \cdot l_c \cdot n_c] \cdot (1 - \eta_{ont}) \cdot T_{op} \cdot \delta \cdot E_{op} \quad (11)$$

4) *Route power Losses Cost (RLC)*: are the costs associated with I^2R losses of the transmission cable. Like the TLC, the RLC is cumulative over the lifetime of the OWPP. The RLC is defined as

$$RLC_{hvac} = \left(\frac{S_T \cdot pf \cdot \eta_{offt}}{n_c \cdot V_n} \right)^2 \cdot r_c \cdot l_c \cdot n_c \cdot T_{op} \cdot \delta \cdot E_{op} \quad (12)$$

D. HVDC

1) *TCC*: TCCs of an HVDC connected OWPP is calculated similarly to HVAC as the sum of OPPC and OPC (1). Converters are assumed to be of type Voltage Source Converter (VSC) with variable cost c_{con} . Cost data from [16] is used to estimate OPC (14).

$$OPPC_{hvd} = FC_{hvd} + [1 + dc \cdot (n_T - 2)] \cdot c_{con} \cdot n_{con} \cdot S_{con} \quad (13)$$

$$OPC_{hvd} = 0.113 \cdot S_T \quad (14)$$

2) *RCC*: As HVDC cables are not subject to reactive power flow due to cable capacitance [17], RCC is composed simply of (CBC) given by (7).

3) *TLC*: (9-11) with appropriate efficiencies substituted and $pf = 1$ are used for HVDC. The onshore inverter efficiency η_{oni} and the offshore rectifier efficiency η_{offr} are substituted for the onshore and offshore transformer efficiencies; η_{ont} and η_{offt} respectively.

4) *RLC*: is found by modifying (12) for a DC system to get (15). Here, k is the cable loss factor and is set to 0.5 for HVDC cables according to [13].

$$RLC_{hvd} = 2 \cdot \left(\frac{S_T \cdot \eta_{offr}}{n_c \cdot V_n} \right)^2 \cdot r_c \cdot l_c \cdot n_c \cdot T_{op} \cdot \delta \cdot E_{op} \cdot k \quad (15)$$

5) *Cost Range of HVDC*: A minimum and maximum cost range for HVDC has been calculated (fig. 4 A,B). The minimum range assumes the entire transmission length is HVDC and no additional HVAC components are required. This would be the case if the wind farm collector grid were connected directly to the HVDC platform. The maximum estimate includes an HVAC collection platform including a transformer and 5 km of HVAC cable feeding into the HVDC converter station. Throughout this paper, unless explicitly stated the minimum estimate of HVDC is used for comparison.

Fig. 4. Single line diagrams of (A) Minimum cost of HVDC. (B) Maximum cost HVDC. (C) OFAC

E. OFAC

1) *TCC*: The single line diagram of the modeled OFAC system is shown in fig. 4C. The TCC of an OFAC system is modeled similarly to a HVAC and HVDC given by (1). As no commercial OFAC OWPP projects exist, however, some further modeling assumptions are required.

The components most affected by a drop in frequency are transformers and reactors. Magnetic flux density does not change significantly with altering frequency, therefore to maintain the desired voltage, the number of turns or the area of the core or both must be changed an equal but opposite amount [18]. This effects the size and cost of the OSS. To account for this, cost factor Cf_{xfm} is added to (3) to obtain

$$OPPC_{ofac} = FC_{ofac} + [1 + dc \cdot (n_T - 2)] \cdot Cf_{xfm} \cdot (fc_T + pc_T) \cdot n_T \cdot S_{ST} \quad (16)$$

In order to size Cf_{xfm} we turn to studies estimating the increase in size required for 1/3 frequency transformers. [18] showed that the overall increase in mass of the transformer could be limited to 77%. [19] however, recommends that a minimum 100% increase be anticipated. To be conservative a factor of 100% is assumed. Extending this assumption for all frequencies, the relationship (17) was developed.

$$Cf_{xfm} = (\frac{50}{f_{opt}} + 1)/2, \quad f > 0 \quad (17)$$

The OPC is primarily due to the AC/AC converter. According to [13], the number of active switches and reactive components for AC/AC converters is greater than for DC/DC therefore an AC/AC converter station would at best be equal in cost to a Line Commutated Converter (LCC) HVDC station

of similar size. Accordingly, the following relation developed by [20] for costing LCC is used:

$$OPC_{ofac} = 0.08 \cdot S_T. \quad (18)$$

2) *RCC*: RCC is modeled using (4) through (8). As above, (5) is modified for increased reactors size resulting in:

$$QC = Cf_{xfm} \cdot Qc_{off} \cdot Q_{off} + Qc_{on} \cdot Q_{on}. \quad (19)$$

3) *TLC*: (9) through (12) with appropriate efficiency substitutions are used for OFAC. The offshore transformer efficiency is assumed to be the same as HVAC, but onshore converter efficiency η_{acac} is substituted in place of η_{ont} .

F. Reliability

In addition to costs described above, system reliability is considered in terms of Corrective Maintenance (CM) and EENS. Total cost, including reliability is given by

$$COST_{wr} = CAPEX + OPEX + CM + EENS. \quad (20)$$

1) *CM*: is considered post fault, meaning it is the cost of replacement or repair of faulty equipment. Preventative maintenance is not considered within the scope. CM is calculated from the Mean Time To Repairs (MTTRs), Failure Rates (FRs) and Mean Cost per Repairs (MCs) summarized in table I and is given by (21).

TABLE I
RELIABILITY PARAMETERS [7]

Equipment	FR [1/yr]	MTTR [months]	MC [M€]
Transformers	0.03	2(PCC) / 6(OSS)	2.75
Converters	0.12	1	0.56
Cables	0.08/100km	2	0.56

$$CM = \left[\frac{n_t \cdot MC_t}{\frac{1}{FR_t} + \frac{MTTR_t}{T}} + \frac{n_c \cdot MC_c}{\frac{1}{FR_c} + \frac{MTTR_c}{T}} + \frac{n_{dc} \cdot MC_{dc}}{\frac{1}{FR_{dc}} + \frac{MTTR_{dc}}{T}} \right] \cdot CF \quad (21)$$

2) *EENS*: EENS is energy which must be curtailed in order to not exceed system capacity or load demand. A system capacity limit may be reached due to intentional under sizing of equipment or due to component failure. The calculation of EENS is as follows: If the per unit constrained capacity of system configuration i ; $S_{cons,i}$, has a probability of occurring, $P_{cons,i}$, then $EENS_i$ is given by

$$EENS_i = A_{cons,i} \cdot P_{cons,i} \cdot S_{pcc}. \quad (22)$$

Where $A_{cons,i}$ is the area under the input profile curve and above the line $y=S_{cons,i}$ of fig 5. The EENS of the entire system is then the sum of all $EENS_i$ over n possible network configurations. A Capacity Outage Probability Table (COPT) is used when calculating the capacities and probabilities of the n network configurations and is constructed as follows.

Fig. 5. Wind Duration Profiles

3) *COPT*: The creation of a *COPT* is illustrated by the following example. If a binary state piece of equipment i has capacity; C_i , $MTTR_i$ and FR_i , then the availability of the system, A_i , is given by:

$$A_i = \frac{1}{1 + FR_i \cdot \frac{MTTR_i \cdot 30 \cdot 24}{8760}}, \quad (23)$$

and the $COPT_i$ is constructed as shown in table II. The overall system *COPT* is achieved through the convolution of all individual *COPT*s by applying equations (24-25) for series and shunt components. Finally, rows with common capacities are combined through the summation of probabilities.

TABLE II
EXAMPLE COPT

State	Capacity ($S_{cons,i}$)	Probability ($P_{cons,i}$)
1	C_i	A_i
0	0	$1-A_i$

$$C_k =: \begin{cases} C_i + C_j & \text{Series} \\ \min(C_i, C_j) & \text{Parallel} \end{cases} \quad (24)$$

$$P_k = P_i \cdot P_j \quad (25)$$

G. Equipment Sizing

The cable characteristics and cost data of cables for HVAC and HVDC systems are those suggested in [7]. Due to reduced skin effect, the capacity of OFAC cables can not be obtained directly from data sheets. Therefore, cable capacity calculations are done according to IEC standard 60287 [21] with data sourced from [22]. Cost of OFAC cable is assumed to be the same as an equivalently sized 50 Hz cable. 50 Hz transformer sizes are restricted to 160 MVA, 250 MVA, 315 MVA, 500 MVA, 630 MVA and 800 MVA while a continuum of sizes up to 2 GW is assumed available for HVDC converters.

H. Intermediate Platform

The effect of an intermediary compensation platform has been investigated. The single line diagram of such a system is shown in fig 6. The foundation, float out and erection costs irrelevant of OWPP rating are modeled as a fixed cost of 10 M€. This value corresponds to the low end cost for a OSS recommended in [9]. The transmission cable is then split in two and compensation placed on the main OSS, the intermediate platform and onshore. The optimal distance from shore for the compensation platform is found by iterating through the entire distance to shore at 5 km spacings.

Fig. 6. Single line diagram of HVAC transmission system with intermediary compensation platform

III. RESULTS

A. OFAC

Examining fig. 7 it is apparent that gradually reducing the frequency creates a quasi linear cost function over the entire range while the cost of 50 Hz HVAC becomes exponential after about 150 km. At 600 MW, a 53 km wide cost effective window is created between 81 km and 134 km. There is obvious improvement over the 16.7 Hz LFAC which is economic only between 96 km and 110 km. This result is supported by the bottom of fig. 7 where it can be seen that a frequency of 16.7 Hz is rarely optimal, best only between 280 km and 300 km. As the capacity of the OWPP increases the viable range shrinks. An analysis up to 1.5 GW showed that beyond 800 MW OFAC has negligible applicability. Work by [13] on 16.7 Hz LFAC supports this conclusion.

Fig. 7. 600 MW HVAC, HVDC, OFAC cost comparison.

B. Cable Selection

An undersized HVAC export cable can be economic. This is due to the limited step sizes of HVAC cable and is best understood by examining in detail several HVAC transmission options. Table III summarizes the cost breakdown of 5 options for an 800 MW OWPP, located 90 km offshore. Option 1 uses 2-1000 mm² export cables with a total capacity of 678 MW, significantly less than the 800 MW OWPP capacity. Still, the lifetime cost of this configuration is less than that of upgrading to 3-500 mm² cables as in option 2. High EENS in option 1 results from power curtailment above 678 MW. However, both lower RLC and RCC more than compensate. Option 3, increases capacity through increased system voltage. A drop in EENS is visible as well as a reduction in RLC. But these savings cannot be justified as the extra cost of RCC results in a net increase.

TABLE III
COMPARATIVE COST BREAKDOWN OF 800 MW HVAC TRANSMISSION
OPTIONS AT 90 KM.

Voltage (transformer)	Cable (Capacity)	Total Cost [M€]	OPPC (OPC) [M€]	RCC (QC) [M€]	RLC (TLC) [M€]	EENS (CM) [M€]
220 kV (2-500 MW)	2-1000 mm ² (678 MW)	339.4	56 (4)	180 (10.9)	27 (16.1)	41.7 (3.7)
220 kV (2-500 MW)	3-500 mm ² (789 MW)	357.2	56 (4)	220 (12.5)	32.6 (16.1)	12.1 (3.9)
400 kV (2-500 MW)	2-800 mm ² (1052 MW)	378.8	56 (4)	252 (26)	9.5 (16.2)	12.1 (3.9)
220 kV (1-800 MW)	2-1000 mm ² (678 MW)	356.2	37.9 (4)	180 (10.9)	27 (16.1)	78.4 (2)
*220 kV (2-500 MW)	2-1000 mm ² (708 MW)	337	66 (4)	180 (12.2)	27.1 (16.2)	27.7 (3.7)

*Intermediary compensation platform placed at 45 km.

C. Transformer Selection

Transformers should be sized based on cable capacity not on system capacity. This may result in undersized transformers. The extra investment required for at least 2 parallel transformers is justified by the gain in reliability. Comparing options 1 and 4 of table III the effect on system cost is apparent. Using a single 800 MW transformer reduces OPPC but this is more than offset by a rise in EENS. The conclusions related to cable and transformer size are supported by work performed in [7].

D. Intermediate Compensation Platform

The use of a compensation platform can be beneficial. Fig. 8 summarizes the cost effective regions of each technology. The upper and lower estimates for HVDC are included creating a boundary region where only the lower bound of HVDC is economic (grey). The true boundary between HVAC and HVDC systems likely lies somewhere inside this region. It is clear that a compensation platform can increase the economic range of HVAC (red). The comparison of component costs shown in fig. 9 demonstrates how an intermediate compensation platform linearizes the HVAC cost function. The economic range created by linearization is shown in the top of fig. 10. On the bottom of fig. 10 the optimal position of the compensation platform is displayed. The cost difference between onshore and offshore compensation pushes the mean optimal placement of the platform slightly past halfway out to sea.

A compensation platform is of benefit in 2 ways. First is when export cable size can be reduced. This situation can be seen in fig. 11. At 1250 MW and 130 km the savings are dramatic. The compensation platform allows for the use of 2-400 kV-800 mm² cables instead of 4-220 kV-630 mm² cables. This results in a savings of over 100 M€. Second, by comparing the first and final option for transmission at 800 MW in table III a more subtle benefit is observable. Note that the cable size is 2-220 kV-10000 mm² for both options yet option 5 is more economic. This occurs as the compensation platform increases the export capacity of the cable resulting in a reduction of EENS. The savings in EENS more than compensate for the extra cost of the platform construction and extra compensation.

Fig. 8. Low Cost Regions of HVAC and HVDC systems.

Fig. 9. Cost Breakdown at 650 MW.

E. Offshore Grid Expansion

A possible advantage of using compensation platforms is the ability to gradually expand the offshore grid in an optimal manner without excessive up front cost as would be required with an HVDC connection. Fig. 11 demonstrates a possible expansion scenario. At 600 MW and 130 km the cheapest option uses 1-400 kV 800 mm² cable with compensation 65 km from shore. To increase the capacity to 1250 MW an additional 400 kV 800 mm² cable can be added in parallel. Expanding the offshore grid in this manner limits the risk of investing in infrastructure based on projected future expansion while still achieving a system with the lowest cost per watt.

A further possibility for cost reduction may exist if existing Offshore structures can be converted to act in addition as compensation platforms. For example, existing OSSs off the coast of Belgium, including Elia's Modular Offshore Grid

Fig. 10. Crossing points of cost functions at 650 MW (Top). Position of compensation platform for (Bottom).

(MOG), range from about 30 km to 60 km out to sea [23], ideally located to act as "stepping stones" to reach wind resources further offshore.

Fig. 11. Cost per watt at 130 km offshore.

IV. CONCLUSIONS

An economic comparison of HVAC options including OFAC and mid point compensation has been compared to HVDC transmission. A range of viable economic regions for each technology has been estimated. The study of OFAC produced a small viable economic window at medium power levels, however, this viable region disappeared as power levels increased. A mid point compensation platform was found to have a large range of applicability. A compensation platform was shown to be useful when the export cable size can be reduced and in the situation where cable size remains constant but increased capacity reduces EENS. Additionally the study found that a reduction in the HVAC export cable is often economic. Furthermore, the increased reliability of two partially sized transformers versus one full sized was found to always be worth while. Further investigation into the optimal undersizing of cables and transformers is needed as well as an investigation into what effects this may have on equipment life expectancy.

APPENDIX A

TABLE IV
MODELING ASSUMPTIONS

Variable	Definition	Assumed Value
FC_{hvac}	Fixed cost of HVAC transformer platform	5.6 M€
FC_{hvdc}	Fixed cost of offshore HVDC platform	28 M€
FC_{ofac}	Fixed cost of offshore OFAC station platform	5.6 M€
fc_T	Variable cost of HVAC transformer platform	0.0224 €/VA
pc_T	Variable Cost of HVAC offshore plant cost	0.028 €/VA
c_{con}	Variable cost of offshore HVDC converter	0.123 €/VA
Qc_{off}	Unit cost of offshore compensation	0.028 €
Qc_{on}	Unit cost of onshore compensation	0.0168 €/VAR
E_{op}	Cost of energy	56 €/MWh
T_{op}	Total operational hours	365x24x15 hrs
δ	Load Loss Factor	23 %
dc	Cost factor for >1 OSS transformer or converter	0.2
pf	Power factor	1
CF	Capitalization Factor	10
η_{offt}, η_{ont}	Efficiency of the offshore/onshore transformer	99.4 %
η_{oni}	Efficiency of the onshore inverter station	98.19 %
η_{offr}	Efficiency of the offshore rectifier station	98.28 %
η_{acac}	Onshore AC/AC converter efficiency	99.12 %

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