Cost Analysis and Comparison of HVAC, LFAC and HVDC for Offshore Wind Power Connection

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Abstract

Low frequency AC (LFAC) has been proposed as a means to avoid some of the large converter station costs of high voltage DC (HVDC) while delivering some of the benefits in terms of better line or cable utilization and its technical feasibility has been established. It is said to offer a lower costs than HVDC or conventional high voltage AC (HVAC) for a range of intermediate distances, with HVDC becoming cheaper over long distances. However, the basis for identifying the distance range and extent of cost saving has not been established. Here, cost estimate methodologies are extended for LFAC. A difficulty is the absence of commercial schemes that can provide practical examples of costs. In this paper, costs are broken down into constituent terms and estimates are made from the most similar equipment from other schemes. The capacity limits and power losses associated with subsea cables are analyzed for low frequency cases. For a given power transfer and for each distance, a choice of operating voltage, cable size and number of parallel circuits is made in order to find the lowest route cost. This yields cost as a function of distance that is a non-linear and discontinuous function. The cost curves for LFAC are compared with HVDC and HVAC options. The results for current cost estimates show that LFAC has a range of route length over which it is the lowest cost option and but this range narrows and eventually ceases to exist for higher power transfer ratings.

1 Introduction

Wind energy is regarded as one of the most important renewable sources around the world [1]-[2]. In recent years, enormous effort has been invested to progress the technologies to connect offshore wind power because of the better wind energy potential [3]-[4]. It is well known that HVAC and HVDC systems, illustrated in **Fig. 1** and **Fig. 2**, are the commercialized solutions for high power transmission connections to generators in offshore areas and they compete against each other on cost [5]-[7]. The overall cost of HVAC and HVDC systems can be separated into the terminal cost and route cost. HVAC has the advantage of relatively inexpensive terminal cost whereas HVDC has expensive power converter stations. On the other hand, the route cost in HVAC rises much more sharply with distance than that in HVDC because of the different transmission capability limits. Over short distances HVAC is favored for its lower terminal costs but beyond some threshold distance, the advantage of lower route costs favors HVDC. The

cross-over point of HVAC and HVDC costs is reported to be in the region of 60 km for subsea cable transmission systems [8][9].
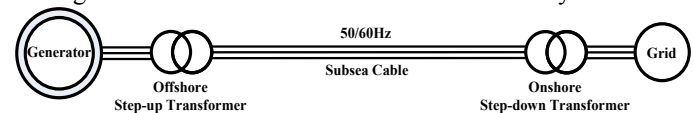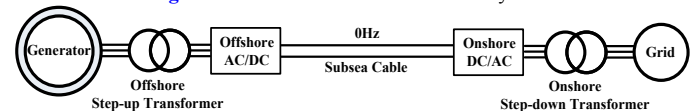

Fig. 1 Structure of HVAC transmission system
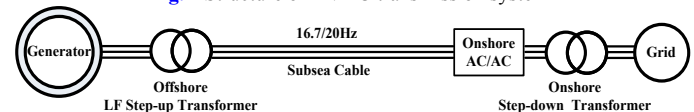

Fig. 2 Structure of HVDC transmission system

Fig. 3 Structure of LFAC transmission system

It has been noted that low frequency AC (LFAC), also called fractional frequency transmission system (FFTS), suffers less from cable shunt susceptance effects than standard AC and so makes more cost effective use of the cable. The transmission frequency in LFAC is usually set as 16.7Hz/20Hz, one third of the standard frequency in HVAC (50Hz/60Hz) and above HVDC (0Hz). Further, LFAC requires only one power converter for frequency conversion if being used to connect a generator that is isolated from the main system, **Fig. 3**. The technical feasibility of LFAC has been comprehensively analyzed [10]-[15] and a laboratory prototype of an LFAC system has also been successfully demonstrated [16][17].

It is postulated that for some range of distances LFAC should be lower cost than either HVAC or HVDC[12][13] because one power converter at one end will give terminal costs higher than HVAC but lower than HVDC and route costs in LFAC will be rise more steeply than HVDC but shallower than HVAC. **Fig. 4** illustrates cost against distance for LFAC for three cases, all of which use terminal costs and unit distance costs between those of HVAC and HVDC. In cases 1 and 2, the cost of LFAC cross the cost of HVAC before crossing the cost of HVDC and so LFAC has a range for which it is cheapest. However, in case 3, the cost of LFAC crosses the cost of HVDC first and there is no distance for which it is the preferred choice. So, knowing that the terminal and unit distance costs of LFAC are between those of HVAC and HVDC is not sufficient to establish that it is ever the lowest cost option, let alone establishing the distance range.

Cost analysis for LFAC has received some attention [12][13][18]-[20] but not to the degree need. Some cost analysis and comparison for offshore subsea cable transmission systems have been presented [12][19] based on the simple and not well-supported assumption that both the terminal cost and route cost per unit distance of LFAC are around halfway between the costs of HVAC and HVDC. Under that assumption, the costs of LFAC follow case 2 in **Fig. 4** and based on typical costs of

HVAC and HVDC, the cost-effective range for cable-based LFAC in an offshore wind application would be about 30km-150km. However, this simple approximation should be questioned since there are reasons to believe that the offshore platform for an LF transformer and an onshore AC/AC HV power converter would be greater than this mid-point. Meanwhile, although a cable operated at 16.7Hz requires less reactive current than at 50 Hz, the AC voltage waveform is subject to a peak/effective ratio underutilization compared to DC and so route costs are unlikely to be the midpoint either. Further, a simple constant cost per unit distance is known to be only an approximation of cost that is closer to being quadratic.
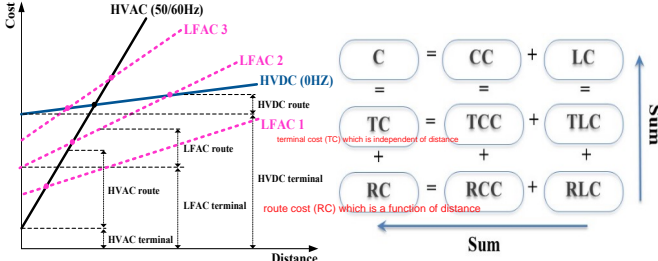

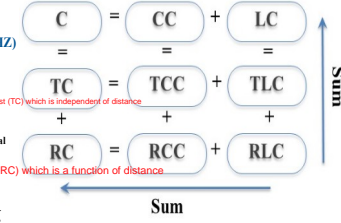**Fig. 4** Three basic possibilities for LFAC cost   **Fig. 5** Relationships between different kinds of costs

This paper sets out to analyze the costs of LFAC in enough detail to identify the cross-over points for its costs with HVAC and HVDC and to identify the cost-effective range of LFAC from the best available data. The cost estimation algorithm compares, for each distance, different choices of operating voltage and choices of numbers of parallel cables in order to meet the specified power transfer at minimum cost for that technology. This yields costs that are a non-linear and discontinuous function of distance. In Section 2, the major factors in cost analysis are outlined in general, and the cost-effective range comparison for cable-based offshore wind farms (COWF) connection is discussed in detail in Section 3, which is the main body of this paper. The conclusions are drawn in Section 4, and future work is illustrated in the last Section.

2 Major Factors in Cost Analysis

A comprehensive cost analysis for transmission routes is complex to conduct in detail in analytical form. It needs to take many factors into consideration, such as the capital cost, maintenance cost, power losses, equipment reliability and so on. For a new approach like LFAC, this analysis is more difficult to complete because there are no commercial LFAC projects that have established design limits and yielded cost data. To make this analysis feasible, some minor factors need be neglected and sources of cost data from comparable individual equipment items should be sought.

For HVAC and HVDC systems, several cost estimation methods have been reported [21]-[25] that can serve as a starting point for this analysis. Cost data suitable for use in these methods have been reported for some commercial transmission projects [8][9][26]-[28]. It is common to separate out the capital cost (CC) and the capitalized cost of power losses (LC) as the major factors within the overall system cost. **Table I** lists the costs of each of HVAC, HVDC and LFAC under the headings of CC and LC. These items will be analyzed in detail in next Sections.

Table I Main capital cost and power losses cost in HVAC, LFAC and HVDC

	CC (capital cost (CC))	LC (capitalized cost of power losses (LC))
HVAC	Offshore step-up transformer plant and platform (compound). Cables and compensation. Onshore step-down transformer plant and compound.	Offshore transformer losses. Cables losses. Onshore transformer losses.
LFAC	Offshore LF step-up transformer plant and platform (compound). Cables and compensation. Onshore AC/AC converter station plant including valves, transformers and filters.	Offshore LF transformer losses Cables losses. Onshore AC/AC converter losses.
HVDC	Offshore converter station plant and platform (compound) including valves, transformers and filters. Cables. Onshore converter station plant including valves, transformers and filters.	Offshore AC/DC converter losses. Cables losses. Onshore DC/AC converter losses.

3 Cost-effective Range Analysis

For subsea cable based offshore wind farms (COWF) connection, voltage-sourced converter HVDC (VSC-HVDC) is chosen as the DC option in this paper for analysis and comparison.

The overall cost *(C)* of a transmission system can be separated into *CC* and *LC* but also into the terminal cost (*TC*) which is independent of distance and route cost (*RC*) which is a function of distance. **Fig. 5** illustrates this decomposition and a further decomposition into terminal capital cost (*TCC*), terminal losses cost (*TLC*), route capital cost (*RCC*) and route power losses cost (*RLC*). Interpreting **Table I** costs for COWF in terms of **Fig. 5** yields that the *TCC* consists of the offshore platform and plant cost (*OPPC*) and onshore plant cost (*OPC*) and the *RCC* consists of the cable cost (*CBC*) and compensation cost (*QC*). The cost analysis of each part in **Fig. 5** will be introduced in the following parts respectively.

3.1 Cost Analysis in HVAC and VSC-HVDC

The estimations for *OPPC* and *OPC*, **(1)-(4)**, follow the empirical formulas in commercial projects report [26], and the relevant variable description and assumptions are summarized in Appendix A.1.

$$OPPC_{HVAC} = FC_{HVAC} + [1 + dc(n_T - 2)] \cdot (fc_T + pc_T) \cdot n_T \cdot S_{ST} = 5 + 0.045 S_T \quad (1)$$

$$OPC_{HVAC} = 0.02621 S_T^{0.7513} \quad (2)$$

$$OPPC_{HVDC} = FC_{HVDC} + [1 + dc(n_C - 2)] \cdot c_C \cdot n_C \cdot S_{SC} = 25 + 0.11 S_T \quad (3)$$

$$OPC_{HVDC} = 0.08148 S_T \quad (4)$$

To calculate the cable cost and compensation cost in HVAC, cable transmission capability needs be analyzed first. In subsea cable transmission, parallel capacitive susceptance is the major parameter limiting active power transmission due to the close proximity of sea water. The reactive power, Q_C, produced by capacitive charging current, can be expressed as

$$Q_C = V_n^2 \cdot 2\pi f_n C \cdot l_c \quad (5)$$

To provide more space for active power current and therefore expand cable transmission capability, an economic option is to distribute compensation power evenly at both ends of cables. With this configuration, cable transmission capability, P_C, could be given by **(6)**, and the compensation cost in HVAC, QC_{HVAC}, can be indicated as **(7)**.

$$P_C = \sqrt{S_C^2 - Q_{off}^2} = \sqrt{S_C^2 - (\frac{Q_C}{2})^2} = \sqrt{(\sqrt{3} \cdot V_n I_{ssn})^2 - (\frac{1}{2} \cdot V_n^2 \cdot 2\pi f_n C \cdot l_c)^2} \quad \text{(6)}$$

$$QC_{HVAC} = Q_{off} \cdot OFC + Q_{on} \cdot ONC = 0.02 \cdot V_n^2 \cdot 2\pi f_n C \cdot l_c \quad \text{(7)}$$

The relevant parameters of some common cables in HVAC are listed in **Appendix Table I**, and the cable cost in HVAC, CBC_{HVAC}, can be calculated by

$$CBC_{HVAC} = t_c \cdot l_c \cdot nc_c \quad \text{(8)}$$

The cables cost in VSC-HVDC option have substantial advantages over AC solutions (HVAC and LFAC), since DC voltage waveform is not subject to a peak/effective ratio underutilization. For the same cable physical conditions, the transmission capability ratio of DC cables to AC cables can be given by

$$\frac{P_{max-DC}}{P_{max-AC}} = \frac{2 \cdot V_{ndc} I_{ndc}}{3 \cdot V_{nac} I_{nac} \cdot pf} = \frac{2\sqrt{2} \cdot V_{nac} I_{nac}}{3 \cdot V_{nac} I_{nac} \cdot pf} = \frac{2\sqrt{2}}{3} \approx 1 \quad \text{(9)}$$

In **(9)**, it can be seen that, for a given power transfer, DC option need only two polar cables while AC solutions need three. The cable cost in VSC-HVDC would be much smaller than that in AC options. If the reactive power and skin effect are taken into calculation, this advantage could be more distinct. The specific parameters of some common HVDC cables are listed in **Appendix Table II**, and **(8)** can be also used to calculate the cable cost in VSC-HVDC system.

With **(1)-(4) (7)** and **(8)**, the main capital cost of HVAC and VSC-HVDC can be expressed as **(10)** and **(11)**

$$CC_{HVAC} = OPPC_{HVAC} + OPC_{HVAC} + QC_{HVAC} + CBC_{HVAC}$$
$$= 5 + 0.045S_T + 0.02621S_T^{0.7513} + 0.02 \cdot V_n^2 \cdot 2\pi f_n C \cdot l_c + t_c \cdot l_c \cdot nc_c \quad \text{(10)}$$

$$CC_{HVDC} = OPPC_{HVDC} + OPC_{HVDC} + CBC_{HVDC}$$
$$= 25 + 0.11S_T + 0.08148S_T + t_c \cdot l_c \cdot nc_c \quad \text{(11)}$$

The power losses cost (LC) in transmission system is an accumulative cost related to operation time, T_{op}, and energy price, E_{op}. The terminal power losses cost, TLC_{HVAC}, and route power losses cost, RLC_{HVAC}, in HVAC are given by **(12)-(14)** [26]

$$TLC_{offHVAC} = S_T \cdot pf \cdot (1 - \eta_{offt}) \cdot T_{op} \cdot \delta \cdot E_{op} \quad \text{(12)}$$

$$RLC_{HVAC} = 3\left(\frac{S_T \cdot pf \cdot \eta_{offt}}{nc_c \cdot \sqrt{3}V_n}\right)^2 r_c \cdot l_c \cdot nc_c \cdot T_{op} \cdot \delta \cdot E_{op} \quad \text{(13)}$$

$$TLC_{onHVAC} = [S_T \cdot pf \cdot \eta_{offt} - 3\left(\frac{S_T \cdot pf \cdot \eta_{offt}}{nc_c \cdot \sqrt{3}V_n}\right)^2 r_c \cdot l_c \cdot nc_c] \cdot (1 - \eta_{ont}) \cdot T_{op} \cdot \delta \cdot E_{op} \quad \text{(14)}$$

Under the value assumptions in Appendix A.1, the power losses cost of HVAC, LC_{HVAC}, can be simplified as **(15)**. And with some adjustments for efficiency parameters, the power losses cost of VSC-HVDC are given by **(16).**

$$LC_{HVAC} = TLC_{offHVAC} + RLC_{HVAC} + TLC_{onHVAC} = 0.00911S_T + 1.51767 \cdot$$
$$\left(\frac{0.994S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c + 0.00911 \cdot [0.994S_T - \left(\frac{0.994S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c] \quad \text{(15)}$$

$$LC_{HVDC} = TLC_{offHVAC} + RLC_{HVAC} + TLC_{onHVAC} = 0.02610S_T + 3.03534 \cdot$$
$$\left(\frac{0.9828S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c + 0.02747 \cdot [0.9828S_T - \left(\frac{0.9828S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c] \quad \text{(16)}$$

The overall cost of HVAC and VSC-HVDC can be obtained as **(17)** and **(18)**

$$C_{HVAC} = CC_{HVAC} + LC_{HVAC} = 5 + 0.045S_T + 0.02621S_T^{0.7513} + t_c \cdot l_c \cdot nc_c$$

$$+0.02 \cdot V_n^2 \cdot 2\pi f_n C \cdot l_c + 0.00911S_T + 1.51767 \cdot \left(\frac{0.994S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c$$

$$+0.00911 \cdot [0.994S_T - \left(\frac{0.994S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c] \quad \text{(17)}$$

$$C_{HVDC} = 25 + 0.11S_T + 0.08148S_T + t_c \cdot l_c \cdot nc_c + 0.02610S_T + 3.03534 \cdot$$
$$\left(\frac{0.9828S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c + 0.02747 \cdot [0.9828S_T - \left(\frac{0.9828S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c] \quad \text{(18)}$$

3.2 Cost Analysis in LFAC

Since there is still no commercial LFAC transmission to date, the offshore platform and plant cost, $OPPC_{LFAC}$, onshore plant cost, OPC_{LFAC}, power losses cost, LC_{LFAC}, and cable parameters in LFAC need be made from the most similar equipment from HVAC and VSC-HVDC actual projects[21][24][26].

First of all, the LF step-up transformers, theoretically, should be three times larger of that in HVAC. But considering that the performance of many operation factors, such as heat dissipation, voltage isolation, system reliability and so on, could be improved with equipment volume increasing, the practical weight, volume and cost of this LF transformer could be decreased to about twice of the standard transformers at best condition[12][18][20][29], where the platform fixed cost keeps the same with HVAC situation, and the platform and plant variable costs increase to twice. Thus, the offshore platform and plant cost in LFAC, $OPPC_{LFAC}$, can be estimated by

$$OPPC_{LFAC} = FC_{LFAC} + [1 + dc(n_T - 2)] \cdot (2fc_T + 2pc_T) \cdot n_T \cdot S_{ST} = 5 + 0.09S_T \quad \text{(19)}$$

Secondly, the topologies of onshore AC/AC converter station in LFAC could have several options, such as clycloconverter, back to back Modular Multilevel Converter (MMC), matrix converter and so on[13][30]-[33], but all of these topologies need more active switches and reactive components than their one DC/AC counterpart[13][33]. Thus, the lowest LFAC onshore plant cost and its power losses cost, would be not less than a LCC-HVDC onshore option. Its capital cost is given by **(20)**[21]

$$OPC_{LFAC} \geq OPC_{LCC-HVDC} = 0.05926S_T \quad \text{(20)}$$

Further, according to **(5)**, it can be seen that the reactive power produced by charging current is proportional to transmission frequency. As a result, the required offshore and onshore compensation power in LFAC will be theoretically one third of that in HVAC, and **(7)** can be still used for the compensation cost calculation in LFAC. Thanks to the one third charging current and lower skin effect, the cables in LFAC transmission could have stronger transmission capability than that in HVAC. The unit price of cable in LFAC is assumed to be same with HVAC. Based on the simulation and experimental data[12][16][18], the electrical parameters of some common cables in LFAC are presented in **Appendix Table III**, and **(8)** can also be used to estimate the cable cost in LFAC.

As for transformer power losses cost, despite the fact that the volume of LF transformer would be at least two times larger than standard one, the core losses per unit could be reduced thanks to the one third frequency. Based on the analysis in **[34]**, the efficiency of LF transformer would be very close to standard transformer. Thus, the power losses cost of LFAC, LC_{LFAC}, can be simplified as **(21)** with some efficient assumptions in Appendix A.1.

$$LC_{LFAC} = 0.00911S_T + 1.51767 \cdot \left(\frac{0.994S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c + 0.01331 \cdot$$

$$[0.994S_T - \left(\frac{0.994S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c] \tag{21}$$

Combining **(7) (8)** and **(19)-(21)**, the overall cost of LFAC, C_{LFAC}, can be written as **(22)**

$$C_{LFAC} = 25 + 0.09S_T + 0.05926S_T + 0.02 \cdot V_n^2 \cdot 2\pi f_n C \cdot l_c + t_c \cdot l_c \cdot nc_c$$

$$+0.00911S_T + 1.51767 \cdot \left(\frac{0.994S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c + 0.01331 \cdot [0.994S_T -$$

$$\left(\frac{0.994S_T}{nc_c \cdot V_n}\right)^2 r_c \cdot l_c \cdot nc_c] \tag{22}$$

3.3 Case Study for Lower Power Rating

According to **(6),** the cable transmission capability in AC systems would slump nonlinearly with transmission distance increasing. With the parameters in **Appendix Table I** and **Table III**, **Fig. 6** and **Fig. 7** are sketched to show the detailed transmission capability of some common cables in HVAC and LFAC. Firstly, it is easy to see that LFAC has a clear advantage over HVAC due to the one third transmission frequency and lower skin effect. More importantly, it can be found that, for AC systems, as long as the required active transmission power is set, different transmission distance requirements could result in different optimal cable choices in order to meet the specified power transfer at minimum cost. As for VSC-HVDC, because DC cables would not suffer from the charging current, one unitary cable choice could satisfy all distance analysis.
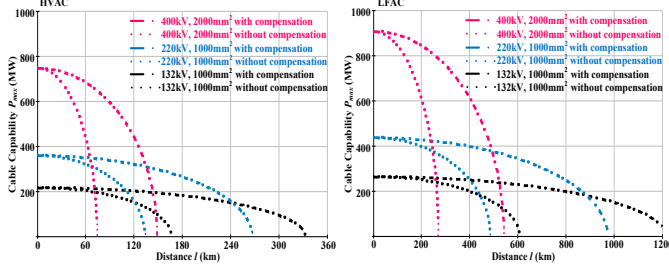

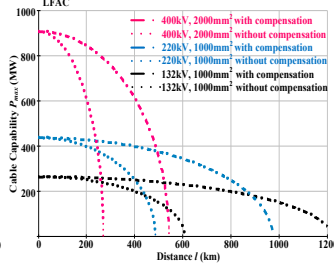**Fig. 6** Transmission capability of some common cables in HVAC   **Fig. 7** Transmission capability of some common cables in LFAC

0.6 GW is selected for the lower power rating case study. After comparing different cable choices of operating voltage and parallel numbers in **Appendix Table I**, the minimum cost options for each distance in HVAC are listed in **Table II.** For this power rating case study, one unitary cable choice in LFAC could satisfy minimum cost for all distance (0-240km) analysis as VSC-HVDC. The cable choices in LFAC and VSC-HVDC are given in **Table III** and **Table IV**.

Table II Cable choices in HVAC for 0.6 GW transmission

Distance l_c (km)	Voltage V_n (kV)	Size (mm²)	Capability per set (MW)	Number of sets nc_c
0-65	400	1000	645.7-603.8	1
65-80	400	1400	638.8-602.933	1
80-120	220	800	319.9-300.1	2
120-150	220	1000	320.6-298.8	2
150-200	220	630	255.2- 205.1	3
200-215	220	800	225.3- 202.9	3
215-230	132	800	157.8- 150.2	4
230-240	132	1000	156.9- 150.5	4

Table III Cable choice in LFAC for 0.6 GW transmission

Distance l_c (km)	Voltage V_n (kV)	Size (mm²)	Capability per set (MW)	Number of sets nc_c
0-240	400	800	733.1-684.8	1

Table IV Cable choice in VSC-HVDC for 0.6 GW transmission

Distance l_c (km)	Voltage V_n (kV)	Size (mm²)	Capability per set (MW)	Number of sets nc_c
0-240	±300	1000	986.0	1

According to **(17)** and **Table II, Fig. 8** and **Fig. 9** are obtained to show the 0.6 GW HVAC cost analysis. There are 8 step points in graphs because of the different optimal cable choices for different distance analysis, which leads to an approximately quadratic overall cost as a function of distance. Similarly, with **(18)** and **Table IV**, **(22)** and **Table III,** the cost analysis for VSC-HVDC and LFAC is presented in **Fig. 10** and **Fig. 11** respectively. The overall costs of both HVDC and LFAC keep linear relationships with distance in this power rating, but the step points will come out in LFAC as long as the power rating and distance keep rising.
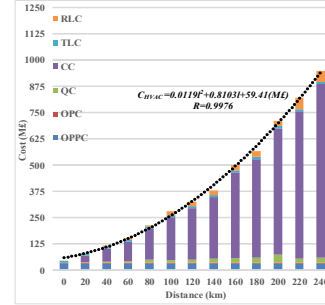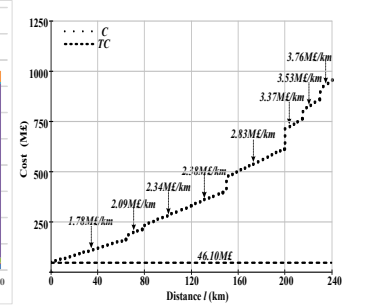

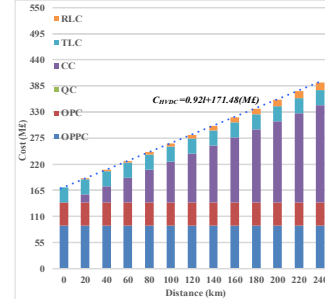**Fig. 8** 0.6 GW HVAC cost analysis   **Fig. 9** 0.6 GW HVAC step points
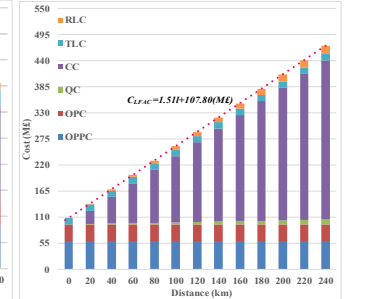

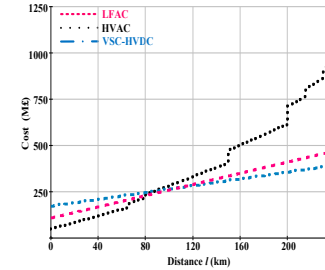**Fig. 10** 0.6 GW HVDC cost analysis   **Fig. 11** 0.6 GW LFAC cost analysis
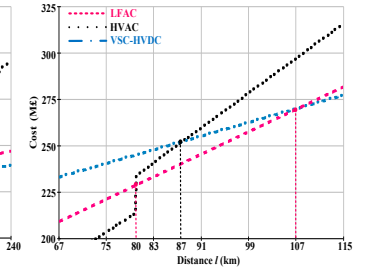

Fig. 12 0.6 GW comparison   **Fig. 13** 0.6 GW detailed comparison

With the cost analysis in **Fig. 8**-**Fig. 11,** the comparison result is illustrated in **Fig. 12.** Zooming in the area from 67km to 115km, the detailed result is given in **Fig. 13.** First of all, it is shown that there exists a cost-effective range, about 30km, for LFAC in the intermediate distance for this 0.6 GW comparison. Further, it is also clear to see that the LFAC terminal cost is higher than HVAC but lower than VSC-HVDC, and the route cost of LFAC is steeper than VSC-HVDC but smoother than HVAC, which corresponds to the general expectations in Section I. Meanwhile, according to **Fig. 12,** it can be found that

in this power rating, both the terminal cost and route cost per unit distance of LFAC approximately lie halfway between HVAC and VSC-HVDC when distance is shorter than 100km. The cross-over points of LFAC with HVAC and VSC-HVDC are 80km and 107km respectively, and VSC-HVDC and HVAC break-even point is 87km. The cost comparison result in this lower power case study is closest to case 2 in **Fig. 4**.
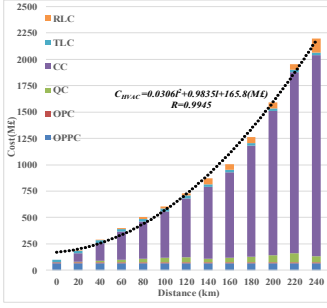
3.4. Case Study for Higher Power Rating
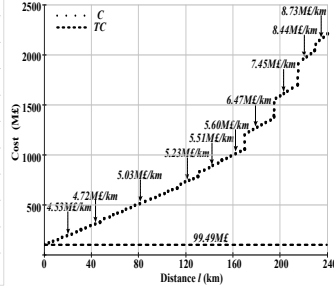

Fig. 14 1.4 GW HVAC cost analysis

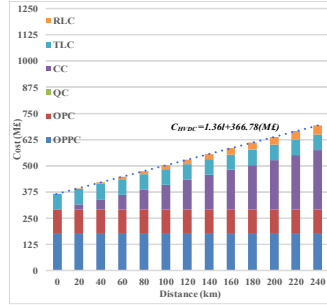**Fig. 15** 1.4 GW HVAC step points

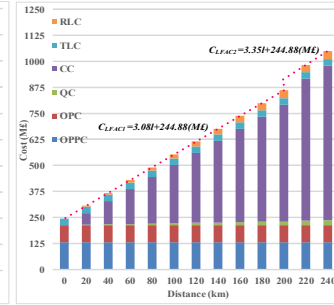**Fig. 16** 1.4 GW HVDC cost analysis
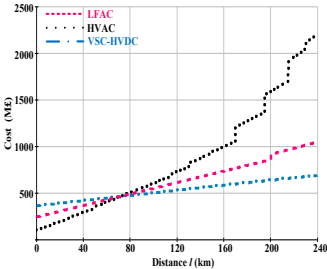

Fig. 17 1.4 GW LFAC cost analysis
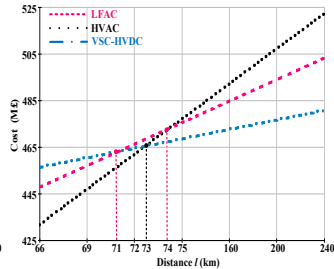

Fig. 18 1.4 GW comparison

Fig. 19 1.4 GW detailed comparison

In the higher power rating case study, 1.4 GW is chosen for detailed analysis. The individual cost analysis is sketched in **Fig. 14**-**Fig. 17**. It can be seen that the overall cost of HVAC still shows a nearly quadratic relationship with distance, and the first step point in LFAC appears when distance grows to 200km, making its overall cost become a non-linear function of distance as HVAC. With the results in **Fig. 14**-**Fig. 17**, **Fig. 18** and **Fig. 19** are obtained to illustrate the comparison results among these three options. It is shown that there is already no cost-effective range for LFAC in this 1.4 GW comparison. The terminal cost of LFAC is closer to VSC-HVDC but the route cost is more inclined to HVAC. The starting point of LFAC cost is near VSC-HVDC, but the cost rises sharply as HVAC with distance growing. According to **Fig. 14**- **Fig. 17,** this situation in LFAC can be explained by the expensive high power AC/AC converter station and LF transformer, which almost approach the terminal cost of VSC-HVDC, and the high cost AC cable structure is also just slightly lower than HVAC. In the higher

power and higher voltage comparison, DC cables shows more decisive advantages over AC options both in cable cost and transmission capability. The break-even point of HVAC and VSC-HVDC is about 70km. After this distance, DC seems to be the only option in these three options. Case 3 in **Fig. 4** is the best hypothesis for the cost comparison result in this higher power rating case study.

4 Conclusion

In order to identify the cross-over points of LFAC costs with HVAC and HVDC and to explore the extent of LFAC cost-effective ranges, some cost estimate methodologies are extended in this paper to make the cost analysis and comparison for these three options more feasible and reliable.

The cost estimates for each constituent terms in LFAC are from the most similar equipment from HVAC and VSC-HVDC commercial projects, and thus it increases the reliability and accuracy of the final comparison results. Meanwhile, the cost estimation algorithm compares all common cable choices in order to guarantee the minimum cost for each distance analysis. A number of cost analysis and comparison results are presented in case studies. It indicates that LFAC has some cost-effective ranges between HVAC and HVDC thanks to the inherent benefits, but these ranges gradually narrows and eventually ceases to exist with transmission power increasing, since DC system could demonstrate more clear advantage over AC options in the higher power higher voltage transmission. In addition, the results also show that, with different conductor choices for different range analysis, the overall cost of AC system is developed as a quadratic relationship with distance rather than the simple linear one.

Appendix

A.1 Assumptions List

Variable	Description	Assumption Value
FC_{HVAC}	HVAC offshore transformer platform fixed cost	5M£
dc	Cost factor for a different number ($\geq$2) of transformers, converters	0.2
n_T, n_C	Number of transformers, converters per offshore platform	2
fc_T	HVAC offshore transformer platform variable cost	0.020 M£/MVA
pc_T	HVAC offshore transformer plant variable cost	0.025 M£/MVA
f_n	Transmission frequency	
l_c, l_o	Cable, OHL transmission distance	
S_{ST}	HVAC single transformer power rating	
S_T	Transmission power rating	
Q_{off}, Q_{on}	Offshore, onshore compensation power	
nc_c, nc_o	Number of cable, OHL parallel circuits	
OFC	Offshore compensation cost per unit	0.025 M£/MVAr
ONC	Onshore compensation cost per unit	0.015M£/MVAr
V_{ndc}, I_{ndc}	DC cable nominal voltage, current	
V_{nac}, I_{nac}	AC cable nominal voltage, current	
pf	Power factor	1
η_{off}, η_{ont}	Efficiency of HVAC offshore, onshore transformers	99.4%
T_{op}	Total operation hours	365×24×15
δ	Loss load factor	0.231
E_{op}	Energy price per unit	50 £/MWh
FC_{HVAC}	VSC-HVDC offshore converter station platform fixed cost	25 M£
c_C	VSC-HVDC offshore converter station variable cost	0.11 M£/MVA
S_{SC}	VSC-HVDC single converter power rating	
η_{offr}	Efficiency of VSC-HVDC offshore rectifier station	98.28%
η_{oni}	Efficiency of VSC-HVDC onshore inverter station	98.19%
η_{onLCC}	Efficiency of LCC-HVDC onshore inverter station	99.12%
η_{onacac}	Efficiency of LFAC onshore AC/AC converter station	99.12%

A.2 Cable Parameters [26]

Appendix Table I Electrical parameters of some common cables in HVAC

Voltage V_n (kV)	Size (mm²)	Resistance r_c (mΩ/km)	Capacitance C (nF/km)	Steady state current I_{ssn} (A)	Cable cost per set t_c (k£/km)
132	630	39.5	209	818	685
	800	32.4	217	888	795
	1000	27.5	238	949	860
220	500	48.9	136	732	815
	630	39.1	151	808	850
	800	31.9	163	879	975
	1000	27.0	177	942	1000
400	800	31.4	130	870	1400
	1000	26.5	140	932	1550
	1200	22.1	170	986	1700
	1400	18.9	180	1015	1850
	1600	16.6	190	1036	2000
	2000	13.2	200	1078	2150

Appendix Table II Electrical parameters of some common VSC-HVDC cables

Voltage V_n (kV)	Size (mm²)	Resistance r_c (mΩ/km)	Steady state current I_{ssn} (A)	Cables cost per set t_c (k£/km)
±150	1000	22.4	1644	670
	1200	19.2	1791	730
	1400	16.5	1962	785
	1600	14.4	2123	840
	2000	11.5	2407	900
±300	1000	22.4	1644	855
	1200	19.2	1791	940
	1400	16.5	1962	1015
	1600	14.4	2123	1090
	2000	11.5	2407	1175

Appendix Table III Electrical parameters of some common cables in LFAC

Voltage V_n (kV)	Size (mm²)	Resistance r_c (mΩ/km)	Capacitance C (nF/km)	Steady state current I_{ssn} (A)	Cable cost per set t_c (k£/km)
132	630	26.2	209	995	685
	800	21.5	217	1080	795
	1000	18.2	238	1154	860
220	500	32.4	136	890	815
	630	25.9	151	982	850
	800	21.1	163	1069	975
	1000	17.9	177	1145	1000
400	800	20.8	130	1058	1400
	1000	17.5	140	1133	1550
	1200	14.6	170	1199	1700
	1400	12.5	180	1234	1850
	1600	11.0	190	1260	2000
	2000	8.7	200	1310	2150

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