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Cost Analysis and Comparison between Modular Multilevel Converter (MMC) and Modular Multilevel Matrix Converter (M^3C) for Offshore Wind Power Transmission

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Keywords: Cost analysis, modular multilevel converter, modular multilevel matrix converter, offshore wind power.

Abstract

This paper focuses on the cost analysis of offshore wind power system using Modular Multilevel Converter (MMC) based HVDC or Modular Multilevel Matrix Converter (M^3C) based fractional frequency transmission (FFT). Capital investment and long-term costs due to unavailability, Operation & Maintenance and power loss are analysed. The total cost is broken down into elements and those have larger impact on the overall cost are highlighted. Cost comparison between the two technologies is presented. Economical breakeven distance is analysed for schemes with different power ratings. In addition, sensitivity analysis is conducted considering discount rate, energy price, capacity factor, wind farm life time and wind turbine type to gain insight into the overall cost.

1 Introduction

UK is leading in offshore wind energy development. Considering the extensive exploitation of near-coast wind resource, future offshore wind development will move further offshore with higher voltage level and larger capacity. In terms of high power converter, Modular Multilevel Converter (MMC) and Modular Multilevel Matrix Converter (M^3C) are two promising candidates with various technical merits, e.g., low harmonics, low switching loss and flexible scalability. The schematic diagram of a MMC-HVDC system is shown in Figure 1(a). It does not suffer from charging current and has lower cable loss. It is considered as an ideal technology for long distance power transmission. Figure 1(b) shows a M^3C fractional frequency transmission (FFT) system. The principle is to use a proportion of the system frequency, mostly 1/3 for the generation side, for power transmission. In this way the charging current is greatly reduced so that more active power can be transmitted. Although MMC and M^3C share some advantages, without a DC link, M^3C is a direct AC-AC converter also with fast decoupled control capabilities and there is no offshore converter station. More details on technical aspect are available in the literature [1, 2].

This paper focuses on cost analysis and comparison between MMC and M^3C technologies. Before modular multilevel devices got popular, early cost analyses often adopted cycloconverter as the frequency changer in FFT. However, it was later proven as unsuitable for offshore wind applications due to defects of poor controllability, severe harmonics and unsatisfactory fault ride through ability [3]. In [4], a comparison is carried out between the traditional HVAC and HVDC. A cost model is developed in [5] to analyse the investment cost for offshore wind power. [6] studies the economic aspect for cycloconverter based FFT system. However, many researches focus only on capital investment or neglect the time effect of the costs. Considering that the life time of an offshore wind power system is usually designed as 20-25 years, long-term costs can add up to be considerable. Therefore, to take this effect into account, all the cost terms are explored and modelled in section 2. Necessary data are collected and presented. Cost comparison is conducted through case studies in section 3 and sensitivity analysis is performed in section 4.

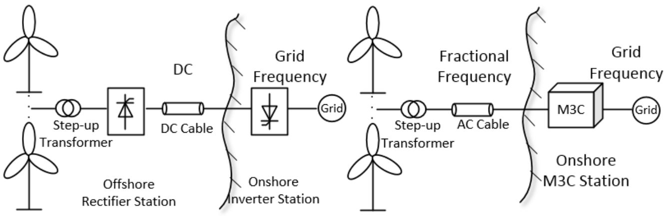

Figure 1: Schematic diagrams of offshore wind connection via: (a) MMC-HVDC (Left), and (b) M^3C-FFT (Right)

2 Cost Analysis for Offshore Wind Power Transmission System

The total cost of an offshore wind power system can be divided by components (wind turbine, transformer, cable and converter station) or by the nature of the cost (capital, unavailability, Operation & Maintenance (O&M) and power loss). According to the latter, the total cost can be calculated as:

$$C_{sys} = C_{CAP\_sys} + C_{UA\_sys} + C_{OM\_sys} + C_{PL\_sys} \quad (1)$$

where C_{CAP_sys}, C_{UA_sys}, C_{OM_sys} and C_{PL_sys} correspond to the capital cost (CC), unavailability cost (UC), O&M cost (OMC) and power loss cost (PLC) of the system respectively. Among those, UC, OMC and PLC are long-term costs throughout the whole project life. To convert them into net present cost (NPC), Equation (2) is used [7] :

$$C_{NPC} = C_{\text{annual}} \frac{(1+i)^n - 1}{i(1+i)^n} \quad (2)$$

where C_{annual} is the annual cost, n is the project life in year and i is the discount rate. The detailed division of the cost can be seen in Table 1.

Total Cost (TC) =	Wind Turbine Cost (WTC)	Transformer Platform Cost(TPC)	Cable & Compensation Cost (CCC)	Converter Station Cost (CSC)
Capital Cost (CC)	Wind Turbine Capital Cost (WTCC)	Transformer Platform Capital Cost (TPCC)	Cable & Compensation Capital Cost (CCCC)	Converter Station Capital Cost (CSCC)
Unavailability Cost (UC)	Wind Turbine Unavailability Cost (WTUC)	Transformer Platform Unavailability Cost (TPUC)	Cable & Compensation Unavailability Cost (CUC)	Converter Station Unavailability Cost (CSUC)
Operation & Maintenance Cost (OMC)	Wind Turbine Operation & Maintenance Cost (WTOMC)	Transformer Platform Operation & Maintenance Cost (TPOMC)	Cable & Compensation Operation & Maintenance Cost (CCOMC)	Converter Station Operation & Maintenance Cost (CSOMC)
Power Loss Cost (PLC)	Wind Turbine Power Loss Cost (WTPLC)	Transformer Platform Power Loss Cost (TPPLC)	Cable & Compensation Power Loss Cost (CCPLC)	Converter Station Power Loss Cost (CSPLC)

Table 1: Cost decomposition of an offshore wind power system

2.1 Capital Cost

Wind turbines capital cost includes manufacture, transportation, installation and foundation construction. It varies from project to project, and due to confidentiality, data that are publicly available are scarce. Two popular wind turbine types nowadays are doubly-fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG). According to the National Renewable Energy Laboratory (USA), offshore wind turbine project cost is approximately £1m/MW [8]. However it does not clarify costs of specific types of wind turbines. [9] gives reference costs on typical turbine types, with DFIG at £1.8m/MW and PMSG at £1.55m/MW. As the technology gets increasingly mature, the price drop of wind turbines is anticipated. Except that the price of PMSG also depends on the price of the expensive rare earth magnets it needs. According to [10], the cost structure of a DFIG can be presented as Figure 2. The study indicates that when the DFIG operates at fractional frequency, the gearbox ratio can be decreased to one third, and the weight of the wind tower is also reduced. Accordingly, the cost of a DFIG can be 5.2% lower [11]. This influence when operating at fractional frequency is neglected for PMSG in this paper as most PMSGs at present are direct-driven. However, it should be pointed out that the newest 8-10 MW PMSG has employed one level gearbox [12], and consequently there is potential benefit for PMSG as well.

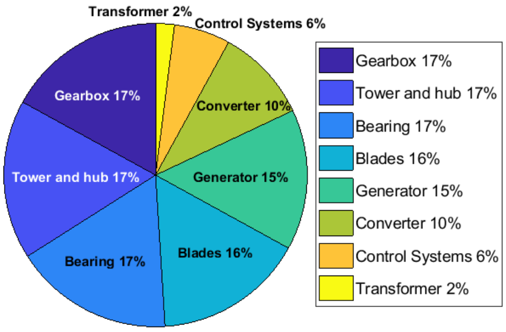

Figure 2: Cost breakdown of a DFIG wind turbine

For transformer platform and converter stations, their average costs can be found in [13] and they are listed in Table 2. Transformer at fractional frequency is bulker and heavier and based on the calculation result from [14] the price is hence 75% more expensive. Capital cost of the onshore converter station covers land use, building, valves etc. M^3C consists of full-bridge submodules and according to [15], full-bridge converter leads to 20% more expensive of the converter station compared to half-bridge counterpart. In addition, there are nine instead of six arms located in the onshore converter station. As a result, the cost of the onshore M^3C station is approximated to be 1.8 times as the onshore HVDC converter station.

The cable capital cost can be expressed as:

$$C_{CAP\_cab} = n_{cab} \cdot l_{cab} \cdot c_{cab} \qquad (3)$$

where n_{cab} is the number of cable sets, l_{cab} is the cable length (km) and c_{cab} is the unit price of cable (£m/km). Power rating and transmission length determine the choice of submarine cable. For AC cables, the main disadvantage is the charging current and it limits the maximum distance the cable can transmit. FFT significantly reduces the required charging current and hence enhances the transmission capability. [16] indicates that AC cable at 220 kV is able to transmit 500-600 MW to 300-400 km away in case of FFT and with reactive compensation. Cable costs of HVDC and FFT are available in [17] and they are extracted and shown in Table 2. Besides, compensation costs for AC cables are collected from [18] and they can be plotted as Figure 3. For the sake of simplicity, it is considered to be linear versus the transmission length.

Component	Capital Cost
DFIG	£1.8m/MW
DFIG at fractional frequency	£1.7m/MW
PMSG	£1.55m/MW
Offshore transformer (plus platform)	£0.129m/MW
Offshore transformer FFT (plus platform)	£0.194m/MW
Offshore Converter Station	£0.254m/MW
Onshore Converter Station	£0.107m/MW
Onshore M^3C Station	£0.171m/MW
AC Cable (FFT)	
132 kV (0-300 MW)	£0.86m/km
220 kV (300-600 MW)	£1.00m/km
400kV (600-1000 MW)	£2.15m/km
DC Cable	
±150 kV (0-500 MW)	£0.785m/km
±300 kV (500-1000 MW)	£1.015m/km

Table 2: Capital cost of offshore wind components

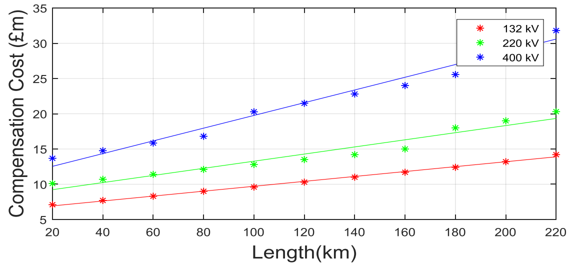

Figure 3: Compensation cost for different voltage ratings

2.2 Unavailability Cost

Unavailability cost corresponds to the energy not supplied to the grid due to unavailability of the offshore wind power system. According to the definition of IEC 61400 standard [19], unavailability is the percentage between the system unavailable time and the total time of the study timeframe, which can be described as (4) on an annual basis:

$$UA_{sys} = \frac{t_{UA\_sys}}{T_{year}} \times 100\% \quad (4)$$

where UA_{sys} is the unavailability of the system, t_{UA_sys} is the unavailable time of the system in a year and T_{year} equals to the total time of a year (8760hrs). The energy not supplied is then converted to unavailability cost based on the energy price using (5):

$$C_{UA\_sys} = UA_{sys} \cdot P_{rated} \cdot CF \cdot EP_{wind} \quad (5)$$

where C_{UA_sys} is the system unavailability cost, P_{rated} is the power rating of the system, CF is capacity factor and EP_{wind} is the energy price. Note that unavailability only considers unplanned down time, with scheduled maintenance excluded from the calculation. Also, it is assumed that when a fault happens to one component, the rest of the system will not operate. As a result, the system total unavailability is the sum of the unavailability of each of the components, which can be described as (6). The definition of variables can be found in Table 3.

$$UA_{sys} = UA_{wt} + UA_{tran} + UA_{cab} + UA_{con} \quad (6)$$

Symbol	Quantity	Value (%)
UA_{wt}	Unavailability of wind turbine	/
UA_{PMSG}	Unavailability of PMSG	2.57
UA_{DFIG}	Unavailability of DFIG at grid frequency	5.11
UA_{DFIGFF}	Unavailability of DFIG at fractional frequency	3.69
UA_{tran}	Unavailability of transformer	0.59
UA_{cab}	Unavailability of cable per 100km	0.18
UA_{con}	Unavailability of converter station	/
UA_{mmc_on}	Unavailability of MMC HVDC onshore converter station	0.35 [23]
UA_{mmc_off}	Unavailability of MMC HVDC offshore converter station	0.8 [24]
UA_{m3c}	Unavailability of M^3C onshore converter station	0.52

Table 3: Unavailability of offshore wind components

Gearbox, generator, rotor blade and converter electronics make up most of the unavailable time of a wind turbine [20]. Their annual failure rates and downtimes are presented in Table 4. Annual unavailable time equals to the product of the failure rate and downtime.

Failure Rate(per year)	PMSG	DFIG	Downtime(/days)
Gearbox	/	0.185	42
Generator	0.046	0.123	32
Rotor Blade	0.16	0.16	42
Converter Electronics	0.593	0.106	2

Table 4: Reliability of wind turbine components [20, 21]

From Table 4, it can be seen that PMSG has a much higher converter electronics failure rate than DFIG. This is due to the larger size and rating of PMSG's fully rated converter than DFIG's partially rated converter. As previously discussed, gearbox can be significantly simplified when the wind turbine operates at fractional frequency. It is assumed that the failure rate of the gearbox would drop to one third of the original.

For transformer, cables and converter stations, unavailability data are gathered and presented in Table 5. Transformer at fractional frequency has been used in railway networks in plenty of countries for over a century [22]. It is therefore considered as reliable as the transformer operating at grid frequency. The calculation of a multilevel converter is based on the assumption that its availability depends on proper function of all arms. A fault in one arm will lead to unavailability of the converter. Calculation results of unavailability are given in Table 3.

Component	Failure Rate(per year)	Downtime(/hours)
Transformer	0.024	2160
AC Cable(/100km)	0.1114	1440
DC Cable(/100km)	0.1114	1440

Table 5: Reliability of transformers and cables [13]

2.3 Operation & Maintenance Cost

The O&M cost of offshore wind power system usually includes accounting expenses, labour, rent, insurance, component expenses, travel and vessel expenses etc. [25]. The actual cost is case-dependent as each wind farm has different geographical condition and accessibility. Maintenance strategy, availability of professional crew and vehicle (vessel/helicopter) and weather condition play decisive roles in offshore wind O&M. In cost analysis studies, the annual O&M cost is often approximated as a percentage of the capital expenditure [26, 27]. This ratio can be calculated as:

$$k_{O\&M} = \frac{c_{O\&M\_sys}}{C_{CAP\_sys}} \times 100\% \quad (7)$$

where $k_{O\&M}$ is the O&M cost ratio and $c_{O\&M\_sys}$ is the annual cost of O&M. The O&M ratios for different components of an offshore wind power system are available in [8, 13] and they are presented in Table 6.

Component	O&M Ratio(/ year)
Wind Turbine	3.4%
Offshore Converter Station	2%
Onshore Converter Station	0.7%
Submarine Cable	2.5%
Offshore Transformer	0.15%

Table 6: Annual O&M ratio of offshore wind components

2.4 Power Loss Cost

Power loss in an offshore wind power system can be in form of mechanical loss, copper loss, iron loss and power electronic loss. The loss is then converted to cost based on the energy price:

$$C_{PL\_sys} = PL_{sys} \cdot T_{rated} \cdot P_{rated} \cdot EP_{wind} \quad (8)$$

where PL_{sys} is the power loss percentage of the whole system and T_{rated} is the scheduled operation time at rated power annually. For wind turbine, converter electronics loss is primary in PMSG due to its bigger converter rating but mechanical loss is small due to low rotor speed. Contrarily, mechanical loss, especially gearbox loss is a main source of DFIG losses. Detailed calculations of losses of wind turbines can be found in [28]. Results are listed in Table 7. Gearbox loss at fractional frequency is estimated to be one third of the original.

Losses of transformer are mainly current heating losses in transformer windings and losses from magnetizing current in the core. For simplicity, the power loss ratio of transformer at fractional frequency is assumed to be unchanged. The discrepancy this simplification brings is negligible since transformers have very high efficiency [29]. In Table 7, it can be confirmed that the main losses come from other components in the system.

The loss of DC cable primarily depends on active power current. However for AC cable, cable capacitance produces reactive current. Together with active current, AC cable has higher power loss than DC cable. Detailed calculations of cable power losses can be found in [18, 30]. Results show that for 100 km cables, power loss for AC cable lies between 3-5% of the wind power system production, while DC cable is only 0.5-2.5%.

Converter losses are mainly switching losses and conduction losses. For MMC-HVDC, the half-bridge valves add up losses of approximately 1% per converter station. In terms of full-bridge valves in M^3C, the switching loss remains the same as half-bridge submodules while the conduction loss doubles [31]. Result gives that M^3C power loss is 1.95%.

Component	Power Loss (%)
PMSG	6.4
DFIG	5.0
DFIG at fractional frequency	3.0
Transformer	0.8
AC Cable (100 km)	3.0-5.0
DC Cable(100 km)	0.5-2.5
Offshore Converter Station	1.0
Onshore Converter Station	1.0
Onshore M^3C Station	1.95

Table 7: Power loss of offshore wind components

3 Cost Comparison between MMC and M3C: Two Case Studies

3.1 Case Study1: Lower Power Rating

In case study 1, the power rating is selected to be 500 MW and costs of both MMC-HVDC and M^3C-FFT are calculated based on the analysis in section 2. PMSG is chosen and other parameters are listed in the appendix. To explore what the total costs are made up of, cost constituents are plotted in Figure 4. As can be seen, two technologies share some similarities. Despite the choice of transmission technology, around half of the total cost of an offshore wind power system is spent on the purchase, installation and testing of the wind turbines. O&M cost ranks second with slightly less than 20%. Power loss cost has relatively small percentage (less than 10%) and unavailability cost has the smallest percentage. In terms of differences, M^3C-FFT has more expensive cable and offshore transformer, while MMC-HVDC is featured by the larger expense on converter stations.

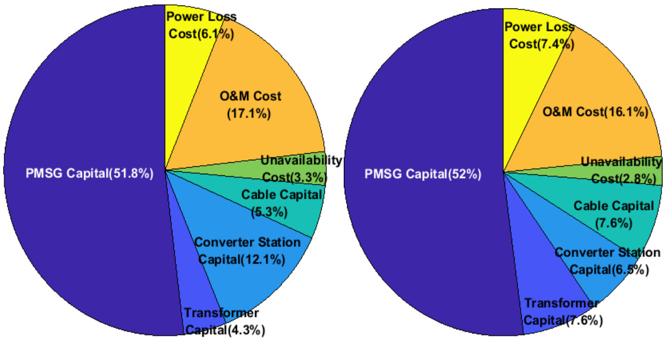

Figure 4: Cost constituents of 500 MW wind power systems at 100 km: (Left) MMC-HVDC, (Right) M^3C-FFT

To determine the economical distance for both technologies, the total costs versus distance are plotted in Figure 5. It shows that the breakeven distance is 109 km, before which M^3C-FFT costs less and after which MMC-HVDC is cheaper. The reason can be explained using Figure 6. The cost differences (MMC-HVDC minus M^3C-FFT) are plotted before and after the breakeven point in this figure. At short distance, the capital cost of the offshore converter station is prominent. And compared to converter station power loss, AC cable loss is larger. So MMC-HVDC has positive capital cost difference, negative power loss cost difference and positive total cost difference. However, as distance gets longer, the AC cable capital, O&M and power loss costs all rise. The increase is significant enough to cancel out the unavailability and O&M cost advantages. Hence, the total cost difference becomes negative and MMC-HVDC becomes more economical at long distance.

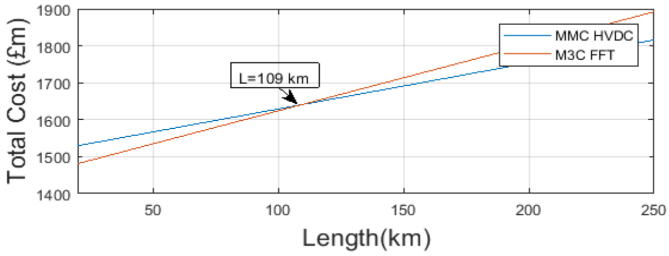

Figure 5: Total cost versus distance at 500 MW

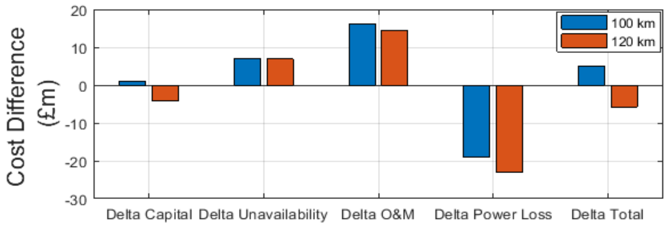

Figure 6: Cost differences at 100 km and 120 km

3.2 Case Study2: Higher Power Rating

In case study 2, parameters remain the same except that the power rating is increased to 1 GW. Cost constituent percentages are similar so it is not depicted again due to space limit. Total costs are plotted in Figure 7 so that cost effective range can be studied. As can be seen, the breakeven distance is pushed closer to 63 km. At such a short distance, the traditional HVAC transmission has advantage over M^{3}C-FFT due to no converter station cost and smaller offshore transformer platform. In other words, M^{3}C-FFT may not have economical distance range at all in this case. The root reason is that the AC submarine cable for high power rating is too expensive compared to the DC cable. In this case it becomes so dominant that the economic advantage gained from other aspects is rapidly diminished as distance grows.

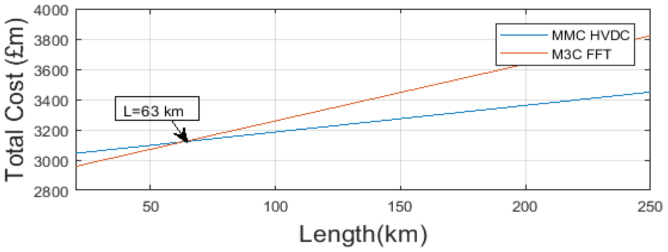

Figure 7: Total cost versus distance at 1 GW

4 Sensitivity Analysis

It should be admitted that the offshore wind power industry is still developing dramatically. Consequently, sensitivity analysis is necessary to investigate how the parameters change would affect the cost analysis and the selection of the more economical technology. In this section, sensitivity analysis is performed considering discount rate, energy price, capacity factor, wind farm life time and wind turbine type. Results are shown in Figure 8.

The choice of discount rate can be influenced by the inflation rate, profit return ability of the project and the risk of the investment. As discount rate gets higher, the capital cost becomes more decisive. This fact magnifies the weakness of the AC submarine cable which has been discussed in section 3.1. Therefore, the breakeven distance decreases. Also, increased energy price brings down the breakeven distance. Both unavailability cost and power loss cost are related to energy price. However, the percentage of unavailability cost is much smaller than that of power loss cost. And more importantly, AC cable power loss grows with length but unavailability cost difference is not sensitive with length changes. Hence, higher energy price leads to shorter breakeven distance. Regarding capacity factor, higher value induces larger unavailability cost of MMC-HVDC. Nevertheless, higher capacity factor also means higher average wind speed or longer operation time, which enhances the power loss cost of AC cable more significantly. Overall, the breakeven distance has a descending trend. In terms of wind farm life time, change of it only affects long-term costs. MMC-HVDC has higher unavailability cost due to an extra converter station, it also has higher O&M cost around the breakeven distance but lower power loss cost. The overall annual cost narrowly surpasses M^{3}C-FFT. As a result, longer project life time favors M^{3}C-FFT but to a very small extent. If DFIG is selected as the wind turbine type, breakeven distance would be pushed much further to almost 300km because of savings from wind turbine costs on capital, unavailability, O&M and power loss.

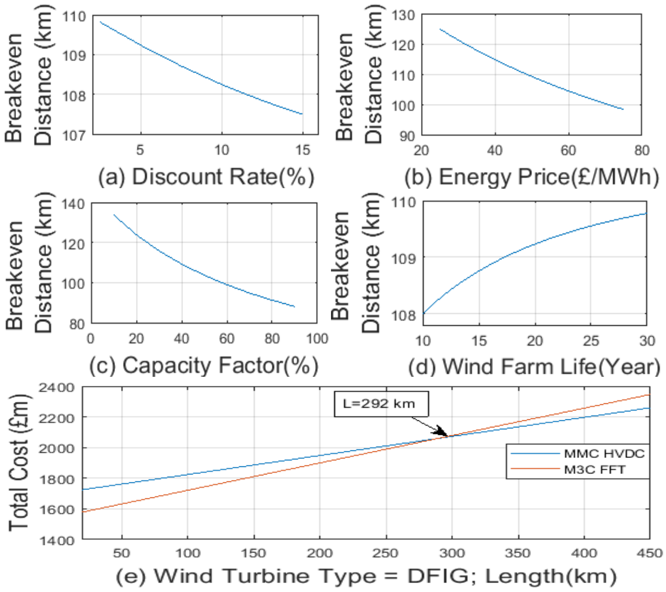

Figure 8: Sensitivity analysis of the wind power system

5 Conclusions

This paper has presented a detailed cost analysis on offshore wind power system and provided cost comparisons between MMC-HVDC and M^{3}C-FFT. For both technologies, wind turbine capital cost takes up around half of the total project cost. O&M cost ranks second at about 20% of the total project cost. At several hundred MW scale, M^{3}C-FFT is a promising solution at medium distance for offshore wind transmission. It is mainly hampered by the disadvantages of expensive AC cable, higher cable loss and bulker offshore transformer. The disadvantages of MMC-HVDC come from the offshore converter station on capital expense, higher chance of unavailability, extra O&M and power loss. For long distance transmission, it is still an ideal solution as the merits on DC cable compensate for its weaknesses. In the sensitivity analysis, it is found that increasing discount rate, energy price or capacity factor would lead to shorter breakeven distance between MMC-HVDC and M^{3}C-FFT. Change of discount rate is less sensitive compared to energy price or capacity factor. Wind farm life time is the least significant among all factors. The economic strength of M^{3}C-FFT is optimised when partnering with DFIG wind turbines. It is the cost-effective solution even at around 300 km.

6 Appendix: Parameters for Case Studies

Symbol	Quantity	Value
CF	Capacity factor	40% [32]
T_{rated}	Rated operation time	2500hrs [32]

i	Discount rate	5% [7]
EP_{wind}	Offshore wind energy price	£50/MWh [33]
n	Project life	20 years

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