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Economic Considerations Underlying the Adoption of HVDC and HVAC for the Connection of an Offshore Wind Farm in Korea

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Abstract – Wind energy is created in mega-sized wind farms situated kilometers off shore. In fact, two possibilities are considered for the transmission system between the offshore wind farm and the onshore grid: high-voltage direct current and high-voltage alternating current. From this point of view, the current paper aims to compare both systems for a 2 GW wind farm situated 80 km from the Point of Common Coupling on an economic basis using a discounted cash flow analysis. A tool is developed in Microsoft Excel to allow for quick insight in the variation of input parameters.

Keywords: Discounted cash flow, Economic analysis, HVAC, HVDC, Offshore wind farm

1. Introduction

By the end of the year 2009, wind energy represented only 2%of the global electricity demand [1]. However, wind energy has been touted as one of the most promising next-generation energy sources to replace fossil fuels. Compared with conventional energy sources, wind power has many merits: it is plentiful, renewable, and clean,. However, wind turbines may be noisy and dangerous to birds. Moreover, onshore wind power potential is limited due to the shortage of installation land. As an alternative, offshore wind power has emerged, especially because winds are usually stronger and more stable at sea.

As part of an effort, Korea intends to execute an ambitious offshore wind farm project at the western coast of the Korean peninsula over a period of ten years. According to the Ministry of Knowledge Economy in Korea [2], a total of 9.3 trillion KRW (approximately USD 8.45 billion) will need to be invested by 2019 to erect 500 wind turbines on the shallow seabed of the West Sea of Jeolla Province. As shown in Fig. 1, the scheme is composed of three phases. By 2013, Korea will have raised 20 5 MW turbines, with an additional 180 by 2016, and 300 more by 2019; combined, these turbines will be able to create 2.5 GWh of energy per year.

Transmission to shore has attracted wide attention with the increasing cable length and power rating of offshore wind farms. Thus far, the transmission of the generated power to the onshore grid has been typically achieved by high-voltage alternating current (HVAC) technology.

The main purpose of the current paper is to conduct a thorough review of the economic feasibility of high-voltage direct current (HVDC) for the connection of a 2 GW offshore wind farm situated 80 km from shore with the main grid, and to compare HVDC with HVAC. This proposed wind farm (rating and distance from shore) is highly relevant in the current offshore wind industry climate in Korea.

Fig. 1. Korea's 2.5 GW offshore wind power project

An economic comparison may be generally performed by various methodologies, as shown in Fig. 2. Most commonly used is the discounted cash flow (DCF) method for its time value of money; all future cash flows are estimated and discounted to give their present values [3]. The systems are economically compared with the DCF calculation that consers the differences in investment costs and annual costs. The annual costs considered comprise the maintenance costs and transmission system losses. However, reliability and possible differences in insurance costs are ignored.

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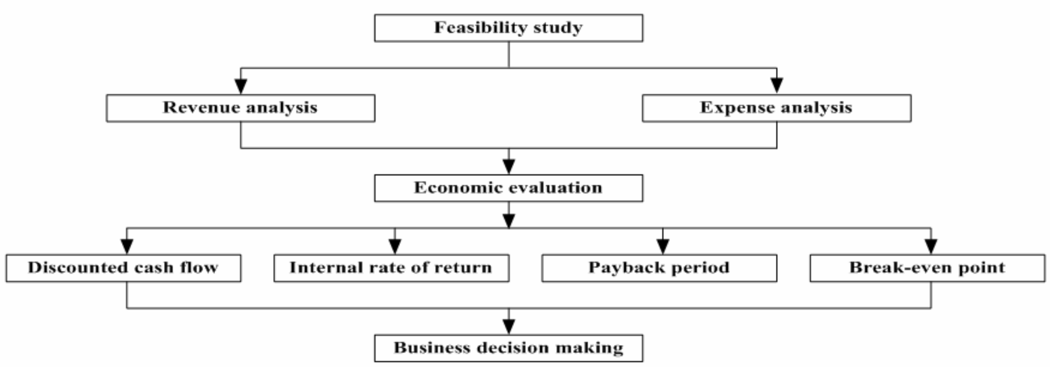

Fig. 2. General process of business decision making

2. Economic comparison of HVDC and HVAC

A general cost comparison of HVDC and HVAC is shown in Fig. 3. The break-even distance between both systems is generally considered to be from 40 km to 80 km for cables [4]. Furthermore, power transfer level criteria, transmission medium, environmental conditions, and comparative cost information have a big effect on the break-even distance (Fig. 3). For offshore wind farms, one of the converters of the HVDC link is placed on an offshore platform, which significantly increases costs.

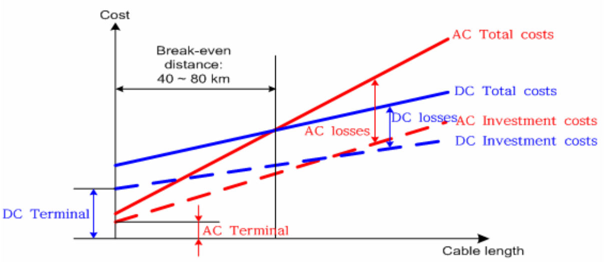

Fig. 3. Comparison of costs for DC and AC cables

For the preliminary feasibility analysis of transmission system types, both HVDC and HVAC systems are considered equal cost alternatives. Both HVDC and HVAC are used for the purpose of shipping electricity only. The investor of the transmission system is assumed to be a party other than the wind farm investor who will not benefit from the possible wind farm optimization. Thus, the wind farm may be regarded as a black box. An important issue in the economic comparison is to determine the system that is the better alternative economically. The current section provides the answer to this inquiry for a 2 GW wind farm connected with an 80 km cable, as depicted in Fig. 4.

The methodology adopted for the economic comparison is DCF analysis. The result of this computation is the difference between the net present values (NPVs) of the compared technologies. DCF analysis incorporates the initial investment costs and the discounted annual costs for each technology.

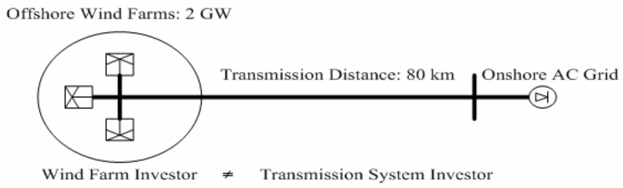

Fig. 4. Scenario for economic comparison

The mathematical formulas are summarized as follows:

- Investment Cost$_{HVDC}$ = Substation cost + Onshore land use cost + DC cable cost + Cable installation cost + Offshore rig cost (1)
- Investment Cost$_{HVAC}$ = Substation cost + Onshore land use cost + AC cable cost + Cable installation cost + Offshore rig cost + Reactive compensation cost (2)
- Annual Cost = Loss cost + Maintenance cost (3)
- Net Present Value = Investment cost + Discounted annual costs = Investment cost + Present value annuity factor × [Annual costs × (1 – Taxation rate) – Depreciation ×Taxation rate] (4)

where the present value annuity factor is formulated by [1 – (1 + discount factor) $^{-(\text{lifetime})}$] / discount factor, and the asset is depreciated until the book value equals the salvage value (zero in this case) by the straight-line depreciation technique [5].

For a more realistic reflection, a taxation rate of 22% is assumed, the lifetime of the transmission system is set at 30 years, and the discount factor is fixed at 7%, leading to the present value annuity factor of 12.409.

2.1 Transmission system investment cost

The choice between voltage source converter (VSC) HVDC [6] and current source converter (CSC) HVDC [7] for the DC option greatly influences the result of an economic comparison. Although the use of VSC topology for transmission system purposes is relatively new, it has several technical advantages over CSC HVDC and HVAC.

In this context, an economic comparison among CSC HVDC, VSC HVDC, and HVAC for a wind farm rated at 2 GW and a cable length of 80 km is made.

A good choice for the proposed wind farm is the 500 kV bipolar CSC HVDC link with a base power of 2 GW. This option uses three DC cables, in which the cross-section of the copper conductor is 2,000 mm^2. The VSC HVDC is also studied. The VSC HVDC is a double module for a 2 × 1 GW connection, allowing for the fact that an installed capacity of no more than 400 MW is used in commercial operation and that the windmill maker intends to construct the VSC HVDC module with a maximum power rating of 1.2 GW. The current study assumes that all submarine cables will be built at the initial stage; one substation will be installed in 2016, and the other substation will be added in 2018. This system consists of 2 × 1 GW VSC HVDC links at 320 kV and 2 × 2 DC cross-linked polyethylene insulated cables, in which the cross-section of the copper conductor is 2,000 mm^2. In HVAC, only the 345 kV offshore substation is to be built because the existing 345 kV Saemangeum substation may be utilized to connect the cable system to an onshore grid node. The establishment of one additional new substation for HVDC makes HVAC economically interesting. A choice between using single-core or three-core cables must also be made. This system has 3 × 3 single-core cables, the advantage of which is a higher current rating than 3 three-core cables with the same amount of copper conductor. The amount of copper is a crucial factor on the price of the cable. The construction of three single-core cables is also simpler than that of the three-core cable. The 3 × 3 single-core cables are, thus, less expensive to purchase than the 3 three-core cables with the same power rating.

A drawing of the transmission system configuration addressed earlier is depicted in Fig. 5.

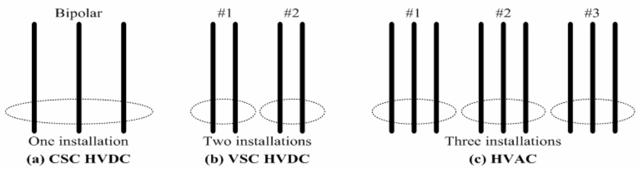

Fig. 5. Transmission system configuration

In Table 1, the cost of a transmission system is broken down into several components for both HVDC and HVAC options: substation, cable, cable installation, offshore rig, and land use costs, and others. Clearly, the economic aspects of converter stations for VSC HVDC undergo far less rigorous analysis. Prices, which depend from project to project and which are often incorporated in larger contracts, are often confidential. The substation cost of VSC HVDC is assumed to be nearly 1.5 times (420 billion KRW) that of CSC HVDC [8]. Technological developments will naturally push VSC HVDC system costs down. By paying due regard to the distance and cross-section of DC cables, the cost for the 80 km CSC HVDC cable is roughly twice that of HVDC #2 on Jeju Island (180 billion KRW). By contrast, the AC cable price is stated as 3 billion KRW/km, adding up to a total cable cost of 720 billion KRW for an 80 km HVAC cable on three routes. According to the installation cost of HVDC #2 on Jeju Island, an installation cost of 1.2 billion KRW/km is applied equally to both DC and AC cables. Furthermore, no offshore rig and land use costs are incurred because the offshore platform will be placed on a small island near Wido Island, whereas the onshore converter stations will be installed in the already-secured site.

Table 1. Investment cost comparison: HVDC vs. HVAC (unit: billion KRW)

Component	CSC HVDC	VSC HVDC	HVAC
Substation	420.00	630.00	50.00
Cable	180.00	240.00	720.00
Cable installation	96.00	192.00	288.00
Offshore substation rig	-	-	-
Onshore land use	-	-	-
STATCOM	-	-	32.87
Inductive compensator	-	-	42.08
Total	696.00	1,062.00	1,132.95

For a detailed review of reactive compensation in the three-phase HVAC system, the capacitive charging current is first calculated by

$$\begin{aligned} I_c &= \left(\frac{V_{cable}}{\sqrt{3}}\right)^2 \cdot 2\pi f_{grid} \cdot C_{cable} \\ &= \left(\frac{345\times10^3}{\sqrt{3}}\right)^2 \cdot 2\pi(60)\cdot(0.23\times10^{-6}) = 17.21\,[\text{Ar/km}] \end{aligned} \tag{5}$$

To compensate for the capacitive charging current, reactive compensation units have to be in place at both ends of the cable. Fig. 6 shows the maximum active power that could be transported through a single cable set as a function of cable length. If only onshore compensation is used, the active power transported via the cable set falls below 666 MW (or 2,000 MW for three sets) when the cable is longer than 68 km. With both onshore and offshore compensation units, the cable can be made as long as 135 km before the cable active power capacity becomes smaller than 666 MW because of its charging current. This capacity is a good match for the demanded cable length of 80 km.

The current distribution at maximum loading is fully described in Fig. 7. The current stay below the maximum current rating of the cables only for a cable system with reactive compensation at both ends.

The total reactive power produced by a cable is calculated as

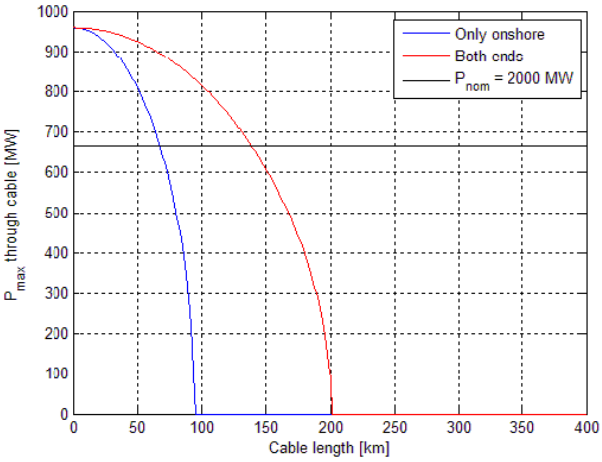

Fig. 6. Active power capacity of copper 2,000 mm² cable set as a function of cable length

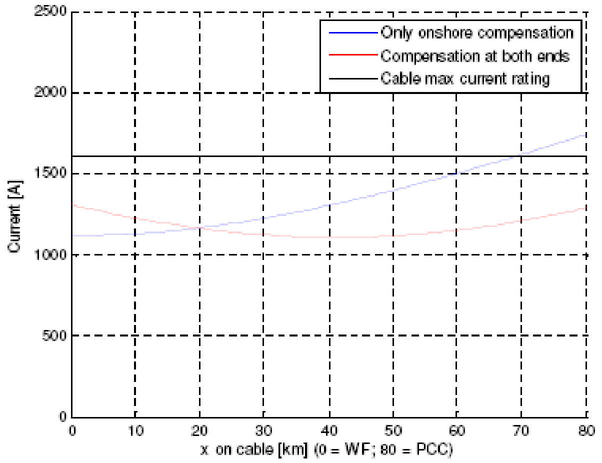

Fig. 7. Current distribution at maximum loading (666 MW) for 2,000 mm² cable

$$
\begin{aligned}
Q_{cable} &= \sqrt{3}V_{cable}\cdot 2\pi f_{grid}\cdot\left(\frac{V_{cable}}{\sqrt{3}}\right)\cdot C_{cable}\cdot l_{cable}\\
&= \sqrt{3}\cdot\left(345\times10^{3}\right)\cdot 2\pi(60)\cdot\left(\frac{345\times10^{3}}{\sqrt{3}}\right)\cdot\left(0.23\times10^{-6}\right)\cdot(80)\\
&= 825.64\left[\mathrm{MVAr}\right]
\end{aligned}
\tag{6}
$$

The compensation units at both cable ends are inductive, to compensate for the capacitive cables:

- Offshore compensation: 3 × 412.82 MVAr (inductive)
- Onshore compensation: 3 × 412.82 MVAr (inductive)

Nevertheless, a maximum reactive power of 657.37 MVAr is needed to achieve a lagging power factor requirement of 0.95, as defined by the grid code.

As a compromise between dynamic controllability and cost, a combination of switched passive elements with a smaller static synchronous compensator (STATCOM) is chosen in the current study. Half of the reactive power on the lagging side is provided by a switched inductor rated at

$$Q_{ind} = \frac{657.37}{2} = 328.68\left[\mathrm{MVAr}\right] \tag{7}$$

The other half (328.68 MVAr) is provided by the STATCOM. The power factor can now be varied safely over the total range for each power output of the wind farm. When the STATCOM cost of 0.1 billion KRW/MVAr is specified and the inductive compensator cost of 15 million KRW/MVAr is reported, these premises result in a STATCOM cost of 32.87 billion KRW (or 328.68 MVAr × 0.1 billion KRW/MVAr) and a compensation cost of 42.08 billion KRW (or 2,805.6 MVAr × 0.015 billion KRW/MVAr), respectively. The total cost for the compensation equipment is estimated at 74.95 billion KRW.

Based on Table 1, the dominant cost component for HVDC are the converter stations, whereas, for HVAC, it is the cable cost. CSC HVDC is less expensive than HVAC, with a total investment difference of approximately 437 billion KRW. CSC HVDC costs 696 billion KRW, compared with a total cost of 1,132.95 billion KRW for the HVAC connection.

2.2 Annual costs

Two operating cost components are incorporated in the economic comparison: losses and maintenance.

The losses of both HVDC and HVAC systems represent one vital economic indicator.

CSC HVDC losses are categorized into two types: converter station losses and cable losses. The losses for a CSC converter depend on many parameters (e.g., thyristors, transformers, filters) and are given to be an accumulated 1.3% in the current study (0.65% per station). The cable losses are Joule losses, and depend on the power sent through the link. The losses of the VSC HVDC system come from the HVDC converter station (e.g., IGBTs, transformers, filters) losses, which comprise approximately 3.6% (1.8% per station), and cable Joule losses. To minimize the total losses of the system, the second cable set is switched on only when the wind farm output power is higher than 50% of the nominal value (1,000 MW). To determine the total losses in the HVAC system, the losses in the HVAC substation (e.g., transformers, compensation coils), which are assumed to be 0.5%, and cable losses are incorporated. The line losses in the HVAC cables consist of losses in the copper conductors, shield, and armor.

For each wind speed value, a corresponding wind turbine power output exists, as shown in Fig. 8. A model is developed by Matlab/Simulink based on [9] and [10].

The wind speed distribution over time in the southern North Sea [11] is defined by a Weibull distribution [12] (Fig. 9). Given that 400 turbines of 5 MW are needed to form a 2 GW wind farm, a probability function for the power output (Fig. 10) is created by combining the power-speed curve with the wind speed probability function. Considering the wind speed probability distribution and the

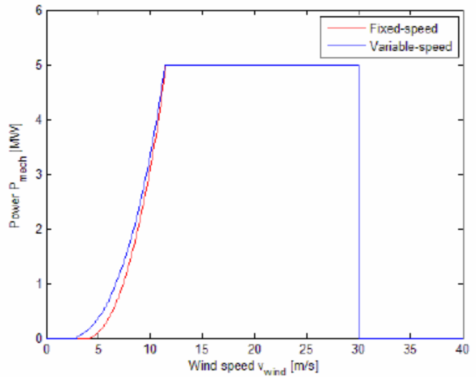

Fig. 8. Power output of wind turbines (5 MW) as a function of wind speed

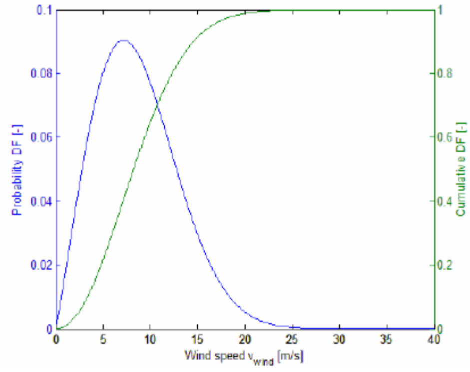

Fig. 9. Probability density function and cumulative density function for wind speeds at North Sea

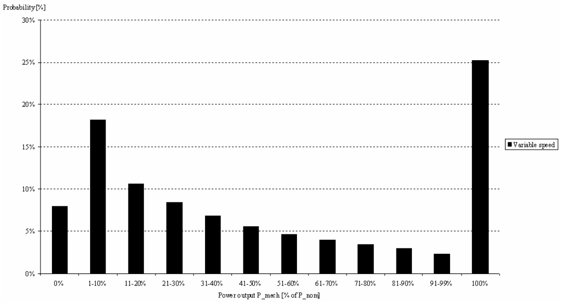

Fig. 10. Power probability density function for offshore wind farm

related power probability distribution, the annual energy losses can be calculated for the HVDC and HVAC technologies. In Table 2, the annual energy losses for both technologies are compared with the annual energy output of a variable speed wind farm. The annual energy losses are given in MWh. To provide a monetary value for these losses in the DCF, a cost of energy in KRW/kWh is needed. A value of 108 KRW/kWh is used in the current study as a base value. The annual loss costs can be obtained by multiplying this value by the annual energy losses, equaling to 14.13, 38.70, and 46.43 billion KRW for CSC HVDC, VSC HVDC, and HVAC, respectively.

Table 2. Annual energy losses between CSC HVDC, VSC HVDC, and HVAC as transmission option for a 2 GW offshore wind farm (cable length = 80 km)

Wind farm power range [%]	Probability [%]	Hour [h]	Average losses [MW]			Energy losses [MWh]		
			CSC HVDC	VSC HVDC	HVAC	CSC HVDC	VSC HVDC	HVAC
0	7.99	699.5	4.380	12.120	7.330	3,064	8,478	5,127
1–10	18.17	1591.6	4.797	13.274	8.726	7,635	21,126	13,889
11–20	10.61	929.8	5.965	16.459	14.726	5,546	15,303	13,692
21–30	8.45	740.6	7.773	21.373	21.777	5,757	15,828	16,128
31–40	6.78	594.0	10.222	28.017	28.934	6,072	16,643	17,187
41–50	5.54	485.2	13.294	36.341	36.752	6,450	17,633	17,833
51–60	4.63	405.6	16.272	44.715	46.331	6,600	18,136	18,791
61–70	3.94	344.7	18.673	51.230	57.672	6,437	17,659	19,880
71–80	3.39	296.7	21.394	58.609	70.773	6,348	17,389	20,999
81–90	2.94	257.7	24.436	66.853	85.636	6,298	17,229	22,070
91–99	2.33	204.3	27.620	75.478	101.373	5,642	15,419	20,709
100	25.23	2210.1	29.400	80.310	110.240	64,978	177,497	243,647
Total	100	8760	–	–	–	130,827	358,340	429,952

An annual maintenance cost is estimated at 0.5% of the capital cost of the components [13]. Cable cost is not included in this capital cost. Annual maintenance costs are thus calculated to be 2.58 and 4.11 billion KRW for CSC HVDC and VSC HVDC, respectively. The complexity of the VSC converter stations gives rise to the higher cost. By contrast, the annual maintenance cost for the HVAC equipment in the substations is 2.06 billion KRW, where extra maintenance costs needed for the STATCOM onshore and inductive compensators have been reflected.

2.3 DCF analysis

The DCF analysis presented in (4) is discussed in this section. The result of the comparison in Table 3 is relevant from a transmission system point of view. The benefits in the wind farm gained by the use of HVDC do not result in economic value for the investor of the transmission link.

Table 3. Net present value comparison: HVDC vs. HVAC (unit: billion KRW)

Component	CSC HVDC	VSC HVDC	HVAC
Net investment	696.00	1,062.00	1,132.95
Losses	14.13	38.70	46.43
Maintenance cost	2.58	4.11	2.06
Net present value	794.39	1,379.73	1,499.28

More specifically, CSC HVDC will be less expensive than VSC HVDC or HVAC on a lifetime basis. The difference is mainly due to the investment costs. Due to the higher annual costs of VSC HVDC or HVAC, the difference in the NPV results is relatively greater than the difference in investment costs.

2.4 Sensitivity analysis

As the technological evolution in VSC HVDC continues, the influence of the decreasing cost of the VSC substation on the financial result is shown in Table 4. When the cost of VSC HVDC is equal to or twice that of CSC HVDC, the NPVs of VSC HVDC are 1,178.67 and 1,580.78 billion KRW, respectively, which are higher than the NPV of CSC HVDC.

Table 4. Effect of variation of cost of VSC HVDC on net present value (unit: billion KRW)

Component	Cost of VSC HVDC = Cost of CSC HVDC	Cost of VSC HVDC = 2 × Cost of CSC HVDC
Net investment	852.00	1,272.00
Losses	38.70	38.70
Maintenance cost	3.06	5.16
Net present value	1,178.67	1,580.78

Thus, CSC HVDC is the more cost-efficient option, irrespective of further progress in the form of a reduction of the cost in the VSC converter stations.

3. Concluding remarks

In the future, wind farms predicted to have a power rating higher than 2 GW will be situated several tens of kilometers from shore; hence, the use of a separate transmission system is unavoidable. The current paper presents an economic comparison between HVDC and HVAC for the connection of an offshore wind farm to the onshore grid.

As proven by the above discussion, CSC HVDC is the cheapest solution for a 2 GW wind farm with an 80 km cable length, with a net present value result of 794.39 billion KRW, compared with the VSC HVDC and HVAC options. Although the cost of VSC HVDC subsequently decreases to the level of CSC HVDC, CSC HVDC is the more cost-efficient option.

However, the lack of black start capability is a critical drawback for CSC HVDC, and may make it unsuitable for the link between an offshore wind farm and the onshore grid. Notably, CSC HVDC always needs additional equipment to overcome the problem of starting up the connected offshore wind farm and re-energizing the network sections that suffer from a system blackout, thereby posing an extra cost burden.

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