Electrical Integration of North Sea Wind Power Plants using Interconnectors

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***Abstract*—**

In this paper the feasibility of an Interconnecting Link (IL) [1] between the Netherlands and the UK is studied for a specific case of two planned offshore wind power plants in the North Sea. First the most promising scenarios and conceptual designs for this combined utilization are presented. The feasibility of these scenarios is being assessed from a technical, socio-economic and legal point of view. Finally an inventory of bottlenecks and required innovations is being performed, with regard to technology as well as on market and regulatory aspects. The paper shows that in 2020 it is technically possible to build an interconnecting link between the UK and Dutch grids via one or both of these WPPs, either by existing HVAC solutions or by HVDC solutions. Under international law it is possible to construct an IL, but EU law and national legislation do not facilitate the operation of an IL.

Keywords- Offshore Wind Farm Integration; Interconnecting Links; Interconnectors; Power Markets; Cross-border Energy Trade; HVDC transmission; HVAC transmission; Multi-Terminal HVDC grids; (Socio)economic Feasibility; Technical Feasibility; Legal Framework

1. INTRODUCTION

The electrical infrastructure for connecting offshore WPPs (wind power plants) to an onshore grid represents a significant share of the cost of energy from offshore wind. When WPPs in different countries are interconnected several synergy advantages can be achieved [1]. First of all, electricity from wind power can be sold to the country with the highest electricity price. Secondly, the infrastructure can be used to trade electricity generated onshore with the neighbouring country. Finally, there is a redundant connection from the wind power plant to shore, leading to a lower risk of power loss. Together these advantages will produce additional revenues for the wind power plant and grid operator, which may outweigh the additional capital costs and thereby contribute to the cost reduction of offshore wind.

In the Synergies at Sea project the feasibility of such an interconnecting link (IL) is being studied for a specific case of two planned offshore WPPs in the North Sea: one in the UK part of the North Sea and a second one in front of the Dutch shore, see Figure 1. The UK WPP has a planned power capacity of up to 1200 MW generated with up to 325 wind turbines in an approximate area of about 300 km^2. The project is being developed by a consortium formed by Scottish Power and Vattenfall. The offshore cable between

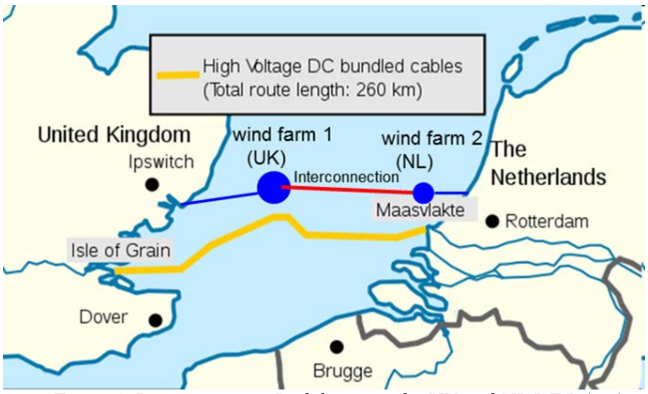

Figure 1. Interconnecting Link between the UK and NL WPP (top), together with the existing BritNed interconnector (bottom).

1 ´Interconnecting Link´ is the term which is used here instead of interconnector. This new term is introduced to explicitly stress the issue that we are dealing with infrastructure for connecting different countries that does not yet have sufficient legal basis.

This work was supported by the program "TKI-Wind op Zee" from the Dutch ministry of Economic Affairs. It was conducted by NUON/Vattenfall, Royal Haskoning DHV, ECN, Delft University of Technology, Groningen Centre of Energy Law (University of Groningen) and DC Offshore Energy.

the UK WPP and the landfall near to Bawdsey is 73 km and the underground cable length from this point to Bramford HVDC substation is 34 km. On the Dutch side the WPP has a power capacity of 279 MW generated with up to 93 wind turbines. This WPP is being developed by NUON/Vattenfall and it has been designed with an HVAC export line of 35.5 km to Maasvlakte substation, near Rotterdam. For the IL we assume a cable length of 100 km, the shortest distance between the platforms in both WPPs. Furthermore we assume that both WPPs and the IL will be operational in 2020, after a two year construction period.

2. Methodology

The feasibility assessment addresses the main technical design trade-offs as well as the business case evaluation from an investor's perspective, the expected socio-economic benefits and the regulatory and legal implications.

A. *Scenarios*

In the project four grid topologies for interconnection have been considered, named ‘IL1’, ‘IL2’, ‘IL3’ and ‘BritNed2’. The baseline for the calculation of costs and benefits as well as for the technical and regulatory evaluation in the project is the ‘Reference’ topology, i.e. two new WPP export links and the existing BritNed interconnection (‘BritNed1’).

In topology ‘IL1’ an IL between the two WPPs, is constructed. It enables cross-border trade via both WPP export links. It requires relatively little investment for additional cables and could possibly be realized and operated by the WPP developers/operators. In topology ‘IL2’ an IL is built between the UK WPP and the Dutch grid. The Dutch WPP remains connected to the Dutch onshore grid with a separate export cable. The third option, ‘IL3’, is an IL from the UK grid directly to the Dutch WPP. This topology is a mirror of topology ‘IL2’ but with different values for the WPP capacity and the distance to shore. Finally there is the ‘BritNed2’ topology, which is a separate new interconnector of 1200MW. It is used to compare an IL with a conventional interconnector. The grid topologies are shown schematically in Figure 2. The light lines represent the infrastructure that is supposed to be existing: the BritNed1 interconnector and the export lines of the planned WPPs. The dark line represents the new transmission line that enables cross-border trade: either an IL, or a conventional interconnector.

For each of these topologies technical scenarios were elaborated by selecting different power ratings for the various transmission lines and connected WPPs, as well as different technical implementations (HVAC, HVDC). Reactive power compensation has been included by equally sized reactors at both sides of the HVAC cables without any further optimization. The HVAC scenarios of the ‘IL1’ topology include mid-point reactive power compensation located on the platform in the Dutch WPP. The HVDC links have been modelled using a bipolar configuration to obtain redundancy in case of failure. Two examples of technical scenarios are shown in Figure 3.

For the IL power rating two options were modelled:
- a 300 MW IL, using a single 220 kV HVAC circuit;
- a 1200 MW IL, using a ±320 kV HVDC circuit.
For the 1200 MW IL a sensitivity analysis is performed, using various power ratings for the UK WPP (900, 1200 MW) and the NL WPP (300, 600, 900 MW). In total 25 different scenarios were designed, taking into account the technologies available by 2020 and their expected cost levels.

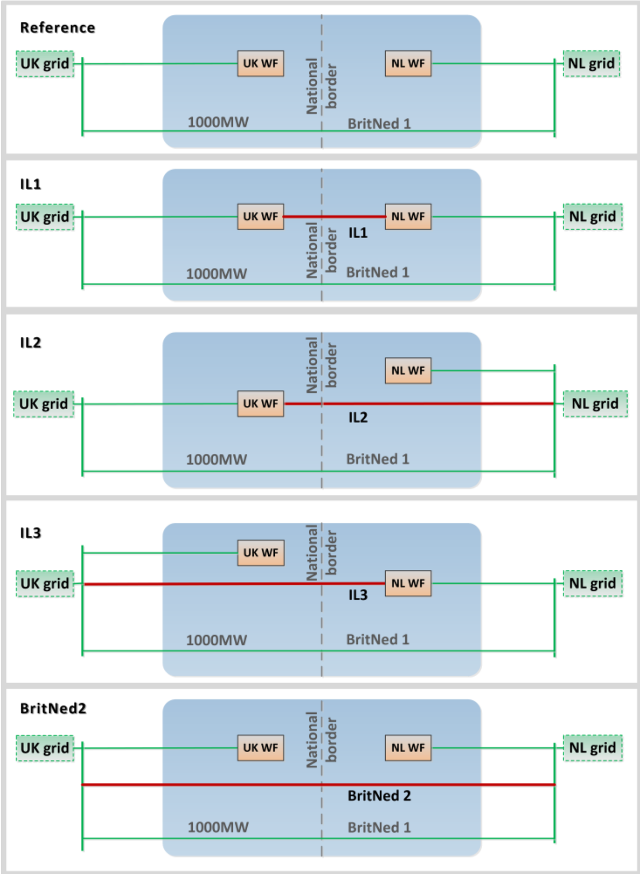

Figure 2. Grid topologies used in this study: IL1, IL2, IL3 and ‘BritNed2’, as well as the reference topology ‘Reference’.

B. *Technical evaluation*

The costs and losses of the technical scenarios modelled have been calculated with the ECN tool EeFarm-II [2], [3]. These losses include transmission losses as well as energy lost due to unavailability (failure) of components. The stationary component models include detailed models for transmission losses as well as for reactive power characteristics, failure rates, redundancy calculation and MTTR (Mean Time To Repair). The model inputs consist of hourly power production of the two WPPs, based on yearly averaged wind speeds provided by Vattenfall. The

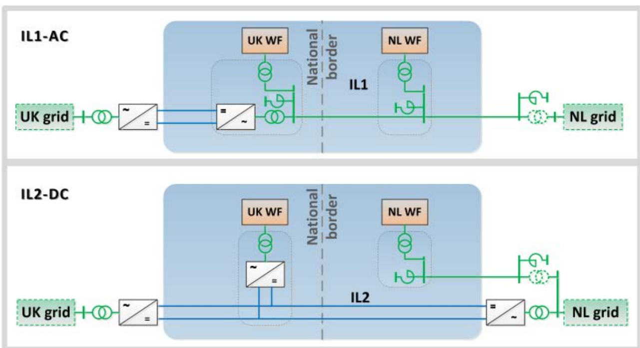

Figure 3. Example of a technical scenario for IL1 and IL2 topology (single line: HVAC; double line: HVDC).

production variations due to wind fluctuations were modelled based on the data from the IJmuiden offshore met mast and the met mast at ECN's test site in the Wieringermeer, which have roughly the same distance to each other as the UK and NL WPPs.

The design ratings and losses were determined using the energy flows in the offshore network imported from the ECN market model COMPETES (see section C below). The losses calculated by the electrical model are fed back into the market model resulting in a reduction of the energy trade and thereby of the social benefits.[2] The flow scheme in Figure 4. visualizes the process of losses calculation and post processing.

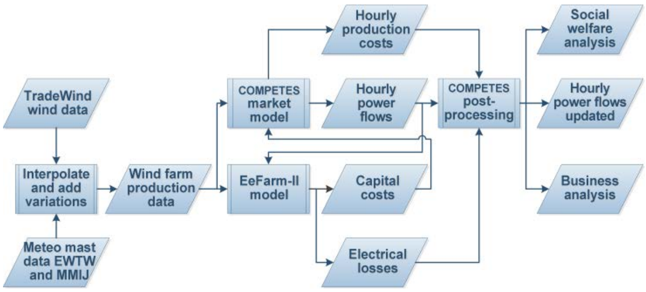

Figure 4. Technical and socio-economic modelling

C. Socio-economic evaluation

In the socio-economic evaluation two separate economic feasibility analyses are being performed:

1. A social welfare analysis, from the point of view of society, taking into account the benefits and costs for the main stakeholders in continental Europe (especially in the Netherlands) and in the UK.
2. A business analysis, from the point of view of a (private) investor who builds and operates an IL.

A common method in social welfare analyses is to calculate the Net Present Value (NPV) of an investment. The social welfare analysis looks at the NPV for all major stakeholders in Europe and the UK as well. The stakeholders included are the power producers, the power consumers and the TSOs (transmission system operators). Producers invest in generation and get paid for the energy generated. TSOs invest in interconnections and receive income from congestion rents. Finally consumers pay for the electricity they consume. The NPVs for these stakeholders are calculated for the UK, NL and Europe. The overall benefit for society can be calculated from the sum of the positive and negative effects for the various stakeholders. Since the costs and benefits accrue at different points in time, the net cash flow in each period over the lifetime (25 years assumed) of an investment needs to be discounted to a base year. Under the assumption that the project alternatives are operational in 2020 with a construction time of two years, the base year we use is 2018. In addition, it is assumed that 50 percent of the investment costs accrue in the first construction year and the other 50 percent in the second construction year. A project alternative can be considered profitable for society when the NPV for society is larger than zero.[3]

For business analyses, a common method is to calculate the Internal Rate of Return (IRR) of project alternatives. The IRR is related to the NPV since it is equal to the interest rate when the NPV is set to zero. A project alternative can be considered profitable when the IRR is larger than the interest rate plus a risk bonus. The minimum required IRR value that investors and banks use varies from project to project and is classified business information. In a recent review KPMG cites a 10.9% hurdle rate for UK WPPs [5].

To determine the cash flow of alternative investments, energy losses and availability data were used from the technical evaluation (see previous section), as well as the estimated data for the energy produced per hour by both WPPs. Additionally in both analyses the expected hourly market prices on both sides of the IL were modelled, in order to determine the energy flow through the IL and the associated congestion rent. In the social welfare analysis ECN's COMPETES model was used for this purpose [6]. In the business analysis the European market prices model of Vattenfall was used. Both models have a similar structure but use different assumptions for the development of the energy consumption and the generation mix across Europe. The COMPETES model uses a combination of public sources for the mix in 2020 [7]-[12]. Later years are assumed to have identical load patterns and market prices. For the market prices of electricity the generation costs of the marginal (most expensive) generation unit have been applied as a proxy. The assumptions of the Vattenfall market price model are not public.

D. Regulatory evaluation

In the regulatory evaluation the existing legal framework concerning offshore wind energy development and interconnection is evaluated, to determine how this framework facilitates or obstructs the realization of cross-border integrated offshore electrical infrastructure. This was done by scrutinizing the legal framework on the international, European and the national level of both the UK and the Netherlands. The main focus was on the legislation dealing with the production and transmission of electricity and the legislation concerning subsidies for the production of electricity from renewable sources. Two perspectives were used when researching the relevant legislation: the TSO perspective and the private investor perspective. Finally, a number of recommendations were formulated to address the legal obstacles that were identified.

3. Technical Feasibility

First, quantitative results of the technical evaluation are presented. Figure 5. and Figure 6. show the calculated investment costs per scenario, relative to the Reference scenario. The costs are attributed to the line segments, from the standpoint that the export lines of the two WPPs in the UK and the NL are realized first and the interconnecting cable is constructed later.

[2] Additional iteration loops between the electrical and market model have not been applied for reasons of time.

[3] An interest rate of 5.5% is assumed in order to calculate the NPV. This interest rate is proposed by the Dutch Ministry of Finance for Social Cost-Benefit Analyses [4]. It is also used as the value for the WACC in the business analysis.

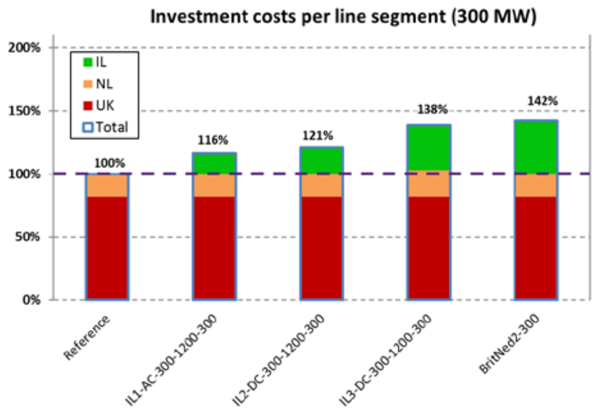

Figure 5. Investment costs relative to Reference for 300 MW interconnecting link scenarios, including the contributions of: IL, NL WPP export link; UK WPP export link.

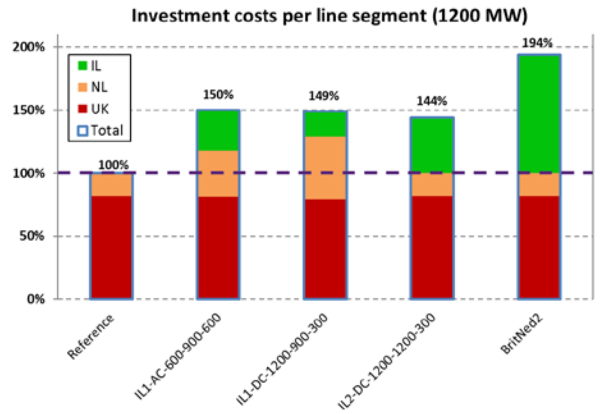

Figure 6. Investment costs relative to Reference for 600 or 1200 MW interconnection link scenarios, including the contributions of: IL, NL WPP export link; UK WPP export link.

The technical analysis shows two advantages of ILs compared to a separate interconnector. First, most[4] technical scenarios for the IL have lower investment costs than the corresponding interconnector with separate WPP export links. Secondly, the fact that a WPP can supply its power through two export lines leads to a higher redundancy and thus to a substantial increase of the availability. For example for the UK WPP the amount of energy not supplied to the onshore grid due to failure of the export link is estimated to decrease from 3.3% to 1.1% when an IL to the Dutch power grid is built. As a result the 1200 MW UK WPP can supply an additional 97 GWh/yr of wind energy to the onshore grids.

On the other hand there are two negative consequences of combining an interconnector and a WPP export line. First, connecting a WPP to an IL decreases the available capacity for cross-border trade (compared to a normal interconnector of the same power rating.) In line with European rules, it is assumed that transmission of renewable energy generated by the WPP to the nearest onshore grid has priority over cross-border trade through the interconnector. A typical load factor of 45% for WPPs results in a decrease of the average capacity for cross-border trade by 45% of the WPP power rating. This will decrease the amount of energy traded and the income from congestion rent substantially. The amount of decrease is difficult to estimate a priori. It will depend on the difference in market prices between both sides of the interconnector during periods in which the WPP is in operation. Secondly, in all IL scenarios the percentage of energy transmitted that is lost due to transmission losses is higher than that of the reference. Also the percentage of energy not transmitted due to failures is higher for the IL scenarios than for an interconnector with the same size. This is a consequence of the higher average load factor of the infrastructure in the IL scenarios. The aggregated values of these figures are presented in Figure 7. and Figure 8.

4. Socio-Economic Issues

The business analysis has not been finished yet, but for the social welfare analysis there are some preliminary results. They show that increasing the interconnection capacity between the UK and Netherlands does significantly influence electric power prices and generator dispatch in the UK and the Netherlands. With the power demand and the generation mix assumed, during most hours of the year the power price in the UK is higher than that in the Netherlands and continental Europe. As a result of that more power will be traded from the Netherlands to the UK than vice versa. In the UK and Ireland this leads to lower average power prices as well as a smaller amount of load hours for generators.

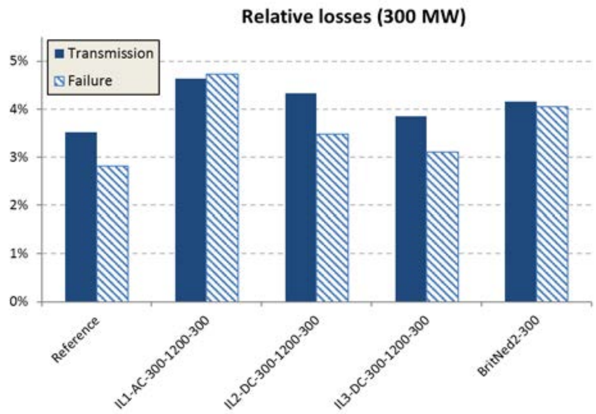

Figure 7. Transmission losses and energy not transmitted due to failure for various 300 MW interconnecting link scenarios.

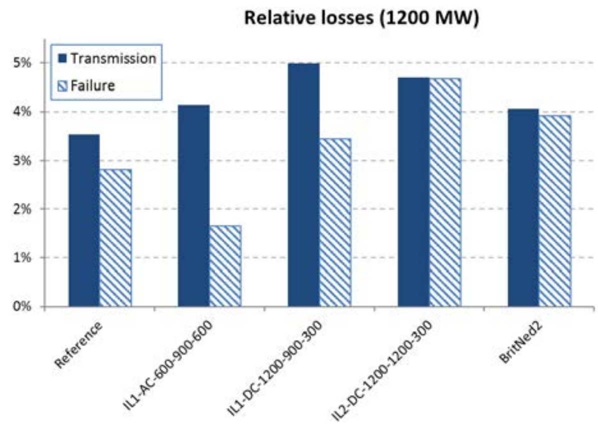

Figure 8. Transmission losses and energy not transmitted due to failure for various 600 or 1200 MW interconnecting link scenarios.

[4] Note that in case an HVDC interconnector is connected to a WPP located close to the shore, the total investment costs for the IL might be *higher* than the conventional solution, because the HVAC export line needs to be replaced by an HVDC export line. This is the case for the Dutch WPP considered in this assessment. See also [13].

Vice versa in the Netherlands average power prices go slightly up and generator load hours increase. This has a positive effect for consumers in the UK as well as for generators in the Netherlands. Consumers in the Netherlands and generators in the UK are negatively affected. The balance of these contrary effects together with the net revenues from the IL (congestion rent minus costs) determines whether or not the net social benefit of an investment alternative is positive. The first results indicate that the net social welfare for the Netherlands is opposite to that for the UK.

5. Legal issues

This section will discuss the relevant international and European legislation that is applicable to the construction of an IL between the Netherlands and the UK.

The United Nations Convention on the Law of Sea (UNCLOS) gives coastal states the right to claim an exclusive economic zone (EEZ) for the purpose of developing wind energy (Art. 56(1)(a)). However, all States (coastal and non-coastal alike) enjoy the freedom of the seas (ius communicationes) in the EEZ, including the right to lay submarine cables (Art. 58(1) and 79). It should be noted that coastal states have the right to regulate the laying of such cables if these are connected to an installation located in the EEZ of coastal states or if subsea cables enter the territorial waters of coastal states.

These rights which are laid down in international law are supplemented by EU legislation. Especially the European legislation on the internal energy market [14], [15], and the Directive on the promotion of the use of renewable energy sources are relevant [16]. Finally, the development of an IL is influenced by national legislation on matters such as subsidies, site selection for WPPs and permits for offshore activities.

The research has shown that under international law it is possible to construct an IL between two WPPs which are located in different jurisdictions. However, numerous challenges have been identified. We shall discuss two of them.

The first challenge is how to define the IL. The IL is a type of electrical infrastructure that serves two purposes. First, the cable is used to convey electricity from the WPPs to the shore, this is a transmission activity. Secondly, the cable is used as an interconnector in order to facilitate the electricity trade between the Netherlands and the UK. However, due to the fact that the IL is not connecting the grids of two TSOs to each other, it is assumed that under EU law[5] it can *not* be considered as an interconnector.

The second challenge is the application of national support schemes for the development of offshore wind energy. Both the Netherlands and UK have a subsidizing regime in place.[6] The Dutch subsidizing regime is based on the idea that in order to receive subsidies, the generated electricity needs to be fed into the national grid. This makes it impossible for a Dutch WPP operator to use an IL to convey the electricity to the UK grid and still receive subsidies from the Dutch government. However, the situation is different should the Dutch WPP operator export the electricity to the UK and apply for subsidies under the UK subsidizing regime. In that case, the Dutch WPP operator is eligible for receiving UK subsidies. It should be noted that a WPP operator in the UK cannot apply for Dutch subsidies should he export his electricity to the Dutch grid, since the Dutch law has no extraterritorial effect and does not apply for foreign generators. This means that the existing subsidy regimes form a barrier to the trade of generated electricity from WPPs.

In other words, it has been shown that under international law it is possible to construct an IL, but EU law and national legislation do not facilitate the operation of an IL. The reason for this could be the fact that energy legislation is drafted to regulate onshore production and transmission activities. An innovative concept such as the IL might be a step ahead of the legal reality. Should an IL be constructed, then it cannot be classified within the existing legal framework and this creates legal uncertainty on the part of the investor. A practical problem regarding the operation of an IL is how to reconcile the priority access for WPPs with the mandatory auctioning of interconnection capacity.

In order to address these issues, two important recommendations can be made. The first recommendation is related to the question on how to define the IL in legal terms. There is the option of drafting a new definition or using a teleological interpretation to extensively interpret the existing definition. It is assumed that the first option is a favourable long term solution and that the second option could be a short term remedy. The second recommendation concerns the issue of national support schemes. The research has shown that the use of the joint support scheme or the joint project instrument from the renewable energy directive is a feasible option.

6. Innovations required

The review of the technical scenarios showed that by 2020 it is possible to build an offshore IL either by combining HVAC technology and point-to-point HVDC connections using VSCs (Voltage Source Converters), or by implementing a MTDC (Multi-Terminal HVDC) scheme with VSCs.

The scenarios studied are close to the technical limits of HVAC technology with respect to transmittable power and connection distance. Considering the power rating of the transmission system, technical solutions, such as dynamic rating, promise to extend the energy throughput and thereby lower the costs. Regarding the maximum cable length, mid-point reactive power compensation is already proposed by TenneT TSO to extend the connection distance and enable the HVAC connection of WPPs far offshore.

At the moment the cost of offshore HVDC systems are still high, especially due to the converters and offshore platforms, while construction time and O&M cost level are uncertain. For the MTDC options the building blocks are available, but practical experience on control and protection needs to be built up in the meantime. So far MTDC networks containing VSCs are in operation, apart from two Chinese pilot projects that were commissioned in the past

[5] Art. 2(1) of Regulation [15]

[6] The Dutch SDE+ regime and the UK Contracts for Difference regime.

year.[7] Regarding control of MTDC grids, several options have been proposed (including voltage droop control, voltage margin control and Distributed Voltage Control) [17]-[22]. However, none of them have been implemented yet on an industrial scale. As a result, demonstration on an industrial scale should be a priority in the coming years.

Another important aspect of multi-terminal HVDC grids is HVDC fault protection. Currently, fast acting AC breakers are used to protect the existing point-to-point HVDC connections. This solution is also viable for small MTDC networks, at the cost of having to restart the complete MTDC network after a fault. A precondition for applying AC breakers is that the power loss is below the maximum level allowed to be disconnected at once from each of the connected onshore grids.[8] For the longer term (after 2020) solutions like a HVDC breaker[9] will be needed, as the size of interconnected HVDC-grids is expected to grow beyond these limits

Finally, as most of the required technology is in place, more focus should be given to interoperability of MTDC systems. In this way, HVDC manufacturers would develop compatible equipment, which increases the competition and subsequently brings down the cost of HVDC systems. Moreover, the standardization of HVDC grids would increase their flexibility, modularity and safety, moving towards future highly meshed networks. Currently, there are several working groups with this objective, such as CIGRE WG B4 and CENELEC [23].

7. Conclusions

In 2020 it is technically possible to build an IL between the UK and Dutch grids via one or both of the two WPPs considered, either by existing HVAC solutions or using VSC-MTDC. For the VSC-MTDC solution it is necessary that in the meantime experience is gained with control of multi-terminal HVDC networks containing VSCs. Whether or not building an IL is more profitable than building a separate interconnector has not been determined yet. It depends upon many factors including the market price difference on both sides of the interconnector, the power rating and length of the IL and the WPP export links. It has been shown that, contrary to a conventional interconnector, an IL can substantially increase the availability of the WPP export link, reducing the amount of energy not supplied to the onshore grid by the UK WPP by two-thirds. From the point of view of regulations several challenges have been identified. New regulation is needed regarding the legal status of an IL, regarding subsidies for energy from WPPs and regarding priority access of WPPs to export link capacity.

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[8] Currently, the values for this limit are: 1320-1800 MW for UK; 3000 MW for ENTSO-E Continental Europe.

[9] Siemens is developing an alternative solution for sectionalizing HVDC grids, using full bridge HVDC converters.