Advanced Transmission Solutions for Offshore Wind Farms

W. L. Kling, *Member, IEEE*, R. L. Hendriks, *Member, IEEE*, and J. H. den Boon

Abstract—**Future offshore wind farms will have large power ratings and will be situated much further offshore than current projects. The associated costs for grid connection will be high. This paper explores alternative methods of grid connection. By creating synergies with other applications for offshore power transmission, the total costs will be lower. Such synergies include the bundling of multiple wind farms, combination with offshore energy sources uncorrelated to wind, connection of oil and gas production platforms, and combination with interconnectors cables. High-voltage ac transmission through submarine cables has restricted application due to technical limitations. Alternative technologies are presented in this paper, such as high-voltage dc transmission, also in multi-terminal configurations, and gas-insulated transmission lines.**

Index Terms—**cable transmission, HVAC transmission, HVDC transmission, offshore wind power**

I. INTRODUCTION

IN January 2008 the European Commission unveiled its action plan to fight climate change and promote renewable energy. One of its spear points is a binding 20% target for the use of renewable energy sources (hydro, solar, wind and biomass). Especially in the Western part of Europe wind power will play an important role to meet this target. Due to space limitations and stringent environmental legislation in this densely populated area, a large share of new wind generation capacity is foreseen as offshore. In other parts of the world, mainly the USA and Asia, some offshore wind power projects are under development as well.

An important question is how the energy produced offshore is to be fed into the onshore power system. Until now grid connection has been considered exclusively on a per-project basis. Since existing offshore wind parks have moderate distances to the shore of up to 25 km and power ratings up to 165 MW, three-phase ac transmission through submarine cables at medium or high-voltage levels has been applied exclusively. New wind parks will be larger, approximating to the power ratings of conventional thermal generation units. Moreover, they will probably be located further away from the shore: spatial planning regulations prohibit energy production in large parts of the European waters that are designated for other purposes, and the wind resources are usually better further remote. New turbine foundation technologies presently under development allow the installation of wind turbines to water depths up to 40 m, enabling turbine installation at these remote sites. The high power ratings and long transmission distances however challenge the realization of cost-efficient grid connections of such wind parks. Technical limitations of ac transmission prevent the simple up scaling of this technology.

With ambitious plans in the North Sea and Baltic Sea regions, one could argue that a more coordinated approach of the grid connection problem could lead to more cost-efficient and technologically optimized solutions. Clustering of multiple wind farms into a dedicated grid-connection infrastructure would offer the advantages of economies of scale. In areas where offshore wind farms are situated in between different countries, synergies with interconnectors are a promising option that could increase the capacity utilization of the offshore electrical infrastructure. This also holds for combinations with other renewable energy sources and offshore clients such as the oil and gas industry. This paper presents an overview of the possibilities.

The organization of the paper is as follows. First it is recapitulated how wind energy production is governed by the characteristics of the wind and the impacts on the transmission system utilization associated with these. In section III the combination of infrastructures and synergies with other applications of an offshore grid are explored. Section IV gives an overview of technologies that are available to realize alternative connection schemes. The paper ends with some conclusions and an outlook.

II. TRANSMISSION SYSTEM UTILIZATION

The prime mover of wind power, the wind, is variable in nature. Wind velocities are distributed according to the Weibull distribution. A typical wind distribution is depicted in Fig. 1. The power output of individual wind turbines, then, is characterized by their power curve: the relation between the wind velocity and the power output. Modern commercially available MW-class wind turbines are of a variable-speed, pitch-control type. The amount of energy that is extracted

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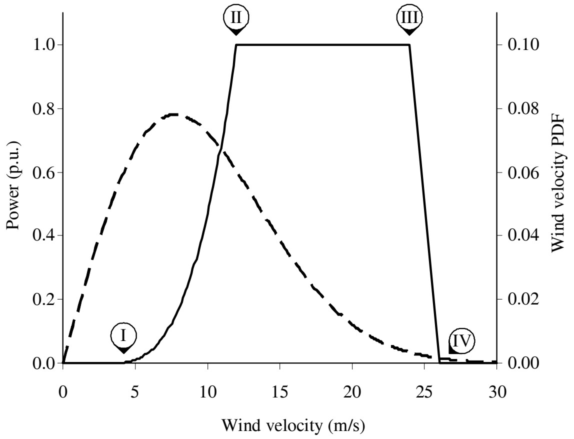

Fig. 1 Typical wind speed distribution (dashed) and wind turbine power curve, with typical points indicated (I–IV)

from the wind is regulated by pitching the turbine's rotor blades, resulting in a variable rotational speed of the rotor. This deviation from the rated speed of the electric generator is enabled by the use of power electronics. The power curve of a variable-speed wind turbine has several characteristic points (see Fig. 1): the cut-in wind speed (I) determines the minimum wind velocity at which the turbine starts producing power. Above cut-in wind speed, the turbine's output power depends on energy in the wind and the wind turbine's power coefficient, which is designed in such a way that energy yield is maximized for a specific location. At rated wind speed (II) the power extracted from the wind is curtailed at the rated output power of the electric generator. Above cut-out wind speed (III), the turbine is shut down to prevent mechanical damage. It must be noted that the newest variable speed-type turbines are capable of decreasing their output power gradually instead of cutting-out (III–IV), with the benefits of increased energy yield and the reduction of mechanical stresses since sudden shut-downs are absent. A typical power curve of a variable-speed turbine is included in Fig. 1.

Wind variations are smoothly averaged over the area of a single wind park, even though influences between turbines may be present (i.e. wake effects etc.). Hence the power curve of the complete park can largely be regarded as a scaled version of the power curve of individual wind turbines. The gradual decrease at cut-out wind speed also accounts for slight differences in wind speed and/or turbine parameters. By combining the aggregated power curve with the wind speed distribution, the energy yield of the park can be evaluated [1]. A common way of visualizing this energy yield is the power duration curve (Fig. 2). This curve indicates the amount of time that a certain output power is exceeded. A major advantage of this representation is that an immediate insight is gained in the capacity factor of wind power, the ratio of energy yield over the theoretical maximum yield, for certain time duration. Furthermore, the integral of the power duration curve directly gives the energy yield in the time interval considered. Modern offshore wind parks have capacity factors in the range of 0.3–0.4 also taking into account wind turbine unavailability.

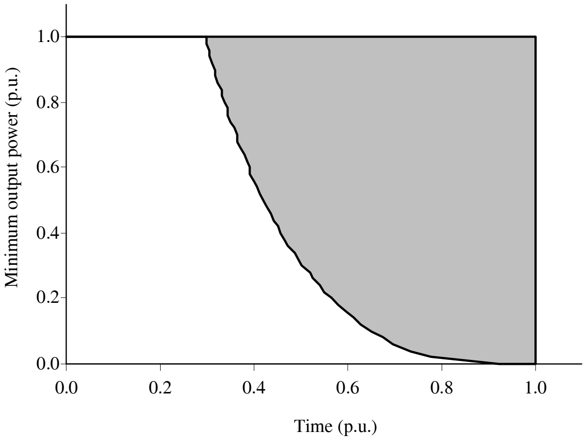

Fig. 2 Production duration curve for a typical offshore wind farm. The white area corresponds to the capacity factor, 44.5% in this example, not taking into account unavailability. The gray area is the unused potential of the transmission system (55.5%).

When the wind farm has an own grid connection, the electrical infrastructure is subjected to the same capacity factor as the wind park itself. Referring to the gray area in Fig. 2, this implies that more than half of the power transmission potential is not used. Worse, wind turbines are usually designed with a lifetime of about 20 years. Licenses are mostly granted for a time span in the same range, after which decommissioning of the installation is usually prescribed. The expected lifetime of switch gear and cables could be twice as long however.

III. CONNECTION ALTERNATIVES

A. *Clustering of Wind Farms*

A first incentive for a more economical grid connection for large-scale offshore wind power could be found in the clustering of the grid connection infrastructure for several wind farms that are situated in the same area. This type of grid integration has for instance been investigated in the Netherlands [2]. In this country, a high number of licensing permits for offshore wind farms in the North Sea have been requested from 2005. The densely populated coastal area makes it challenging to connect these projects to the high voltage network. Hence, a coordinated approach has been considered. Connection alternatives have been looked at in which the power of multiple wind farms was bundled on offshore platforms and then transmitted to the shore with various transmission technologies, including 380 kV high-voltage ac (HVAC) and high-voltage dc (HVDC).

Other reasons could lead to such a bundling as well, such as environmental legislation that limits the right of way assigned for offshore cable routes. Also in a study in Germany it was proposed that offshore substations will be created that serve as a hub to where the individual wind park projects connect to [3], see Fig. 3. The higher power rating at the collection platform makes the application of other transmission technologies more realistic than in the case of individual connections. The German legislation has recently been changed, making the transmission system operator

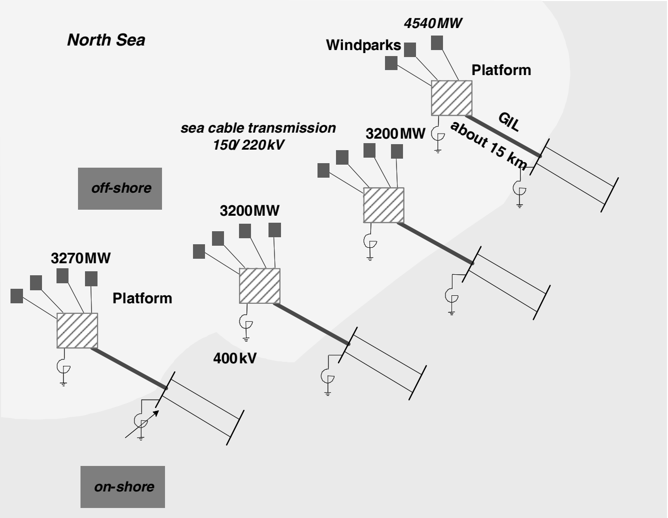

Fig. 3 Proposal for the clustering of offshore wind farms in the North Sea in Northern Germany. Each offshore substation collects the power of several wind farms (figure from [3]).

(TSO) responsible for the grid connection of wind energy. Such a regulatory framework, also under discussion in other countries, of course stimulates the development of clustered connections, since the TSO will be inclined to optimize the grid extension.

However, clustering of multiple wind parks does not lead to a significant increase of the capacity utilization of the transmission infrastructure. Even in an area of several hundreds of km cross section wind speeds are correlated [4]. Besides, if the infrastructure lacks redundancy, the amount of energy not used could be rather high, in case of outages in the transmission system. Thus, synergies must be sought with other possible applications of submarine transmission cables in order to increase their utilization.

B. Synergies with Other Sources of Energy

The capacity utilization of grid connection infrastructure could be increased if synergies are sought for with offshore producers or consumers whose production or load profile has a low or negative correlation to wind speed. Other sources of renewable energy that can be found offshore are wave and tidal energy. However, these technologies are not yet at the same level of commercial exploitation as offshore wind energy. Moreover, these sources of energy are mostly applicable only close to the shore.

More potential could be gained from the connection of oil and gas production platforms. The majority of these platforms are relying on own generation, based on gas turbines or diesel-generator sets. A connection to the mainland power system enables the use of more efficient and environmentally friendly produced energy for these industries. Large platforms have a power demand of several tens of MW, most of which is base-load. Connection of such a platform would shift the power duration curve of the transmission system downwards, while most of the time the wind farm feeds the consumer. Most important effect is that the peak of the curve is lower and hence a transmission system with a lower rating would suffice. In periods of low wind, power could be supplied from the onshore network. The grid connection is then operated bi-directionally.

Another possibility is the further exploitation of gas fields that are at the end of their lifetime. If the gas pressure drops below a certain threshold, it is not considered economical to continue production. In situ conversion of the remaining gas to electricity is an interesting alternative. Since gas-fired generation units have a wide operating range, their production could be matched to be complementary to the fluctuating wind farm output. Such a co-utilization scheme could have a high capacity factor.

C. Synergies with Interconnectors

With the deregulation of most of the energy markets in Europe, the concept that production and consumption are balanced regionally is abandoned. Interconnectors between power systems, that have traditionally been built to increase system security, now form the backbone for long-distance transmissions resulting from international electricity trade. In certain areas the limited interconnection capacity between national power systems represents physical transmission bottlenecks and thereby barriers in the creation of single European electricity market.

Such bottlenecks are for instance identified in the North Sea and the Baltic Sea regions. These areas do also have sound conditions for offshore wind power production: good wind resources and shallow waters. It is an obvious next step to study the synergy of new interconnectors between the coastal states and grid integration of wind farm projects.

Besides the technical challenges associated with the connection of offshore wind parks and interconnectors, such a connection scheme requires a coordinated set of regulations and market designs between different power systems connected to this scheme. The power direction on the interconnector will mainly be influenced by the market prices at both ends of the link. The energy will flow towards the system with the highest price. If no special precautions are taken to prioritize the infeed of wind power, it will mean that the wind power, with its low marginal costs, can only be fed into the system with the lowest market price.

D. Trans-national Offshore Networks

The abovementioned options indicate that there is potential to gain by efficiently combining wind power with other applications for offshore power transmission networks. Further coordination could lead to the creation of trans-national offshore networks. A single network would connect several states, offshore wind power plants and other sources of energy, and large consumers such as oil and gas platforms. There are a number of market and regulatory issues associated with this type of network, apart from the technical challenges [5]. The simultaneous integration of wind power into different electricity markets requires efforts to harmonize market type, market closure times and arrangements for balancing wind power. Regarding regulations, particularly the differences in financial support schemes form a barrier to such an integrated approach. Also, the different national legislation regarding the construction and operation of cables needs to be harmonized, at first instance by the creation of bi-lateral agreements between interconnected states.

IV. TRANSMISSION TECHNOLOGIES FOR OFFSHORE APPLICATIONS

A. Limitations of AC Transmission

AC transmission is the first choice for the connection of offshore wind farms, since the main power grid is built around this technology. Modern submarine cables apply cross-linked polyethylene (XLPE) insulation. Cables up to a voltage level of 150 kV have been successfully applied for connecting wind power. Up to this voltage level, three-core cables are available that have the added benefit of simple installation. The maximum voltage level at which XLPE submarine cables are presently available to the market is 245 kV, designed as single-core cables. Scaling up to 400 kV is foreseen.

The application of ac submarine cables is limited due to the capacitive nature of the cable itself. It produces a reactive current, which limits the current capacity available for the transport of active power. The amount of reactive power depends on the cable length and on the square of the system voltage. Theoretically the transmission distance could be increased as long as reactive power production is compensated along the route, which is only practical when it can be combined with a platform for client connections. Installing compensation reactors only at the line ends extends the transmission distance, but the effect is limited [6].

Several solutions have been proposed to increase the transmission distance. One is the operation at a lower frequency, such as 16⅔ Hz. This requires extra frequency conversion equipment and larger transformers and reactors. Another method to increase the maximum distance is found in using more than three phases [7].

B. HVDC Transmission

The main alternative to ac transmission is the use of dc. Since the 1950s HVDC schemes have been successfully installed. Power electronic converters are required to convert ac to dc and vice versa. Two families of converters are available: the line-commutated converter (LCC) and the more recently introduced voltage-sourced converter (VSC).

At dc the capacitive phenomena are absent and, hence, the transmission distance is not limited by reactive power production of cables. This advantage however comes at the added costs of the required converter stations at both sides of the connection. Also, due to the switching losses of the power electronics, the total transmission losses are increased compared to HVAC. For small power ratings HVDC therefore is not considered an economical solution. However, for large-scale wind power integration, it could be competitive to, or be even cheaper than HVAC transmission [8].

C. LCC-Based HVDC

The LCC is based on power-electronic switches with turn-on capability, mainly thyristors. Robust converters up to several thousands of MW have been realized onshore. For offshore wind power applications this type of converter is not very suitable. The LCC requires a strong network voltage to commutate against. Wind farms usually have weaker grids that cannot supply such a strong voltage. Also the capability to energize the system from shore (black start) is a challenge. These issues are alleviated by combining the LCC-interface for an offshore wind farm with some auxiliary source of reactive power. Moreover, the LCC produces considerable ac-side current harmonics that require filter banks. The large space footprint of such equipment will make it challenging for installation on an offshore platform.

D. VSC-Based HVDC

The disadvantages of LCC-based HVDC can to a great extent be overcome by the VSC. The VSC is able to control active and reactive power independently and generates a voltage on the ac-side. It is therefore able to operate in weak networks. Since it operates at a much higher frequency than the LCC, it produces considerably less harmonics. A negative aspect is that due to this higher frequency switching losses increase, up to 2% per converter. VSCs have been realized to power ratings of 350 MW, but the technology can be scaled to ratings of about 1 GW. Limiting factor is the availability of cables for higher voltage levels. The first wind farm project that applies a VSC-transmission link is to be commissioned in 2009.

A VSC-connected wind farm requires a tailored control system. In normal operation the offshore converter is functioning as a slack node which absorbs the fluctuating power of the wind turbines. These power fluctuations exhibit themselves as variations in the direct voltage. The onshore converter keeps the power in the circuit balanced by regulating this direct voltage.

The main drawback of the VSC is its limited current capability. Even for very short durations, over-currents cause thermal stresses that degrade or cause permanent damage to the switching elements. In the case of a grid-side fault the system voltage is temporarily reduced. Since the current is limited, the power that can be fed to the ac system is reduced as well and the onshore VSC cannot regulate the direct voltage. A very fast reduction of the offshore power generation is required to keep the scheme in operation.

Several strategies are available to quickly reduce the offshore generated power [9]. First is to equivalently decrease the offshore ac-system voltage. A too fast voltage reduction however, could lead to too high currents damaging the offshore converter. Besides, if the wind farm consists of doubly-fed induction generator-based turbines, there exists the risk of triggering the crow-bar protection system of these machines. A second method is to temporarily increase the offshore network's frequency. If the wind turbines are equipped with power-frequency control [10], the output power will be changed accordingly. A disadvantage is that a very steep frequency-droop characteristic is required, which could lead to strong undesired power fluctuations during range of other fault scenarios. Third strategy is to use communication links to signal a power-reduction order to the wind turbines. Problem with this strategy is that it is likely to be too slow, and not inherently fail safe, since telecommunications are part of the control loop. A final strategy can be found by equipping the DC circuit with a chopper-controlled resistor. When the direct voltage exceeds a threshold value, this braking resistor is used to dissipate excess power from the circuit to restore power balance. This strategy has the important benefit that it is robust, although somewhat un-elegant.

E. Multi-Terminal DC Networks

Some of the synergetic transmission systems introduced in the previous section require the connection of more than two terminals to a common DC-bus, leading to the creation of multi-terminal dc (MTDC) schemes. This is especially relevant for the synergy with interconnectors discussed previously, since in most cases the power systems at both ends of the submarine link are not synchronized. From the early days of HVDC, LCC-based MTDC systems have been considered highly complicated or even problematic because of the high number of different operating modes and the associated complexity of the control systems. Especially the task of maintaining the power balance in the dc network, while on the other hand reacting adequately to ac-system faults, is cumbersome. Only a handful of LCC-based MTDC schemes have been realized, of which only two are still in operation today.

The VSC offers better possibilities for multi-terminal operation modes. In fact, in industrial drive systems the parallel operation of multiple VSCs is common practice. The direct voltage serves conveniently as a measure for unbalances in the system. The well-known concept of power-frequency control in ac systems can then be easily extended to dc systems [11]. Converters are to be equipped with a direct-voltage droop characteristic that regulates the amount of power that is fed into or absorbed from the ac system. In such a way the fluctuations of the wind power infeed can be equally divided among both interconnected systems, or in any other desired distribution.

F. Gas Insulated Lines

Another method to overcome the limitations of ac cable transmission is the use of a different type of conductor that has a lower capacitance. Such a conductor is the gas-insulated line (GIL). The technology is a continuation of the successful gas insulated switch gear (GIS) to power transmission. A GIL conductor consists of an outer conductor at earth potential, and an inner conductor that is kept centered by specifically designed spacers. The area in between is filled by SF_6 gas under low pressure that has excellent isolating properties.

Only few GIL systems have been built yet, none of which offshore. The high experience with offshore pipe-laying gives rise to belief that the technology could be adapted to submarine circumstances.

V. OUTLOOK AND CONCLUSIONS

The development of future wind farms, both further away and with higher ratings than current projects, highly depends on the realization of an economical solution for grid connection. This paper has given an overview of solutions that enable synergies for increasing the capacity utilization of the transmission infrastructure, as well as new technologies to realize these.

The German case demonstrates that the clustering of multiple wind farms into a single transmission infrastructure is becoming reality. Clustering platforms are foreseen that collect the power of several wind farms from where it is transmitted to the shore. Still, in the area of such a collection platform wind speeds are highly correlated and hence the capacity utilization of the transmission infrastructure does not significantly improve by clustering.

The capacity utilization could be increased further by finding synergies with other applications of offshore power transmission infrastructure. The most promising are the combination with oil and gas production platforms, which add a certain base load, reducing the transmission system rating, and the combination with interconnectors, which can utilize the capacity that is not used by wind for energy transactions between interconnected countries.

The extent to which these initiatives could become an integrated whole and form a trans-national offshore grid, for instance spanning the North Sea and Baltic Sea regions, is a question to be answered both by research and by policy makers. Project developers and TSOs have as primary goal keeping the costs for (inter)connection low, and such a high degree of integration seems to overreach that goal. Governmental support will be needed to start initiatives on this.

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VII. BIOGRAPHIES

Wil L. Kling received his M.Sc. degree in electrical engineering from the Technical University of Eindhoven in 1978.

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Ralph L. Hendriks received the B.Sc. and M.Sc. degrees in electrical engineering from Delft University of Technology in 2003 and 2005 respectively.

Since 2005 he is a Ph.D. researcher at the Electrical Power Engineering Department at Delft University of Technology, the Netherlands. His main research topic is grid integration of offshore wind farms through high-voltage direct-current transmission, with a special focus on synergies with interconnectors. From 2007 he is also a consultant with Siemens AG, Energy Sector, Erlangen, Germany. His research interests include power system stability and control, grid integration of large-scale renewable energy sources and modeling of power electronics.

Henk den Boon received the M.Sc. degree in chemical engineering, specialization in energy technology, from Delft University of Technology in 1977.

Since 1986 he is CEO of E-Connection Group, the Netherlands, a major project developer of onshore and offshore wind parks. Among others E-Connection developed the offshore wind park Q7-WP of 120 MW, located in the North Sea 25 km west of IJmuiden harbor, which is now under construction. He has been responsible for the engineering of the grid connection of many wind parks; including the 35 km long HVAC grid connection for offshore wind park Q7-WP, consisting of a 150-kV cable connection with reactive compensation by the offshore wind turbines.