THE GERMAN OFFSHORE GRID - A SUCCESSFUL INTEGRATION OF OFFSHORE WIND POWER

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Abstract - **The ambitious expectations of politic and industrial sectors are stimulating the planning activities for offshore wind power. Under the Infrastructure Planning Acceleration Act, which entered into force on the 17th of December 2006, the transmission system operators (TSO) in Germany are required to provide grid connections for offshore wind parks up to their offshore substations. This has prompted E.ON Netz to plan for a "first of its kind" bulk power offshore grid connection in the North Sea. With a total offshore wind power requesting for grid connection ranging up to 12 000 MW by the end of 2011, the design of an ecologically, economically and technically efficient offshore grid is extremely complex. The ongoing work to reach this goal is described in this paper.**

I. INTRODUCTION

By the end of 2006 around 30 wind parks were planned in the area of the German North Sea with a total requested installed capacity up to 12 000 MW. The Infrastructure Planning Acceleration Act came into force on the 17th of December 2006 and changed the basis of planning an offshore wind park (OWP). Before this act all OWP-planers had to plan and finance their own interconnection to the onshore grid, i.e. obtaining the routes and planning permissions. Now the transmission system operators (TSO) are required to provide the grid connection right up to the offshore substation of the wind parks. The general aim is to generate ecological, economical and technical advantages by reducing the number of individual interconnections by using bulk power transmission through a co-ordinated overall planning by the transmission system operator.

In order to minimise the number of transmission routes it is useful to combine the OWP to clusters based on their location and to connect these clusters with high power links to the onshore grid.

There are some fixed boundary conditions for the whole planning activities like onshore grid connection points, distances between OWP-clusters and coastline and the distances between coastline and onshore substations.

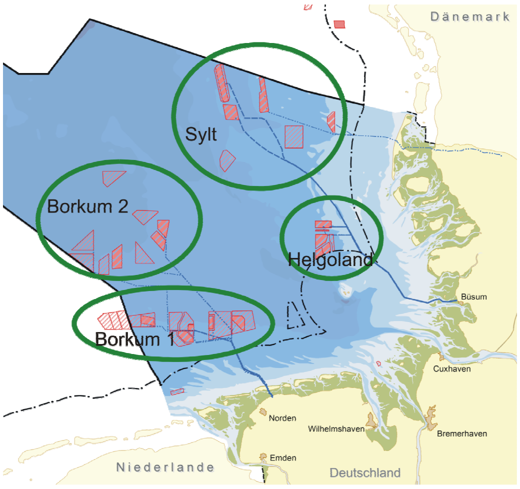


Fig. 1: Planned offshore wind parks (clusters marked in green) and transmission traces in the German North Sea. [1]

The grid connection points, Diele, Brunsbüttel and Jardelund, were established for offshore wind power under the dena Study [8]. The OWP-clusters will be connected to these grid connection points.

The first grid connection point, Diele, is located about 65 kilometres south of the shoreline nearby the island Norderney. The offshore distance from the shoreline to the clusters Borkum 1 and 2 is ca. 65 and 130 km respectively. The second grid connection point is the substation Brunsbüttel, close to the nuclear power plant. Because

Rated voltage	Rated operational voltage	Insulation material	Cross section	Transmission capacity	Reactive power
170 kV	155 kV	XLPE	3x1x630 mm² Cu	180 – 200 MVA	1.4 Mvar/km
170 kV	155 kV	XLPE	3x1x800 mm² Cu	190 – 210 MVA	1.6 Mvar/km
170 kV	155 kV	XLPE	3x1x1000 mm² Cu	220 – 230 MVA	1.8 Mvar/km
170 kV	155 kV	XLPE	3x1x1200 mm² Cu	240 – 250 MVA	2.0 Mvar/km

Table 1: 170 kV XLPE Submarine cables

of the planned routing on land, the onshore distance between shore (near Büsum) and the substation is around 50 km. The third grid connection point is Jardelund, located about 70 kilometres east of the island Sylt. The offshore-distance from Brunsbüttel landing point to the clusters Helgoland and Sylt is ca. 95 and 160 km, and from Jardelund landing point ca. 80 and 75 km. The planned OWP-clusters together with the different offshore transmission routes are shown in Fig. 1.

Based on the specifics of grid connections, the envisaged time schedules and using routes already developed by the project developers, the onshore transmission sections have to be planned as cable routes.

E.ON Netz faces a great challenge to develop an optimized grid connection for all offshore wind parks and to use the synergy effects of a structured planning especially as the planning criteria are not clear. Uncertainties in the total installed park capacities due to unclear rated power of available wind turbine generators, unclear timelines for the erecting phases and expected delivery bottlenecks of nearly all equipments (i.e. primarily in the high- and medium-voltage cables) are only some of the factors which make the planning extremely complex. An additional challenge is the ambitious time schedule and the different state of planning activities previously carried out by the individual OWP planners up to now.

II. AC VOLTAGE OFFSHORE

To allow optimization of the wind park clusters, it is important that the system voltage is standardised. This provides the ability to interconnect the wind parks in clusters. Most of the previous individual plannings were based on different voltages. With a consistent offshore voltage level is it possible to connect two or more wind parks without the need of an extra transformer.

For the wind park planners it is also important to define the AC voltage level of the offshore grid as soon as possible, because of the long delivery and commissioning time especially of the transformers, which can take up to more than 24 months.

The most important factor in defining a standardised voltage level is the availability of submarine cables. There are two different types of insulation technology:

- Paper insulated cables
- Extruded cables
  (crosslinked polyethylene)

Extruded cables offer advantages in weight, diameter and cost compared to paper insulated cables. Additionally the cable laying is easier. However, up to now, the maximum available rated voltage level is around 170 kV for extruded submarine cables. In the near future, 220 kV XLPE cables will be available.

The standardised voltage level must be based on the available cable technology, as well as suitable for the distance and power rating required for most offshore wind parks. Higher voltages can transfer larger power at lower losses. However, the higher the voltage, the amount of reactive power compensation required becomes larger and as a result, the maximum transmission distance shorter. Based on these considerations and the current available technology, only the 170 kV cable is considered suitable. In order to have +/-10% operating range, the operating voltage of 155 kV is suitable for the offshore systems.

With a transmission capacity of one three- core-cable system at about 200 - 240 MVA (Table 1), for most wind parks it is necessary to lay two systems in parallel.

III. WIND PARKS WITH INDIVIDUAL CONNECTIONS

Although a standardised AC voltage should be used for the connection of OWP in the German North Sea, there are some exceptions. These are some projects with a special position because of their location, size or purely advanced planning state. The following characteristics define these wind parks, which are connected with individual transmission links:

- Parks outside the areas where clustering is possible
- Parks with only few wind turbine generators
- Parks with distances to the onshore connection point significantly shorter than 100 kilometres
- Parks which are close to their construction phase

Four projects are identified as OWP with individual connections. These projects were planed with a direct AC connection to the onshore grid. For validation the planned concepts including parks and the intended grid connections were simulated. Loadflow and dynamic calculations have been carried out to assess the compliance to the E.ON Netz Grid Codes [3]. The four main results are:

1. Grid interconnections using medium voltage cables cause problems with the voltage level at the offshore substation. Overvoltages could occur up to critical levels of the cables.
2. For short lengths between the OWP and the onshore connection point, the reactive power infeed into the onshore grid could be too small to meet the Grid Codes requirements [Fig. 2].
3. Individual AC connected OWP must be assessed together with the connection system. Compliance to the Grid Code is only possible for a combined system. Otherwise, in some cases additional capacitor banks are required if the connection assessment is carried out offshore.
4. Wind turbine generators have great influence on the results based on the different control abilities and the range of possible reactive power.

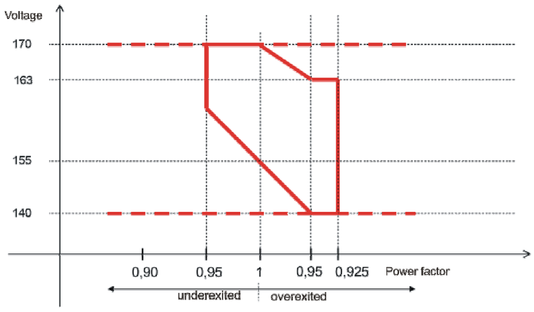


Fig. 2: Grid Code reactive power exchange

IV. TECHNOLOGY SCAN

Due to the locations of the OWP and their distances to the grid connection point, high voltage direct current (HVDC) transmission appears to have the greater advantage. In the last decade, a lot of development took place in the field of HVDC technology (e.g. reduction of converter losses or increase of the available rated power of self commutated HVDC modules). A technology scan was carried out to get an overview of capability of the modern systems.

Although the manufacturers were asked to present AC solutions for these wind park grid connections, none did so because of the benefits DC technology offers and the well known disadvantages of long AC cable connections. Three different concepts for grid connection are available:

- Self commutated HVDC link with pulse width modulation (PWM)
- Self commutated HVDC link with multilevel converters
- Hybrid line commutated HVDC link

a. Self commutated HVDC link with pulse width modulation (PWM)

In self commutated HVDC converters, also called voltage source converter (VSC) HVDC, IGBT semiconductors are the main components. It is possible to multiple switch on and off the valves during one period.

PWM controlled converters switch between maximum and minimum voltage with a variable ratio of on and off time. By low pass filtering the desired fundamental frequency voltage is generated [6] (Fig. 3).

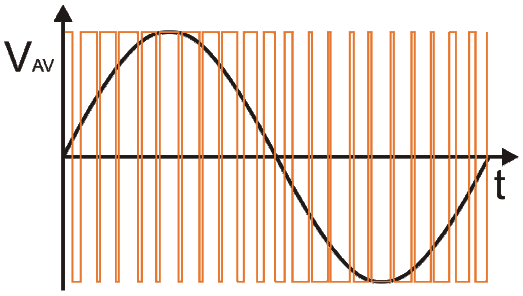


Fig. 3: Voltage characteristics of a PWM converter

b. *Self commutated HVDC link with multilevel converters*

Multilevel self commutated HVDC converters do not switch between the full voltage range but in small voltage steps. The converter bridge consists of many individual modules with valves and a capacitor. Each module acts like a discrete voltage source which is controlled individually and so it is possible especially for high voltages resulting in high number of modules to generate an almost sinusoidal output voltage with low harmonics [5, 7] Fig. 4.

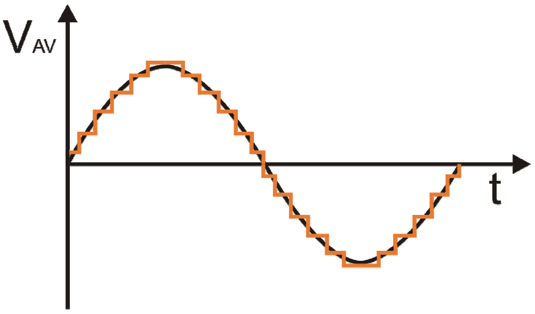


Fig. 4: Voltage characteristics of a multilevel converter

c. *Hybrid line commutated HVDC link*

In a grid consisting only of wind generators the system frequency and voltage has to be supplied by the interconnection. The use of a classic line commutated HVDC (LCC) with thyristor valves need to be combined with a static compensator (STATCOM) installed at the offshore platform to provide voltage and frequency control, Fig. 5. This allows combining the advantages of an LCC HVDC with dynamic performance of a voltage source converter to reduce capital costs and losses [4].

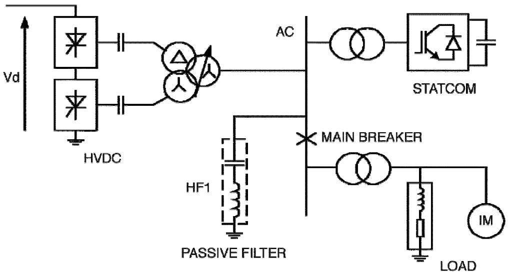


Fig. 5: Single line diagram of the hybrid HVDC system [4]

V. CHARACTERISTICS OF THE HVDC FOR CONNECTION OF OFFSHORE WIND PARKS

It is important to identify the capabilities of the HVDC technology available before 2009. In discussions with major manufacturers, a generic case with an upgradeable HVDC connecting three different wind parks was used (Fig. 6). The parks had different AC cable length of 1, 30 and 50 km respectively and rated active power infeed of 200, 150 and 50 MW. The DC cable was defined with a length of 170 km. With this setup a possible cluster construction phase can be investigated.

Using this generic case, the following requirements concerning the operation of the HVDC were defined:

- Grid Code compliance onshore
- Startup capability of the whole powerless offshore wind park cluster network
- Stable operation of the system in all operational relevant conditions, especially during defined onshore and offshore network faults
- Support of the OWP during fault conditions by using the control capability of the interconnection

It was identified, that the critical points for the design and operation of the HVDC operation were:

- Network startup
- Reactive current for network support during and after faults (Grid Code compliance)
- Continuous operation during a short circuit in the 33-kV network
- Continuous operation during a short circuit near the onshore connection point

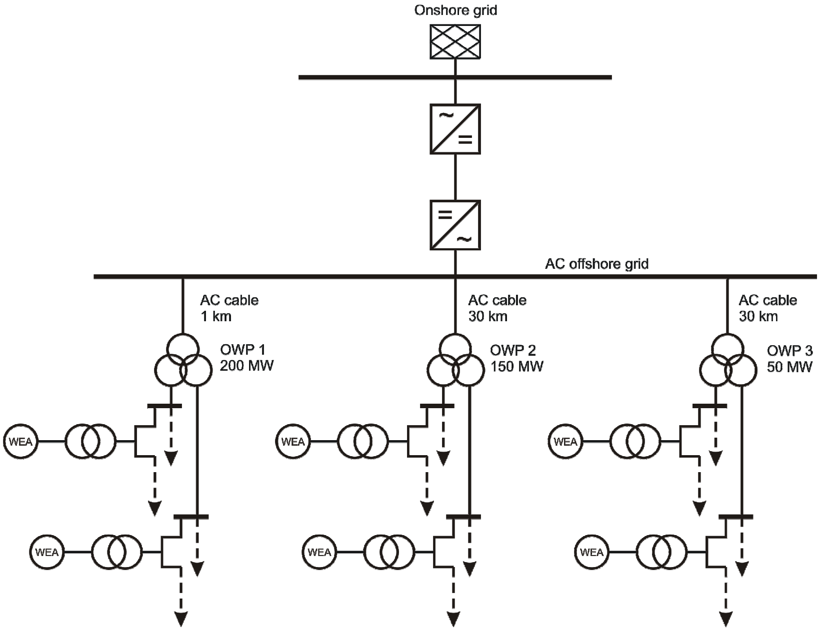


Fig. 6: Generic study case with an HVDC connecting of three different wind parks

To achieve Grid Code compliance for the reactive current support during and after fault VSC HVDC offer the independent controllability of reactive power at both ends (4-quadrant-operation). Due to the characteristic of the thyristors absorbing reactive power LCC HVDC needs extra equipment (e.g. STATCOM) onshore to fulfil this requirement.

The most onerous design criterion is to ensure a continuous operation of the overall system during a short circuit near the onshore connection. During a short circuit, it was identified that the onshore HVDC converter cannot feed active power into the grid because of the low system voltage. However, because the connected offshore wind park continues to feed active power into the DC circuit through the offshore converter, the DC voltage will rise and can exceed the maximum level. This causes the shutdown of the whole DC link resulting in the shutdown of all wind turbine generators or, in extreme situations, damage to the DC cables.

One method to prevent this overvoltage in the DC circuit is to lower the offshore voltage in the same way the onshore voltage decreases. The active power infeed of the wind turbine generators will then reduce because of their own control and protection system (Fig. 7). Depending on the depth of the undervoltage and on the type of wind generator this may trigger internal protection procedures like crow-bar operation which could result in significant stress for the turbine and generator. This solution needs to be further investigated.

Another solution is to use a DC chopper which can absorb the occurring surplus energy during the undervoltage period onshore. Thus the offshore grid is decoupled and the wind turbine generators do not notice any changes, due to the DC chopper, and they stay connected (Fig. 8). After fault clearance, the onshore converter can immediately feed in active power again. Thus the interconnection is able to provide support for the wind generators and improves stability and reliability of the wind energy infeed.

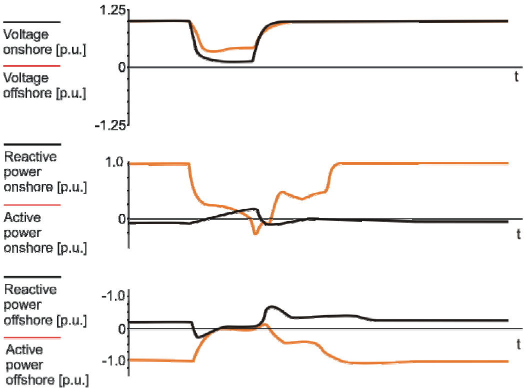


Fig. 7: Typical behaviour of a VSC HVDC during three-phase-fault onshore without DC chopper

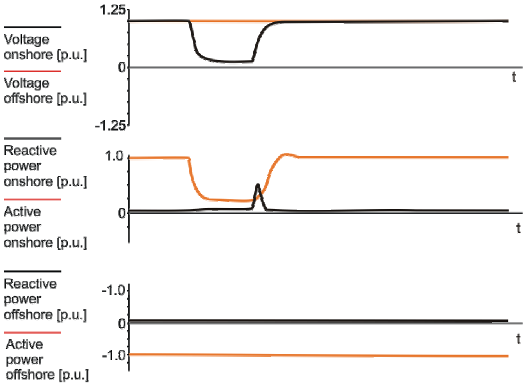


Fig. 8: Typical behaviour of a VSC HVDC during three-phase-fault onshore with DC chopper

From this study the VSC HVDC links appear to be the best technology for the first step to build up a high power transmission system to connect the OWP-clusters.

In the ongoing extension of the offshore connection it might be reasonable also to integrate HVAC-transmission and especially bulk power LCC HVDC links because of lower converter losses. Extensive studies have to be performed on the parallel operation of the different technologies to investigate chances and risks. For the given connection of offshore wind parks the main advantages of the VSC HVDC are:

- Inherent startup capability
- Dynamic control of the AC voltage in the offshore grid
- Independent active and reactive power control (within ratings)
- Decoupling of the offshore and the onshore grid resulting in maximum support of the wind generators during fault condition
- Relatively small or even no harmonic filters required
- No synchronous compensator in the offshore grid is necessary
- Fulfilment of the onshore Grid Code requirements without extra equipment
- No commutation failures
- Compact site area

VI. TECHNICAL REQUIREMENTS FOR OFFSHORE

The offshore wind parks are connected to a relatively weak system with low short circuit currents. If it is connected via a HVDC system, the offshore wind park will be decoupled from the onshore transmission system. This type of network necessitates specialized requirements typical to ensure the security and stability of islanded networks. It is essential that the overall system still has the same characteristics and features as required for a large onshore connection. In order to provide clear guidelines and interface for the offshore wind park developers for their design, the current Grid Code needs to be transposed to the new boundary. These transposed offshore requirements must:

- Ensure that the overall system fulfils the current Grid Code onshore
- Provide an efficient overall system
- Ensure that the connection system is neutral to all types of offshore wind turbines / generators
- Allows the possibility of multiple connection from different wind parks
- Ensure the stability of an islanded network
- Ensure the continuous operation of the overall system for minor faults (onshore and offshore)
- Ensure that design of the connection system matches the designed wind park

The following aspects are identified as necessary requirements to the design and operation of the offshore system.

a. Voltage

The voltage level is standardised to 155 kV for the offshore systems.

As defined onshore, during system faults, it is essential that similar voltage support is required from the offshore wind parks. This ensures that a continuous operation is achieved, with minor impact on the onshore system. Due to the large total installed capacity planed in Germany, a large change in power injection can result in instability in the onshore transmission system. As a result, the offshore voltage support and reactive power range must be retained as for onshore systems [Fig. 2].

An optimal operating point, which allows the largest flexibility and lowest losses, must be selected within the available operating region by retaining the reactive power range and support, this will also provide unbiased requirements for wind parks connected via HVDC or HVAC system. With less system inertia, the deadband for the voltage support should also be reduced (Fig. 9).

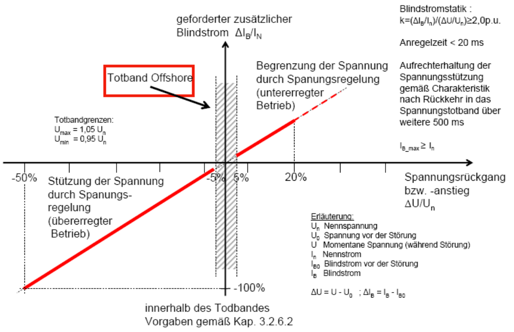
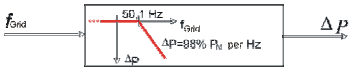


Fig. 9: Voltage support offshore

b. *Frequency band*

Due to the absence of load (motors) and generators with large inertia, and the low short circuit level, the frequency variation in the offshore system is expected to be larger than in the onshore grid. In order to keep the system in operation for most minor faults, the frequency band of the offshore system needs to be increased to 46.5 – 53.5 Hz [Fig. 10].

With only the wind parks connected to the offshore system, these wind parks must also have a larger contribution to frequency control. During cases where the HVDC is unable to control the frequency, the wind parks must be able to quickly reduce their real power to mitigate the rise in frequency [Fig. 11].



$$\Delta P = 49\ P_M\ \frac{50{,}1\ Hz - f_{Grid}}{50\ Hz} \qquad 50{,}1\ Hz \leq f_{Grid} \leq 51{,}1\ Hz$$

P_M	available power
ΔP	power reduction
f_{Grid}	frequency of the grid

Fig. 11: Active power reduction during over frequency

c. *System design*

Fault level - Based on simulations carried out with typical HVDC-links (both VSC and LCC) and short circuit current contribution of 1.7 – 11.5 kA from the wind turbines, the fault level is expected to remain less than 16 kA.

Reactive power compensation - As it is inefficient to transport reactive power through large distances, decentralised cable compensation strategy will be the most efficient. Each cable must be compensated locally, 80% for the 155 kV cable and 100% for the wind park internal networks. This strategy also ensures that for the lost of a network section, the corresponding reactive power balance is more or less maintained.

VII. CONCLUSION

This paper describes the state of the ongoing work to design an ecologically, economically and technically efficient offshore grid and transmission system which can integrate up to 12 000 MW wind power into the German transmission grid.

It is essential that the design of the con-

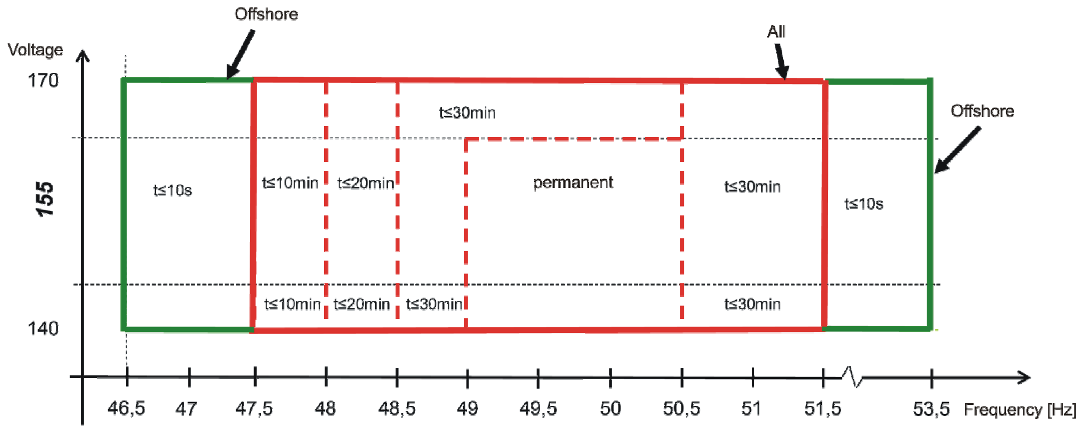


Fig. 10: Frequency band offshore with minimum connection duration

nection system and the offshore wind parks guarantee the security and stability of both the onshore and offshore network.

With this in mind, the E.ON Netz Technical Requirements for Offshore were defined and provided to the wind park developers. These requirements contain:

- Definition of a standardised voltage level
- Requirement for voltage support with a smaller deadband and the required reactive power capability
- Requirement for a larger frequency band and faster response
- Provision of additional information for equipment specifications

Through an intensive technology scan and generic study case, it was established that compliance to the Grid Code onshore and the requirements offshore using HVDC technology is complex. The critical design criteria were discussed in this paper and the solutions identified but need to be further investigated.

For the first grid connection system, the VSC HVDC technology was found to be advantageous. The first 400 MW transmission system connecting offshore wind power using VSC HVDC technology, the *NordE.ON 1*, will be designed based on these criteria and includes the relevant requirements for a stable and secure operation.

Future developments of the grid connection for offshore wind parks must be carried out in the most cost efficient manner. However, due to the lack of concrete information on the progress of the wind parks, the most cost effective way seems to be the development of the offshore connections in incremental stages. Each stage will need to be compatible to the existing onshore and offshore network, and must be technically and economically optimised.

In addition, in view of the technical complexities, these future development stages need to be specified and designed well in advance. Furthermore, compliance monitoring of the connected wind parks must be continuously carried out.

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Rolf Witzmann received the Dipl.-Ing. (M.S.E.E.) and the Dr.-Ing. (Ph.D.E.E.) degrees from Technische Universität München in 1982 and 1989, respectively. From 1990 to 2004 he was with Siemens AG in Erlangen, Berlin and Frankfurt. For more than 10 years he was Senior Consultant and Director in the Network Analysis and Consulting Division of the Power Transmission and Distribution Group. His fields of activity were stability of large interconnected power systems, HVDC-transmission, FACTS (Flexible AC Transmission Systems) and power quality. After this he was active in research and development being responsible for the R&D project in High-Temperature-Superconductivity. From 2002 he was head of technology department of the Medium Voltage Division of the Power Transmission and Distribution Group. In December 2004 Rolf Witzmann was appointed professor of Technische Universität München, Associated Institute of Power Transmission Systems. His main fields of activity are system stability, decentralized generation of renewable energy and the impact on the transmission and distribution systems.

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