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1. Background Material

LITERATURE USED:

- [1] Ministerie van Economische Zaken en Klimaat; Voortgang uitvoering routekaart windenergie op zee 2030; (link); 05-04-2019
- [1] Ministry of Economic Affairs and Climate; Progress of implementation of Offshore Wind Energy Roadmap 2030; (link); 05-04-2019

2. Scope and Considerations

For the roadmap offshore wind 2030 (routekaart windenergie op zee 2030) TenneT is tasked with the connection of several offshore wind farms up to 2030. The wind farm zones 'Hollandse kust West' and 'Ten Noorden van de Waddeneilanden' will be connected with TenneT's previously established and consulted standardized 700 MW grid connection concept. Due to its size and distance to shore, a new grid connection concept has been established for the wind farm zone IJmuiden Ver. The figure below shows a schematic cross-section of this new grid connection concept. Wind turbines are connected through 66 kV “inter-array” cables (in orange) to an offshore (HVDC) converter station. Using 2 GW high voltage (525 kV) export cables (in green) the electricity is transported to shore. TenneT will be responsible for the offshore grid, from the onshore substation up to and including, the offshore substation. TenneT intends to create a new standard HVDC grid connection concept for both connections to IJmuiden Ver and potential future far shore wind farms.

This paper describes the how TenneT assessed various grid connection systems to come to the most optimal grid connection for IJmuiden Ver wind area.

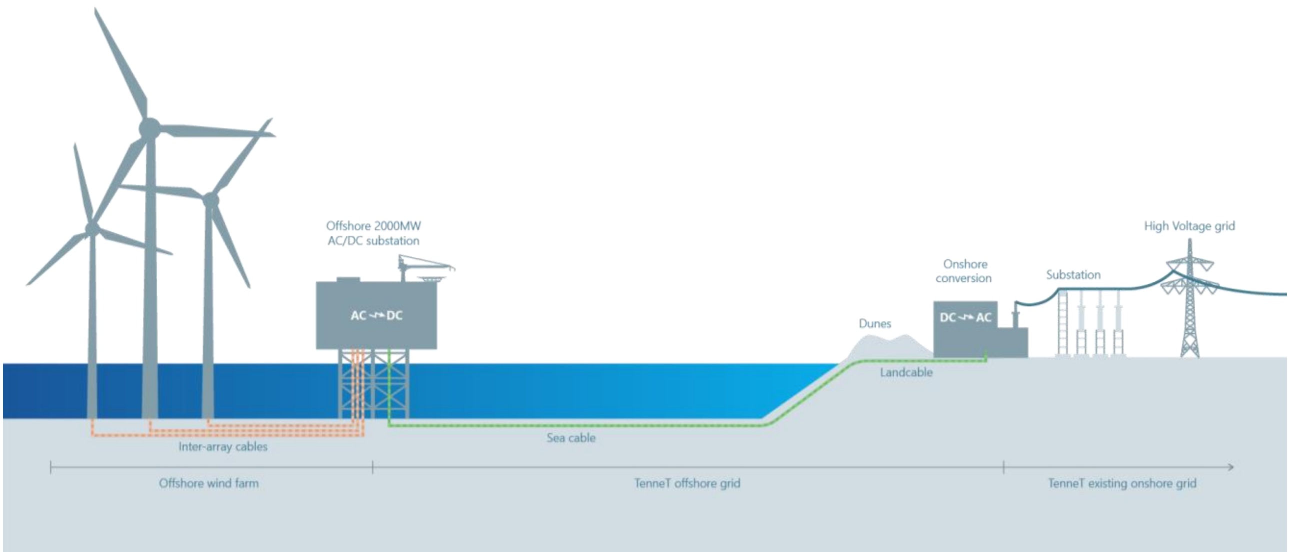

Figure 1 - HVDC grid connection concept

This position paper is structured as follows:

- Process with Ministry of EAC to select 2 GW HVDC 525 kV and platforms.
- Assessment of HVDC grid connection systems and HVDC design aspects
- Reliability and Availability of optimal Grid Connection system
- Results of assessment and position of TenneT

3. Process with Ministry of EAC to select 2 GW HVDC 525kV and platforms.

The Minister of Economic Affairs and Climate published the letter *"Roadmap offshore wind energy 2030"[1]* which entails the realization of 10,6 GW offshore wind in 2030 to make a significant contribution to the reduction of CO_2. In the letter, TenneT is made responsible to develop the offshore grid for the respective wind areas and connect the offshore wind farms timely and cost efficiently. The roadmap stipulates the 4 GW wind area of IJmuiden Ver to be connected in steps of 2 GW in 2027 and 2029.

TenneT started the development of new offshore grid concepts following the publication of the Energy Roadmap[1] in 2016. In an intensive collaborative process with TenneT, the Ministry of Economic Affairs and Climate, consultants & research company's and external stakeholders the most optimal grid concept has been developed. The aim has been to develop a grid connection with lowest societal cost (LCOE), minimal spatial and environmental impact, feasible to realise within the timelines of the roadmap 2030 and future proof.

TenneT has developed and assessed various Grid Connection Systems (GCS). The seven most promising alternatives are listed in the table below. TenneT has also assessed other more innovative solutions (GIL, LFAC, DRU) but has deemed these solutions to be inferior or unfeasible in the timeline.

	Technology	Island/Platform	Capacity	Voltage Level	# GCS
Alternative 1	HVAC	Platform	666 MW	220 kV	6
Alternative 2	HVDC		1000 MW	320 kV	4
Alternative 3			1350 MW	400 kV	3
Alternative 4			2000 MW	525 kV	2
Alternative 5		Island	1350 MW	400 kV	1
Alternative 6			2000 MW	525 kV	1

Table 1; List of Alternatives

The alternatives are based on three principal choices. The choice between HVAC or HVDC technology, the choice between an island or platform based solution for the offshore substation and the capacity of the grid connection.

[1] Energieagenda: naar een CO_2-arme energievoorziening (7-12-2016)

HVAC vs HVDC

The Ministry of EAC and TenneT performed an extensive study and stakeholder process to identify and funnel possible connection locations[2]. This has resulted in the following possible connection locations. These locations will be the starting point for the permit application.

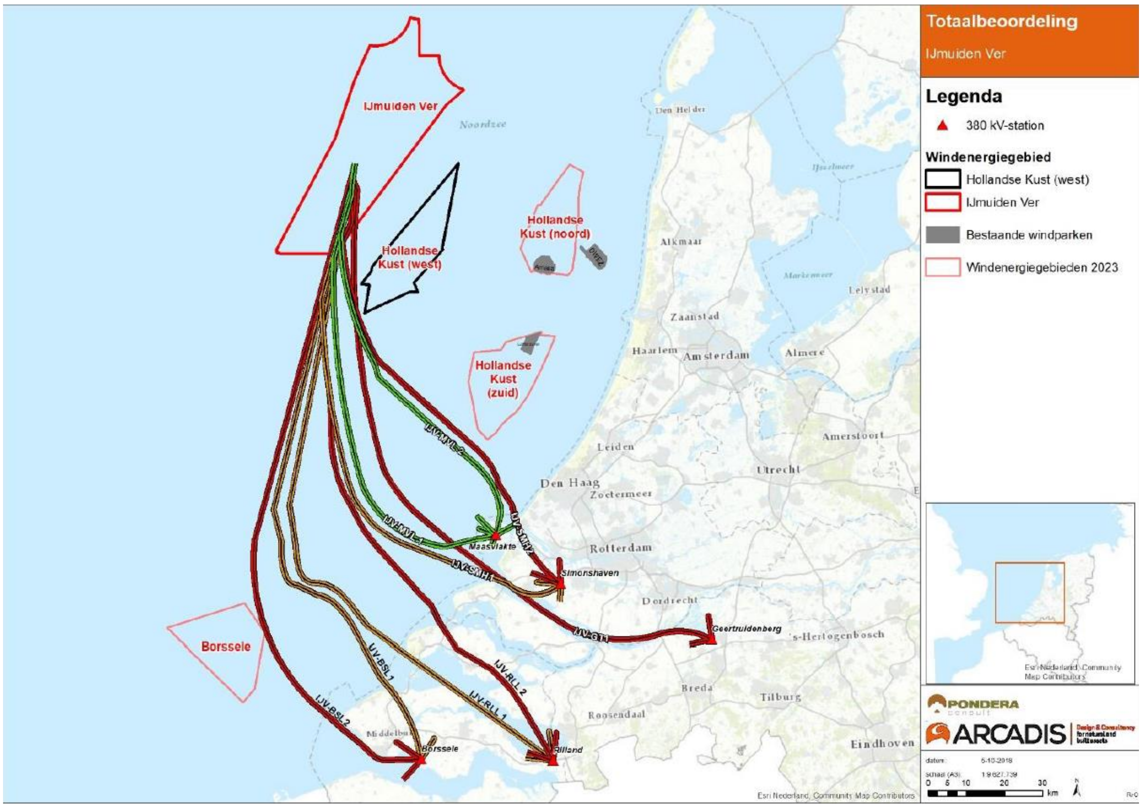

Figure 2; Result of the "Verkenning Wind Op Zee 2030", onshore connection locations IJmuiden Ver.

The most promising connections are to South Netherlands (~175 km) and Maasvlakte/Simonshaven (~125 km).

The assessment of the alternatives has shown that HVDC alternatives have a better performance than the HVAC alternative. HVAC solutions are less cost effective (higher LCOE) over long distance offshore connections and have a negative impact on the power quality of the onshore grid. In addition the HVDC solutions have a lower spatial and environmental impact due to the fewer cable routes required.

Grid connection capacity

The assessment of the alternatives has shown that alternatives based on higher connection capacities are more cost effective (lower LCOE) and have a lower spatial and environmental impact due to less cable routes. A connection capacities of 2 GW will however increase the largest potential outage in the

[2] Afwegingsnotitie Verkenning Aanlanding Wind op Zee 2030

Netherlands from 1.35 GW to 2 GW and would result in additional costs for increased system reserve under the current market conditions.

TenneT has extensively assessed the impact of a 2 GW offshore connection and concluded that, when considering the market conditions in 2027, the possible worst case forecast error of renewable electricity production will have a larger impact on the security of supply than the largest outage in the Dutch system. The required adaptations of the regulatory framework and market model will also provide a solution for the outage of a 2 GW offshore grid connection. Therefore it is deemed acceptable to apply the more cost effective grid connections based on 2 GW connection.

Island vs Platform

The assessment of alternatives has shown that alternatives based on islands are technically feasible, more cost effective and provided various additional benefits (future proof). The alternatives based on islands however need more time for realization and have a high risk for delays during the permitting process due to the new and unknown impact of an artificial island.

In the Letter *"Roadmap offshore wind energy 2030"[1]* The Ministry of Economic Affairs has decided for a platform solution based on the aspects: compliance with roll-out schedule, project certainty, low cost variance, flexibility and safety.

Optimal Grid connection system

Based on the extensive technology and cost (LCOE) analyses TenneT has advised the Ministry of EAC to select a grid connection based on 2x 2 GW 525 kV HVDC connections located on a platform. Main rational is the significantly lower amount of transmission cables and offshore platforms for a 2 GW solution. This results in lower cost (lower LCOE) and environmental impact (cable corridors and number of platforms).

The Ministry of EAC has selected an independent consultant (BLIX) to validate the recommendations on the grid concept provided by TenneT to the Ministry of EAC in September 2018. BLIX has extensively examined the LCOE study, the planning, the technologic feasibility and the underlying assumptions and concluded *"The pre-initiation phase for TenneT appears complete, correct and robust".*[3]

The Ministry of EAC has adopted TenneT's advice and has decided for a grid connection system (GCS) based on VSC-HVDC technology rated at 2 GW and ±525 kV [1]. The decision of the Ministry of EAC for a 2 GW and 525 kV is not for consultation.

[3] BLIX: Validation of studies regarding the Grid Connection of Windfarm Zone IJmuiden Ver, (link), 5-11-2018

4. Assessment of HVDC grid connection systems

4.1 Assessment Structure and Base Assumptions

The HVDC topologies (section 4.2) and other technical design options (section 4.3) are evaluated against each other in terms of the net added value considering the following:

- CAPEX (electrical equipment, platform and civil works)
- OPEX (the value of the electrical transmission losses and the non-transmitted energy due to system unavailability)

In doing so, the following approach is followed:

- Failure rates and MTTR figures of the equipment are selected based on the internal data and Cigre articles.
- Fixed average cost of energy throughout the asset lifetime
- Cost of equipment and services are based on internal data obtained in previous projects and market consultations with potential suppliers

4.2 HVDC topologies

The topologies considered to transmit 2 GW at ±525 kV are the following:

- Symmetrical monopole (as shown in Figure 3)
- Rigid bipole (as shown in Figure 4)
- Bipole with a dedicated metallic return cable (as shown in Figure 5)

All the above mentioned topologies are based on a single platform solution per 2 GW transmission system.

4.2.1 Symmetrical Monopole

The symmetrical monopole topology is the lowest CAPEX solution that requires a single HVDC converter per station to be connected to two HVDC cables operated at a voltage of the same magnitude (but opposite polarity).

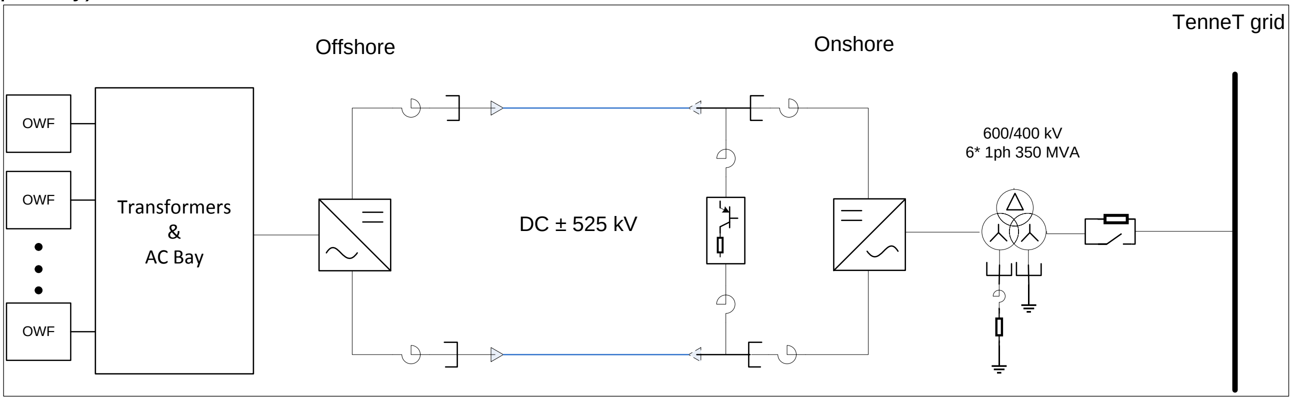

Figure 3: Grid connection system based on symmetrical monopole

This topology so far has been the preferred solution of the offshore HVDC grid connection systems (up to 900 MW) deployed by TenneT in Germany. However, given the higher power rating and nominal voltage level of IJmuiden Ver, the drawbacks of the symmetrical monopole topology refer mainly to the low availability performance when compared to the other options. The main reason is the fact that a pole outage results in the complete loss of the transmission system. As depicted in Figure 6, this means that no active power can be delivered by the grid connection system. The events that cause pole outages are:

- Pole outage due to converter failure (forced outage)
- Pole outage due to HVDC cable failure (forced outage)
- Pole outage due to scheduled maintenance (planned outage)

Furthermore, the risk of very high overvoltages in the healthy pole in case of a pole to ground failure could result in stringent requirements on the insulation coordination as well as on the 525 kV HVDC cable design.

In terms of the OPEX, the capitalised value of the lost generation due to unavailability is quantified as the loss of revenues. Therefore the lower availability figures results in higher OPEX.

The offshore AC grid faults occurring at the 66 kV side are also a concern for a 2 GW symmetrical monopole scheme. As the entire offshore grid is connected to the single offshore converter, a fault could easily result in an instantaneous loss of 2 GW power infeed. Furthermore, the associated short circuit currents at the 66 kV side could be excessive for the individual components such as the GIS system which would lead to significant over-dimensioning.

4.2.2 Rigid Bipole

The rigid bipole scheme comprises of two HVDC converters per station that are connected in series. Consequently, each converter is rated at half of the transmission capacity and subject to a unipolar voltage of 525 kV. Similar to the symmetrical monopole, there are two HVDC cables operating at the opposite polarities.

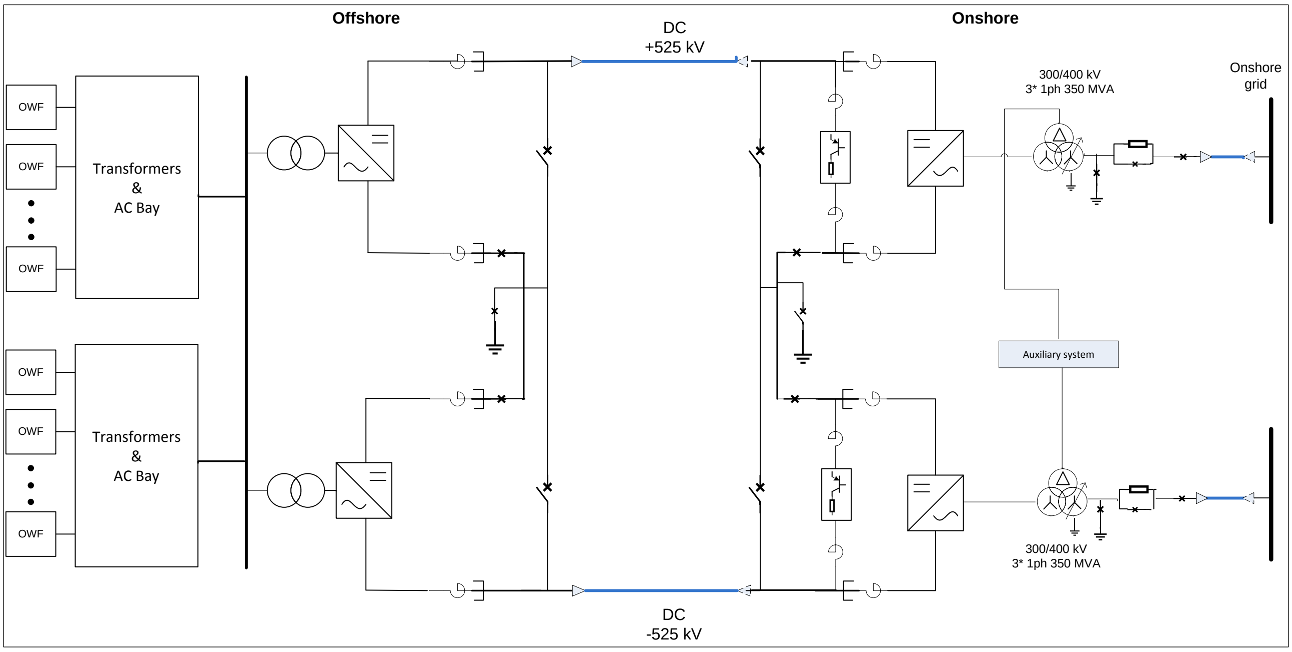

Figure 4: Grid connection system based on rigid bipole

A benefit of the bipole scheme is that, in case of converter pole faults, it can be re-configured to an asymmetrical monopole topology while retaining 50% of the transmission capacity, thus increasing the overall availability of the HVDC transmission system. For the rigid bipole option, this is achieved by disconnecting the converters of the faulty pole and utilizing its cable as the metallic return. Since the long term ground current operation is not allowed in the North Sea, the asymmetrical monopole operation via the ground current is not considered. As a result during the pole outages caused by converter failure or scheduled maintenance, the availability increases. On the other hand, a failure in the HVDC cable itself means the entire system has to be shutdown.

Any power imbalance among the poles results in either a difference in the DC voltage or in the DC current. For a rigid bipole scheme, neither are preferred. The margin for a DC voltage imbalance is very low due to the converter technology and it would also mean a reduction in the active power transfer capability. DC current imbalance on the other hand would result in ground current. Consequently the poles have to be interconnected on the AC side. For the offshore AC grid, this requires an additional interconnection stage at higher voltage than 66 kV for 2 GW, thereby increasing the CAPEX.

Similarly, having the offshore AC system interconnected at all times poses the same challenges that are addressed for the symmetrical monopole topology. Furthermore, there is no operational experience regarding the interconnection of two separate grid forming converters at the AC side, which leads to increased control complexity.

4.2.3 Bipole with a Dedicated Metallic Return (DMR)

The bipole with a dedicated metallic return topology consists of two HVDC converters per station, two HVDC cables and a metallic return cable. Each converter is rated at 1 GW and subject to a unipolar voltage of 525 kV. The two HVDC cables have similar properties as of the cables of the other topologies. The metallic return cable is preferably rated for the continuous operation at the full DC current, whereas the voltage rating is much lower.

Although the metallic return cable causes an increase in the CAPEX, the operational advantages it brings result in lower OPEX as the bipole with DMR configuration offers the highest availability amongst the considered topologies. The existence of the DMR cable enables an instantaneous transition from bipole to monopole operation in case of pole outages, retaining 50% of the transmission capacity, even during the high voltage cable failures (pole-to-ground). As shown in Figure 6, this translates to the fact that there is always a 1 GW transmission capacity available during the converter pole outages. Considering the asset lifetime, the bipole with DMR option prevails as the lowest TOTEX solution.

In addition to the above aspects, the bipole with DMR configuration also offers the following non-quantified benefits:

- Electrical separation of the offshore AC grid to two identical 1 GW grids per pole, resulting in lower short circuit currents and lower power loss during the offshore AC grid faults.
- The risk of having an outage that causes a 2 GW power loss becomes extremely low, which is highly preferable from the perspective of system stability and the associated re-dispatching costs.

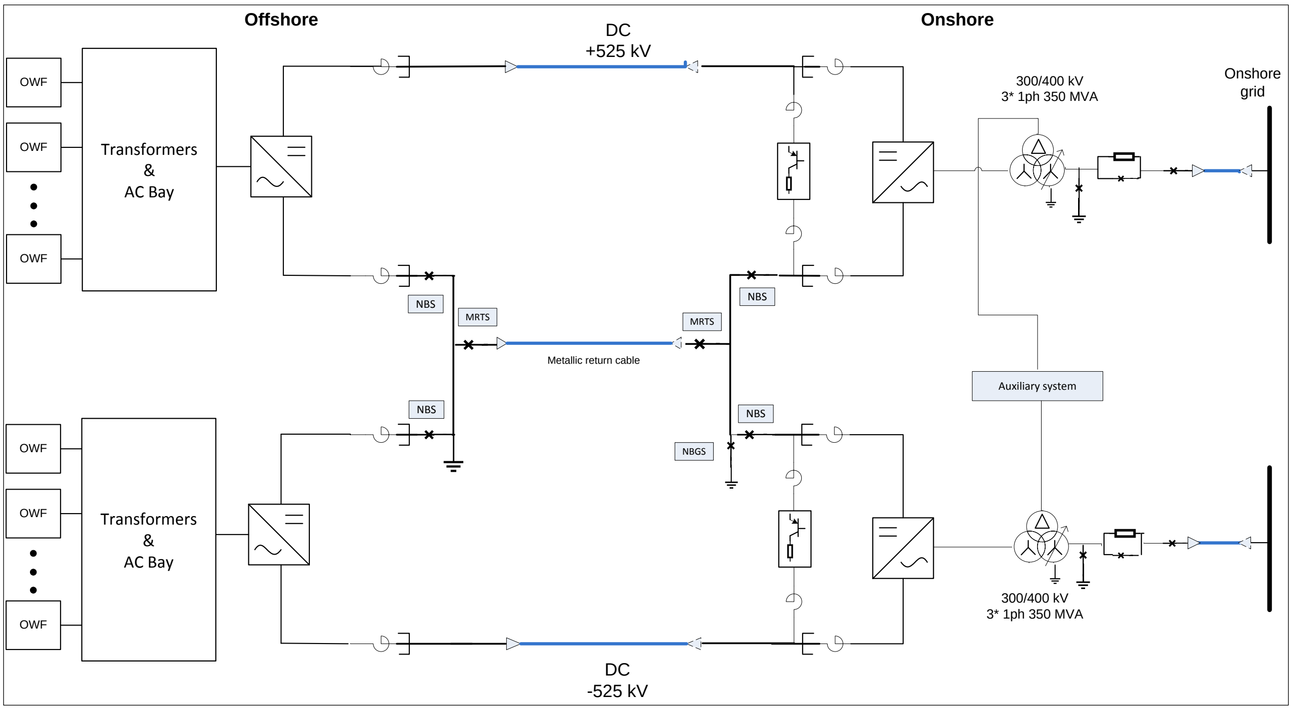

Figure 5: Grid connection system based on bipole with dedicated metallic return

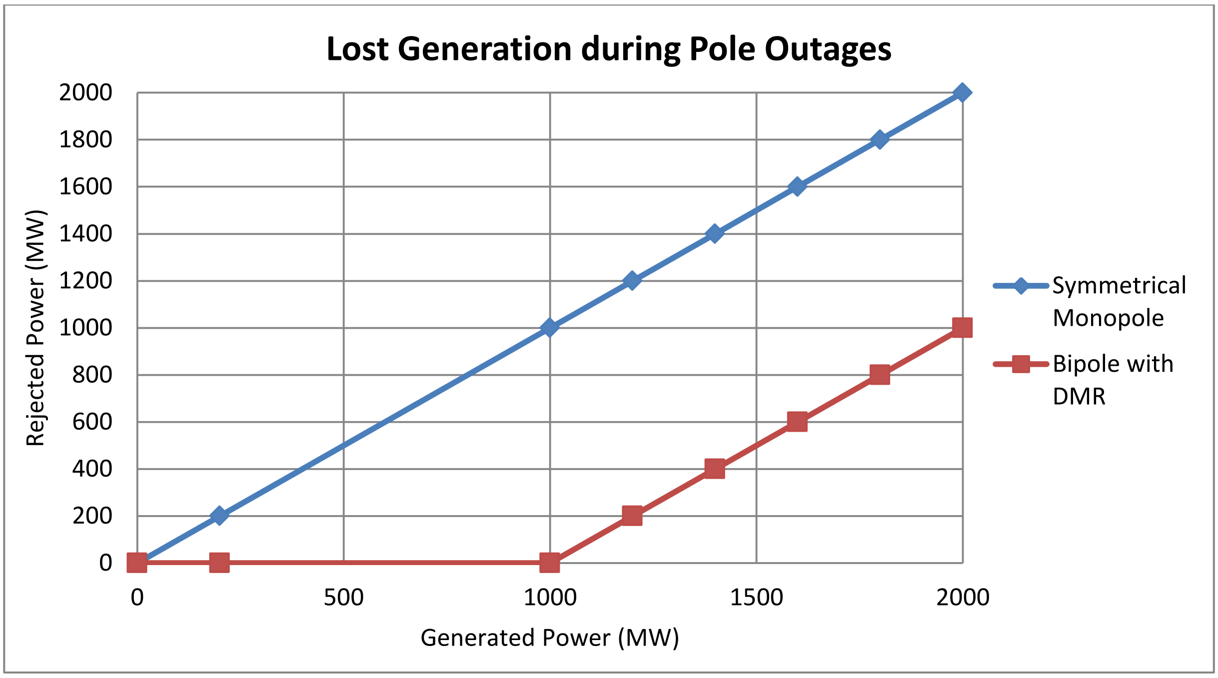

Figure 6: Rejected power as a function of the generated power in case of pole outages for different topologies

4.3 Other Design Aspects

4.3.1 Direct-Link Grid Connection System (GCS)

The wind farms of IJmuiden Ver will connect their inter-array cables directly to the HVDC platform of TenneT. This means that no intermediate collection AC platform is needed. The proposed concept of the Direct-Link GCS is a more cost-effective solution compared to the existing offshore HVDC-based installations in Germany with intermediate collection AC platforms which were obligatory from a regulatory perspective.

It is important to note that also in Germany there is a development towards a Direct-Link GCS. The DolWin5 transmission system of TenneT will be the first connection to be based on the Direct Link GCS concept. Commissioning is planned in 2024.

4.3.2 Onshore Transformer Arrangement

TenneT has considered the following transformer arrangement options for the onshore converter stations:

- Four three-phase units per station (2 GW), each rated at 750 MVA, no spares
- Four three-phase units per station (2 GW), each rated at 550 MVA, one spare per station
- Two three-phase units per station (2 GW), each rated at 1050 MVA, one spare per station
- Six single-phase units per station (2 GW), each rated at 350 MVA, one spare per station

The associated operational costs of non-transmitted energy due to transformer unavailability, which are higher in the case of the single-phase transformer arrangement, are outweighed fully by the lower investment costs due to the reduced number of HV components around the transformer areas. Additionally, the technical feasibility of manufacturing three-phase transformer units of that power range (and voltage complexity) becomes very challenging and introduces significant transportation limitations. Therefore, there is a strong preference to use single-phase transformer units for the onshore converter stations. The same technical choice has been applied to all 525 kV HVDC systems of TenneT (NordLink, Süd-link and Südost-link) which are currently under construction/preparation.

4.3.3 Offshore Transformer Arrangement

TenneT has considered the following transformer arrangements for the offshore platform:

- Four three-phase two-winding units per platform (2 GW), each rated at 550 MVA, no spares
- Four three-phase three-winding units per platform (2 GW), each rated at 550 MVA, no spares
- Six three-phase two-winding units per platform (2 GW), each rated at 350 MVA, no spares

The associated operational costs of non-transmitted energy due to transformer unavailability, which are higher in the case of the four transformer units per platform, are outweighed by the lower investment costs due to the reduced number of HV components around the transformer areas and the significantly reduced volume and weight on the platform. From a transformer design point of view, it is less complicated to build two-winding transformer units, hence they become the preferred solution for IJmuiden Ver.

The star-point of the 66 kV grid at the offshore converter transformers will be solidly grounded. This configuration is chosen based on the fact that in a small grid which is almost 100 % fed by power electronics, the short circuit current is always determined by the maximum power output of the converter station and the wind turbines. The impedance of the star-point has almost no influence on the short circuit currents. A solidly grounded star-point limits the voltage stress on the cables which are not affected by the fault.

The star-point shall be capable to withstand the short circuit currents. For continuous operation it shall be capable to carry 10 % of the nominal current, due to the fact that an asymmetric operation of the grid of up to 1.5 % is allowed. Taking a safety margin and uncertainties into account 10 % will be enough. As most wind turbines which are available on the market use a delta winding on the grid side of the machine transformer, it is not preferable to realize the star-point treatment with the use of the wind turbine machine transformers.

4.3.4 Cable laying configurations

The complete cable system (two HVDC cables and the DMR cable) for IJVER can be laid in one out of three different configurations:

1. Bundled
2. Unbundled with one metallic return
3. Unbundled with two metallic returns

The bundled configuration is the preferred laying configuration as this has the lowest ecological footprint (less spatial impact, lowest magnetic field emission) lowest cable installation costs and lowest maintenance costs. Unbundled configurations with 2 DMR cables has the highest availability (revenue) however this gain is evaluated to not cover the additional cable manufacturing, installation and maintenance costs.

4.3.5 Technology readiness of 525kV XLPE DC cables

The 525 kV DC XLPE cable design is a new technology. In Germany the four TSO's (including TenneT) together with the cable suppliers are investing in this development by means of a long duration test program (PQ test) for the SuedLink and Sued-ÖstLink land cable systems. A number of suppliers are finalizing the long duration tests within a few weeks. The results are promising.

TenneT is in the preparation phase of a similar development program (PQ test) for 525 kV DC XLPE submarine cable systems. Since the first land cable systems are now qualified it is expected to have this technology for submarine cable systems available in time for IJmuiden Ver, from multiple suppliers. In case the development of 525 kV DC XLPE will not succeed, IJmuiden Ver can fall back on the 525 kV DC MI cable technology, which is already available. TenneT prefers the XLPE over MI technology due to better ampacity performance and lower CAPEX.

Regarding the HVDC converters, the technology readiness is already mature enough. No particular concerns arise there, therefore no additional risks to be considered.

4.4 Generic Single Line Diagram (SLD)

The above analysis results in the following figure, which illustrates the generic SLD for the IJmuiden Ver connections. It must be noted that the two poles of each 2 GW connection shall be connected to the same onshore AC substation. Furthermore, the offshore wind farms will be grouped in four generator blocks of 500 MW each as illustrated below. Each OWF of 1 GW will be transmitted equally both converter poles. The number of bays depicted in this figure is only for illustration purposes; the exact number will be the topic of another position paper (T11 – J-tubes and number of bays).

An essential feature that is introduced in the SLD is the cross-coupling arrangement between the offshore transformer units and the offshore converter poles (i.e. transformer units 1 and 3 are connected to the upper pole, whereas transformer units 2 and 4 are connected to the lower pole). Alternatively, the cross-coupling arrangement may be achieved via the grid side of the converter transformers (between transformers and 66 kV busbars). However, such decision will be made during detailed platform engineering. The added operational value will be the same: it enhances significantly the availability of the transmission system in case of offshore transformer or pole outages.

The term "generic" means that certain elements of the SLD may differ depending on HVDC supplier specific solutions.

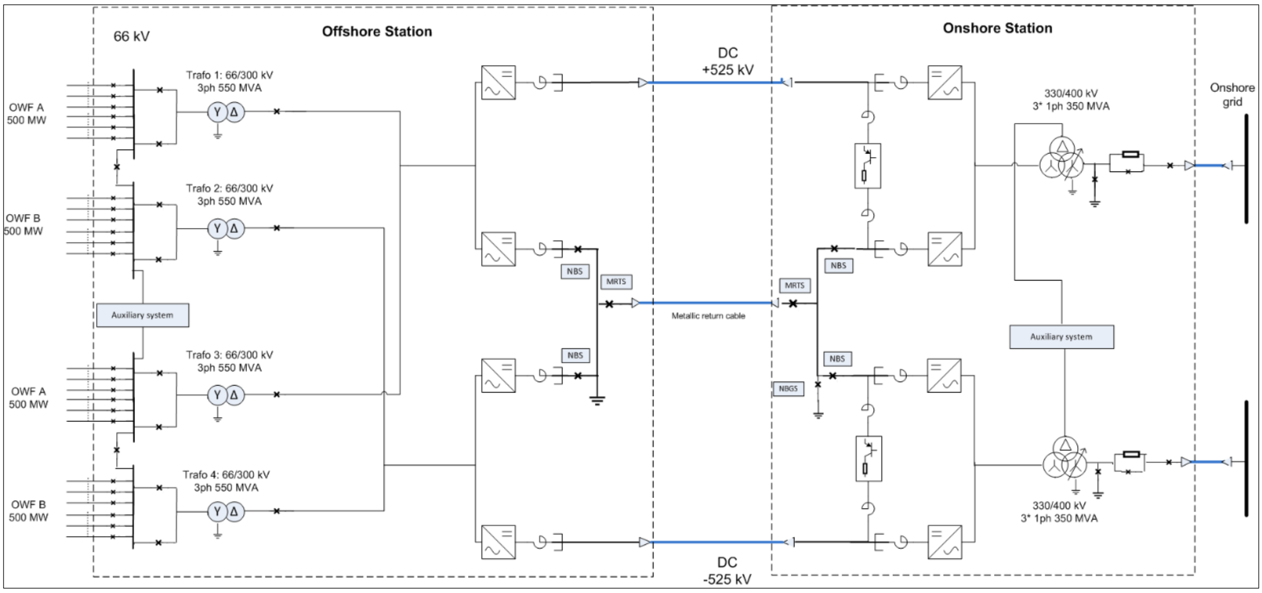

Figure 7: Generic SLD for IJmuiden Ver

5. Reliability and Availability

Below listed are some essential definitions and terminology according to Cigre:

1. *Outage*: The state in which the HVDC system is unavailable for operation at its maximum continuous capacity due to an event directly related to the converter station equipment or DC transmission line is referred to as an outage. Failure of equipment not needed for power transmission shall not be considered as an outage.

a. Scheduled Outage: An outage, which is either planned or which can be deferred until a suitable time, is called a scheduled outage.

b. Forced Outage: The state in which equipment is unavailable for normal operation but is not in the scheduled outage state is referred to as a forced outage.

2. *Energy Unavailability*: A measure of the energy which could not have been transmitted due to outages is referred to as the energy unavailability.

a. Forced Energy Unavailability (FEU) is a measure of the energy which could not have been transmitted, due to forced outages.

b. Scheduled Energy Unavailability (SEU) is a measure of the energy which could not have been transmitted, due to scheduled outages.

For assessing the overall reliability and the availability of the grid connection system, the following major events are considered:

1. *Converter pole outage (scheduled)*: the bipole converter topology allows for scheduled maintenance campaigns at one of the two poles once per year, while the other pole remains in operation. Due to

the bus-coupler possibilities between the 66 kV busbars, the converter pole outages that occur when the generated power is less than half of the installed capacity do not result in any lost generation. Hence, by planning the scheduled maintenance activities to take place during the low wind conditions, the impact of such an event to the transmitted power will be negligible.

2. *Converter pole outage (non-scheduled)*: according to conservative reliability calculations, a pole outage is not expected to occur more than twice per year. It must be noted that the existing experience from numerous HVDC systems within TenneT asset base is more positive and such failures are normally restored within a day. During a pole outage, the remaining pole remains in operation without being interrupted and is always capable of transmitting up to 1 GW.
3. *Converter bipole outage (scheduled)*: the impact of such an event to the transmitted power is negligible, due to its rare and short occurrence.
4. *Converter bipole outage (non-scheduled)*: this is a unlikely event, since the only electrically common area is the neutral bus. If such an event occurs, the complete transmission system will be shut down until the reparations are completed.
5. *HVDC cable pole failure*: in case one of the HV cables fail, the power transmission of the healthy pole will not be interrupted. Thus, the overall system will maintain transmission capacity of 1 GW.
6. *HVDC cable bipole failure*: in case there is a severe external damage that affects both HV cables simultaneously, the entire transmission system will shut down immediately.
7. *DMR cable failure*: in the very unlikely event that the DMR cable fails, there will be negligible impact to the amount of transmitted power, if the power infeed to the poles are balanced. Otherwise, as an immediate restoration process, the HVDC controls will enter a "rigid bipole" control mode, which will enable the reduction of the ground current in case of asymmetrical power infeed to the two offshore poles. This operation means curtailing the power infeed of the wind farm at the higher production to the point where both poles have equal infeed.

6. Impact on LCOE

To determine the relative impact on costs of the different considered topologies the LCoE impact is calculated for the following deviations of the 2 GW at ±525 kV schemes:

- Symmetrical monopole and bipole topology
- Bipole with and without a dedicated return cable (DMR)

The difference in LCoE is caused by deviating cost assumptions for the following cost parameters:

- CAPEX (electrical equipment, platform and civil works)
- OPEX (the value of the electrical transmission losses and the non-transmitted energy due to system unavailability)

The tables below show the results of the LCoE impact analysis for the monopole and bipole topology and for bipole with DMR and without DMR.

LCoE impact: monopole versus bipole (base case)

Quantitative	LCoE Impact	Comment
LCoE impact		
Developer	2,0%	Increase in costs by substantial increase in unavailability and only limited decrease in electrical losses.
TenneT	-3,8%	Decrease in costs mainly because of strong decrease in CAPEX of platform, electrical equipment and civil works.
Total LCoE impact		
Societal	0,9%	Combination of the LCoE impact from separate items above.

Although the CAPEX of the monopole topology is significantly lower than that of the bipole topology, the upside is cancelled out by the substantial increase in unavailability of the grid connection system (OPEX).

LCoE impact: no DMR versus DMR (base case)

Quantitative	LCoE Impact	Comment
LCoE impact		
Developer	1,2%	Increase in costs caused by increase in OPEX (unavailability and electrical losses).
TenneT	1,5%	Increase in costs by increase in CAPEX and OPEX (unavailability and electrical losses).
Total LCoE impact		
Societal	1,2%	Combination of the LCoE impact from separate items above.

Both from the perspective of the developer as from TenneT the relative cost impact of choosing the bipole topology without DMR is negative because of the higher CAPEX assumptions and the higher percentages for the electrical losses and the unavailability of the grid connection system.

7. Position TenneT

Above considerations lead TenneT to the following position regarding the 2 GW HVDC Grid Design:

TenneT will apply the *Direct Link* solution for the grid connection system of IJmuiden Ver.

TenneT will apply the *"bipole with dedicated metallic return"* topology as the basis of design for the grid connection system.

TenneT will apply the *"six single-phase units per station (2 GW), each rated at 350 MVA, one spare per station"* option for the onshore transformer arrangement.

TenneT will apply the *"four three-phase two-winding units per station (2 GW), each rated at 550 MVA, no spares"* option for the offshore transformer arrangement.

TenneT will apply a cross-coupling arrangement possibility between the offshore converter poles.

TenneT intends to apply a bundled 525kV XLPE cable and will consider a unbundled 525kV MI cable as fall back option.