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Operation practice and regulatory framework of offshore wind grid connection system

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Abstract. Offshore wind is experiencing rapid growth around the world, and is moving towards large-scale and far-reaching sea. Grid connection has become an important challenge for large-scale development of offshore wind power. In this paper, technology and regulatory framework of offshore wind grid connection are systematically summarized and complied. Europe has accumulated rich experience in this field, therefore taking UK, Denmark and Germany as examples, the practical experience of offshore wind grid integration is analyzed in terms of technology choice, framework, operation and maintenance, and recovery of connection costs. which is a good reference for China when dealing with the coming challenges.

1. Introduction

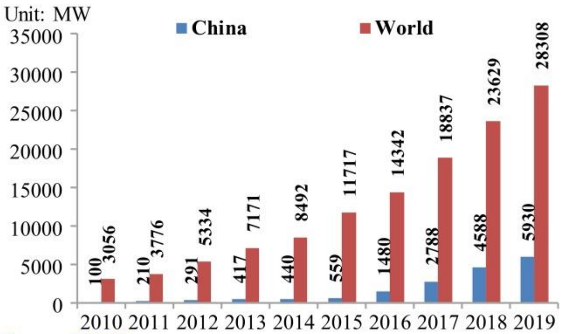
The offshore wind resources offer a great potential for clean energy supply and tackling climate change challenges. According to the International Renewable Energy Agency's (IRENA) projections, global offshore wind installed capacity will reach 228 GW by 2030 [1]. In the past decade, the development of offshore wind power has been booming. As shown in figure. 1, benefitting from the rapid technology improvements and costs reduction, between 2010 and 2019 the offshore wind installed capacity in China and the world has increased 59.3 and 9.3 times respectively [2]. By the end of 2019, the global total installed capacity has reached 28 GW, among which the UK ranks first (9.9 GW), Germany ranks second (7.5GW) and China ranks third (5.9 GW), China has become one of the most important offshore wind power markets in the world and expected to become the world's largest offshore wind market during the 2020s [3]. Europe remains the technology leader to 2040, but China closes the gap spurred by recent efforts to expand their construction capacities for offshore wind [4].

At present, offshore wind is moving towards large-scale and far-reaching sea. Grid connection has become an important challenge, Europe has accumulated rich experience in this field, which is a good reference for China [5, 6]. Therefore, in this paper technology and regulatory framework of offshore wind grid connection are summarized and complied. Taking three European counties: UK, Denmark and Germany as examples, the practical experience of offshore wind grid integration is analyzed, and related development suggestions are proposed.

2. Technology for offshore wind farm (OWF) grid connection

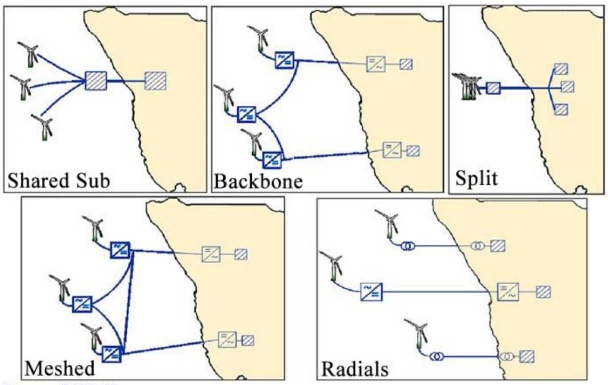
2.1. Topology of offshore wind grid connection

Five most referred topologies for offshore wind connections are illustrated in figure. 2 [7] and further compared in Table 1 with their main advantages and disadvantages, which are uniform across all the three European counties: UK, Denmark and Germany.



Source: IRENA

Figure 1. Offshore wind installed capacity of world and China (2010-2019).



Source: DNV GL

Figure 2. Overview of offshore connection concepts.

Table 1. Generic overview of offshore connection concepts

Principal design concept	Description	General advantages	Disadvantages
Dedicated radials / gen-tie	Connecting each project to onshore via dedicated radials	1. Lowest offshore grid costs 2. Best expandability (e.g. ability to add future wind power plants to the same offshore grid), due to low interconnectivity	Weak resilience and redundancy 1. Weak capacity of offshore grid to deliver power after a failure event in one component (n-1) 2. Weak auxiliary systems redundancy 3. Low level of benefit from over dimensioning components and amount of over dimensioning needed to compensate for loss of a connector
Split connection	AC: Connecting projects to onshore with spared cable lines. DC: Separate landing points for each DC pole		
Shared substation	Hubs to collect power from nearby projects and deliver to onshore	Competitive costs combined with much stronger resiliency and redundancy compared to dedicated gen-tie.	1. Weakest / riskiest operationally due to large amount of AC cables 2. Hard to expand with future, uncoordinated build out
Backbone	Connecting projects and exporting power to onshore from closest platforms	1. Additional operational benefits by offering grid support which can improve offshore POI utilization and optimize onshore grid reinforcement	1. Higher offshore grid costs than dedicated radials / gen-tie 2. Low flexibility when it comes to expandability due to high interdependence among

		2. High resiliency and redundancy, driven by multiple parallel circuits	windfarms 3. Higher environmental footprint from longer cabling
		Requires a coordinated build-out from central authority	
Meshed	Connecting projects in a meshed connection.	1. Highest operational benefits by offeringgrid support which can improve offshore POI utilization and optimize onshore grid reinforcement 2. High resiliency and redundancy, driven by multiple parallel circuits	1. Higher offshore grid costs than dedicated radials / gen-tie 2. Low flexibility when it comes to expandability due to high interdependence among windfarms 3. Higher environmental footprint from longer cabling
		Requires a coordinated build-out from central authority	

2.2. OWF grid connection

2.2.1. HVAC. Most used connection in Europe is AC transmission. Table 2 shows typic design of High Voltage Alternating Current (HVAC) grid connections [8], which also includes the typical voltage levels and feasible length of export cables.

2.2.2. HVDC. Table 3 shows the general design of High Voltage Direct Current (HVDC) grid connections [8]. For HVDC grid connections there are no restriction for the length of the export cable.

Table 2. HVAC grid connection concepts

Concept	**Voltage levels**	**Cable design**	**Maximum length of cable**	**Stations**
Nearshore	11 kV, 22 kV, 33 kV	Three-core submarine cable and single-core land cable	20-30 km	Direct connection to Distribution Network Operator (DNO), without an offshore substation
Offshore	66 kV, 132 kV, 150 kV, 220 kV		Up to 100 km	Connection to the transmission operator (TSO) with an offshore substation

Sources: TenneT B.V.

Table 3. HVDC grid connection concepts

Concept	**Voltage levels**	**Cable design**	**Maximum length of cable**	**Stations**

Offshore	±150 kV, ±250 kV, ±320 kV, ±525 kV	Bipolar submarine cable (plus and minus pole) XLPE, single-core land cable	Theoretically no limitation	Connection to the TSO with an offshore and onshore converter station, flexible HVAC voltage for OWF (66~220 kV) with or without separate offshore substation

Sources: TenneT B.V.

Different HVDC converter technologies have been developed. Voltage sourced converter (VSC) technology has been selected as the basis for several recent projects due to its controllability, compact modular design, ease of system interface and low environmental impact. VSC converters used for power transmission permit continuous and independent control of real and reactive power. This capability can increase the overall transfer levels. Forced commutation with VSC even permits black start. In contrast to line-commutated HVDC converters, VSC maintain a constant polarity of DC voltage and power reversal is achieved instead by reversing the direction of current. This makes VSC much easier to connect into a multi-terminal HVDC system or “DC Grid”.

Line-commutated converter (LCC) are not capable of forming an AC voltage, hence the need to be connected to a strong AC network. As such, they are not suitable for the connection of offshore windfarms, where the converter needs to form an AC grid into which the wind turbines can export the generated wind power.

In general, also outside the application of offshore wind export, there is a clear trend for using modular multi-level (MMC) VSC technology.

3. Regulatory scheme on offshore wind transmission system

As far as regulatory frameworks are concerned, different frameworks have developed and implemented at different stage offshore wind sector’s development and in different countries, which covers installation and operation and costs sharing transmission system of OWFs. The following are among key considerations in relation to the regulatory framework of offshore wind grid connection:

- Compare to onshore wind, offshore wind technologies are still at relatively early stage of maturity. Offshore transmission costs, as part of cost of electricity from offshore wind projects, are relatively uncertain, thanks for the different locations of OWFs, technologies being used, which contribute to the increased perspective risks of connection investments.
- In Europe, offshore transmission costs are a much larger share of overall investment costs (up to 25%) than for onshore (5%). In China, this difference is less pronounced: 13% compared to 11~12% [9, 10].
- Offshore connection investments required are very large; In China the costs for offshore wind is about 14,000~19,000 RMB/kW in 2019, which is about twice as much as onshore wind [9].

3.1. Entity responsible for constructing the offshore wind connecting and for its operation / ownership

TSO model: Traditional regulatory economics would consider the establishment and operation of offshore grid infrastructure a natural monopoly and hence it should be less costly if these economic activities are carried out by one firm compared to two or more firms. Similar to the onshore grid, the TSO should be best placed to realize the efficient coordination of the demands of all potential users when constructing and operating the offshore transmission infrastructure.

Generator model: An alternative view is that the connection of isolated single OWFs is not characterised by natural monopoly, and hence should be a competitive activity. Moreover, in practice, both developers and regulators prefer such a “generator model”. Developers feel they have more control over costs, design, and timing of the connection. In addition, the very high connection costs and the uncertainty related to rapid technological development make it attractive for the regulator to use competitive elements in order to assert pressure for cost efficiency.

Third-party model: To take the advantage of both, an intermediate organisational option can be used, developed in the UK but subsequently contemplated by other countries, which is to have a third party owning and operating the offshore transmission assets with a wider focus than a single offshore generator. The party is separated from the generator and can be separately regulated, and yet a competitive process can be used by the party using advanced technology and allowing cost effective option.

3.2. Mechanism that offshore wind generators have to pay for their connection to the power grid

Mechanism 1: The generator bears cost only for the actual power plant including internal wiring, the costs of all other connection assets and for required network reinforcements are paid by all users of the transmission system.

Mechanism 2: The generator bears the costs for the actual power plant, including internal wiring, and also for the connection assets required for the particular connection; the costs for required network reinforcements are paid for by all users of the transmission system.

Mechanism 3: The generator bears the costs for the actual power plant, including internal wiring, and also for the connection assets required for the particular connection as well as for network reinforcements.

From Methods 1 to 3, the more paid by generator for the connection, the more price signal theoretically to play. If the prospective generator is confronted with more connection charges, the location for the plant will consider the required connection costs, including grid reinforcements. However, for an interconnected transmission system, where the configuration of generators and load is changing all the time, it is not possible to realistically calculate and allocate the system costs caused by a particular connection. Therefore, Method 3 is not an applicable option. Method 2 avoids the need to calculate the costs of network upgrading in the overall system while still providing some price signal, but it still has the problem that subsequent connections in the same location might make use of assets paid for already by the previous developer.

To effectively support the development of offshore wind, Method 1 has the advantage in terms of implementation. Separately form the initial payment for connection, all costs will eventually be paid by the costumers.

4. Practices of offshore wind grid connection

4.1. Technology choice of offshore wind grid connection

4.1.1. UK. At present, offshore wind projects in the UK have only used HVAC technology. The transmission network operates up to 220 kV AC. However, future projects are expected to also use HVDC technology, including the Dogger Bank group of OWFs, which are expected to have a total capacity of up to 3.6 GW.

Allows for easing the integration of offshore generation to the National Electricity Transmission System. VSC is superior to LCC to create multi terminal HVDC systems, and therefore, achieve this configuration. For HVDC, connection voltage ranges at ±320kV ~ ±525kV DC with a point-to-point or multi-infeed network topology.

4.1.2. Denmark. All Denmark’s offshore wind parks are connected using AC cables with dedicated gen-tie designs. Energinet and the German TSO are now planning the world’s first offshore interconnector by connecting one region in Denmark with one region in Germany via two OWFs, the German Baltic 2 and Krieger Flak. The two wind parks are less than 30 km apart and are linked by means of two sea cables of 400 MW each. A back-to-back converter, converting the Danish AC to DC and back to AC, but now adapted to the phase of Continental Europe.

4.1.3. Germany. In Germany there are 9 HVDC grid connections projects and 7 HVAC grid connections with a total capacity of 11.7 GW in operation or under construction in the German North Sea and Baltic Sea. With focus on the German Grid Development Plan, it is planned to install 20 GW until 2030. One onshore HVDC system is under construction and 8 additional ones are planned until 2030.

4.2. Framework for OWF connection

Table 4 elucidates the different frameworks for the UK, Germany and Denmark. No single way to operate an OWF and the respective transmission system exists at the moment, given the associated range in scale of water depth and distance from shore. Optimal, broadly spread, solutions are still in development. Multiple stakeholders exist but can be primarily categorized in the following:

Developer: Brings the offshore wind from construction through COD. This may include building the transmission system for the offshore wind , depending on the jurisdiction.

Offshore wind TSO: Responsible for operating the offshore transmission system, between the offshore wind substation through the onshore substation. In the UK, offshore transmission owners (OFTO) operate the transmission assets.

Onshore wind TSO: Responsible for operating the offshore and onshore transmission system. Power over control starts at the offshore wind substation.

Table 4. Overview of frameworks for OWFs connections in the three countries

Transmission Asset	Description	Jurisdiction and responsibility		
		UK	Germany	Denmar
Onshore transmission	Transport power on land to be distributed and supplied to end	NG ESO	TenneT, 50Hertz	Energinet
Onshore substation	Point of connection from the offshore substation. Power is received and transferred to the	OWF Developer's Scope / divested to OFTO	Offshore TSO Scope	TSO Scope
Export cable	Infrastructure to transfer power via undersea high voltage cables			
Offshore substation platform (OSP)	The OSP collects the power from the and depending on the proximity to shore, the OSP may		Mixed Offshore TSO and OWF	
Array cables	Collector system interconnection the wind turbines offshore. Typically at 33 kV, but recently being at 66 kV.		OWF Developer's Scope	
Wind turbines	Generators producing electricity form wind.	OWF Developer's		

Source: K&L Gates, 2018

4.2.1. UK. Securing grid transmission for an offshore wind project involves the following parties: National Grid ESO (NGESO); National Grid Electricity Transmission (NGET); Office of gas and electricity markets (Ofgem); Offshore Transmission Owner (OFTO); The Crown Estate; Developer; Stakeholder consultations. The developer is responsible for securing a Connection Agreement with NGESO. Construction of transmission assets is led by either the developer or the OFTO. Through an Ofgem led competitive tendering process, the transmission infrastructure is transferred to an OFTO who is responsible for securing a separate transmission asset lease agreement with The Crown Estate.

In the UK, grid costs are split between generators through transmission charges for the transmission grid, while any offshore connection costs are paid for solely by the project developer.

The UK government favors an open and competitive approach to offshore transmission. This approach is summarised as the competitive transmission regulatory regime, regulated by Ofgem. This regime means power transmission from offshore wind projects to the onshore grid can be either designed and built by the developer or a separate OFTO. Once the asset has been built, it is awarded to an offshore transmission owner, through an Ofgem led competitive tendering process, who is responsible for operating and maintaining the transmission asset.

4.2.2. Denmark. Terms and conditions for grid connection are stipulated by Danish Energy Agency (DEA) in the construction license and electricity production license. Requirements for grid connection mainly follow from the RE act, the executive order on grid connection of wind turbines and Energinet’s technical regulations. Offshore wind generation has priority access to the grid, which provides assurance that the generated electricity can always be sold and transmitted.

So far, for projects build out under the tender procedure, the Danish TSO has been responsible for the construction, ownership and operations of the offshore grid connection for the build out of offshore wind power plants. However, the government follows the cost reductions achieved in renewables closely and continuously evaluates which mechanism provides the optimal socio-economic support [11]. This has resulted in that the concession winner of the upcoming tenders will be responsible for constructing and operating the OWF, offshore substation, export cables, nearshore substation all the way to the point of connection (POC). The Danish TSO Energinet provides the onshore POC and is responsible for the construction and operation of the onshore grid connection from the second onshore substation to the overall transmission grid [12].

4.2.3. Germany. In Germany, the so called “proactive TSO model” implemented in 2013 sets an objective, transparent and non-discriminatory allocation procedure that allows for transmission assets to be shared across individual wind farms. By making the TSO responsible for the connection, coordination among generation projects is encouraged. Consenting for the majority of projects is done by central authority, the federal maritime and hydrography agency (BSH). BSH was selected as main permitting authority (one stop shop) for offshore wind in order to enable fulfilment of the offshore goals. The TSO of the respective area is obliged to provide and operate the offshore grid connection, which are included in the site development plan. The plan is developed by BSH, but the four German TSOs are consulted in a public consultation and can thus influence the planning process. The plan also specifies the standardized technologies which are to be used for the connection [13].

4.3. Operation and maintenance of offshore wind transmission system

4.3.1. UK. The transmission system will be maintained by the OFTO, which may generally have two approaches for maintenance: an on shore or an offshore vase. The former is through using a CTV to shuttle technicians to-and from the offshore substations; however, if the OFTO has enough volume, the offshore base would be a preferred approach via an SOV. Careful planning of routine and unscheduled activities with due consideration of weather conditions and availability of spares and specialist vessels is critical. Currently a CTV is the approach in place; however, SOVs is expected to become common practice as offshore wind develops.

4.3.2. Denmark. For larger OWFs with more than one offshore substation, it is common practice to install an interlink among the offshore substations to offer improved redundancy. There is also a tendency to unmanned operations. Offshore operations are cost intensive and strongly depends on the weather. Two approaches are often utilized, “shore-based” or by maintenance vessels / platforms.

4.3.3. Germany. For offshore substation the large transformers are operated separately. This means that they are not connected on the high voltage side and the medium voltage side during normal operation. In the event of a fault, only part of the wind farm is affected. After the faulty equipment has been disconnected, the entire wind farm can be put back into operation by switching operations. All switches of the medium voltage level as well as the high voltage level in the OWF should be switchable from the onshore control room. For the export cable maintenance the TSO's are responsible. Therefore, the TSO's generally install cable monitoring systems by using the fibre optic cables inside of the cable. The aim is to observe the cable and identify damages before they occur. In case of a cable damage they have a strong interest in ensuring that export cable faults are rapidly fixed. To reduce maintenance operations of substation, as much as possible systems will be obverted by remote, or maintenance free components will be installed.

5. Summary

(1) Standardized HVAC and HVDC technology used in all three European countries, and grid connection process is highly country specific. Compared with HVAV grid connection, HVDC grid connection has no restriction for the length of the export cable and can higher voltage level and connection capacity, and it has become the future development trend, especially there is a clear trend for using MMC VSC technology. In the future, long-distance and large-scale offshore wind power in China will become the main development direction, China should accelerate the research and exploration of HVDC grid connection related key technologies.

(2) European development experience shows that the third-party model, which is to have a third party owning and operating the offshore transmission assets, combines both advantages of the TSO model and the generator model, can have a wider focus than a single offshore generator, and is recommended to be used in regulatory scheme on offshore wind transmission system; The mechanism, that the generator bears cost only for the actual power plant including internal wiring, the costs of all other connection assets and for required network reinforcements are paid by all users of the transmission system, is recommended to the offshore wind generators to pay for their connection to the power grid. In order to provide good incentives for offshore wind transmission investments in China, it is suggested that China should learn from of European countries' experience to improve and modify its own regulatory mechanism according to the characteristics of domestic power system.

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