Major Offshore Wind Farm BOS Components

• Foundations
  • Grounded (monopile, gravity, tripod, etc.)
  • Floating (ballast, mooring, buoyancy stabilizations, etc.)

• Wind farm collector system
  • Inter-turbine Medium Voltage (MV) AC cables (typically 34.5 kV)
  • Substation platform with transformer and electrical equipment
  • Converter platform if High Voltage (HV) DC transmission is used

• Transmission to shore
  • HVAC or HVDC submarine cable
  • Cable landing
  • HVAC or HVDC land cable
  • On-shore converter station for HVDC
  • Onshore substation/interconnection

BOS = Balance of System or Balance of Station

Source: NSW Submarine Power
Key Principles of Electrical Systems

Maintaining a high level of power quality is driven by:
- Regulation / Grid codes
- Low voltage ride-through
- Active frequency and power control
- Reactive power control

Much depends on:
- Configuration
- Type and age of equipment
- System integration and control

Power System Basics:
- Power: $\text{Power} = \text{Volts} \times \text{Amps (VA)}$
- Ohms Law: $\text{Volts} = \text{Amps} \times \text{Resistance}$
- Resistance = electrical resistance $\times$ (length of run / area of cable)

### Standard AC Transmission Voltage Ratings

<table>
<thead>
<tr>
<th></th>
<th>Overhead</th>
<th>Submarine cable technology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>US, (kV)</td>
<td>Europe, (kV)</td>
</tr>
<tr>
<td>MV</td>
<td>34.5</td>
<td>33</td>
</tr>
<tr>
<td>HV</td>
<td>69</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>115</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>230</td>
<td>220</td>
</tr>
<tr>
<td>EHV</td>
<td>345</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>765</td>
<td>750</td>
</tr>
<tr>
<td>UHV</td>
<td>1100</td>
<td>1200</td>
</tr>
</tbody>
</table>
Balance of Station  Land-based – Offshore Differences

BOS technical and economic aspects of land based wind farms are well understood, but still need improvements. Optimization tools are available.

- Some variations in BOS capital cost not related to site’s geographical characteristics are still present
- In many cases, such variations can be tracked down to suboptimal design and/or specifications
- Improvements and further standardization, bidding optimization can help
- Need in larger mobile cranes, improved road infrastructure, etc.

Many BOS components for offshore still need significant improvements. Valid optimization tools designed specifically for offshore are needed

- Optimize construction and building practices
- Optimize project layout
- Optimize electrical infrastructure / Maximize reliability
Onshore Plant Cabling – Current State of the Art

• Typical on-shore wind turbine in US generates up to 2.5 MW at 690V
• Stepped up to 34.5kV by pad-mount or nacelle transformer
• MV collector system connected to substation via underground or overhead line
• The voltage is stepped up to transmission level (69 kV or above) by a substation transformer facility
• In North America Wind Power Plants (WPP) are predominantly connected to HV transmission
• Interconnection to distribution systems level is common for only small wind farms
Offshore Plant Cabling – Current State of the Art

- Radial designs have been used in European offshore wind farms
- 22-33 kV MV infield cables
- Usually single substation platform (in some cases 2 platforms)
- 132-155 kV export cables
- Spacing between turbines in a row: 5-10 rotor diameters
- Spacing between rows: 7-12 rotor diameters

# Existing Offshore Wind Farm Characteristics

<table>
<thead>
<tr>
<th>Wind farm</th>
<th>Total Capacity / Single Turbine (MW)</th>
<th>Diameter / Hub Height (m)</th>
<th>Distance / diameter ratio</th>
<th>Water Depths , (m)</th>
<th>Cable to shore</th>
<th>Cable infield</th>
<th># of offshore substations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thanet, UK</td>
<td>300/3</td>
<td>90 / 70</td>
<td>5.55</td>
<td>14 – 23</td>
<td>2x132 kV / 26 km</td>
<td>33 kV / 75 km</td>
<td>1</td>
</tr>
<tr>
<td>Greater Gabbard, UK</td>
<td>504 / 3.6</td>
<td>107 / 78</td>
<td>6.1 – 6.77</td>
<td>4 – 37</td>
<td>3x132 kV / 45km</td>
<td>33 kV / 173 km</td>
<td>2</td>
</tr>
<tr>
<td>Bard 1, Germany</td>
<td>400 / 5</td>
<td>122 / 90</td>
<td>-</td>
<td>39 – 41</td>
<td>2x155 kV / 125 km</td>
<td>33 kV / 107 km</td>
<td>1</td>
</tr>
<tr>
<td>Horns Rev1, Denmark</td>
<td>160 / 2</td>
<td>80 / 70</td>
<td>7.0</td>
<td>6 – 11</td>
<td>150 kV / 21 km</td>
<td>30 kV / 63 km</td>
<td>1</td>
</tr>
<tr>
<td>Horns Rev2, Denmark</td>
<td>209 / 2.3</td>
<td>93 / 68</td>
<td>-</td>
<td>9 - 17</td>
<td>150 kV / 42 km</td>
<td>33 kV / 70 km</td>
<td>1</td>
</tr>
<tr>
<td>Rodsand 2, Denmark</td>
<td>207 / 2.3</td>
<td>93 / 68</td>
<td>5.4 – 6.4</td>
<td>6 – 12</td>
<td>132 kV / 80 km</td>
<td>33 kV / 75 km</td>
<td>1</td>
</tr>
<tr>
<td>Princes Am, Netherlands</td>
<td>120 / 2</td>
<td>80 / 59</td>
<td>6.88</td>
<td>19 – 24</td>
<td>3x150 kV / 29 km</td>
<td>22 kV / 45 km</td>
<td>1</td>
</tr>
<tr>
<td>Nysted, Denmark</td>
<td>166 / 2.3</td>
<td>82 / 90</td>
<td>10.5 (5.8)</td>
<td>6 – 9</td>
<td>132 kV / 11 km</td>
<td>33 kV / 48 km</td>
<td>1</td>
</tr>
<tr>
<td>Robin Rigg, UK</td>
<td>180 / 3</td>
<td>90 / 80</td>
<td>-</td>
<td>4 - 12</td>
<td>2x132 kV / 12.5 km</td>
<td>33 kV / 42 km</td>
<td>2</td>
</tr>
</tbody>
</table>
Still needs significant improvements as optimization must consider:

- Site specifics, such as distance to shore, water depths, seabed geology, number & type of wind turbines, construction & maintenance operations
- Turbine spacing, trade-off between increased wake effect if placed too close together and increased infrastructure costs if placed too far apart
- Reliability, dependent on many factors
- Electrical loss minimization
- Where to place substation platform(s)?
- Layout for collector system – trade-off reliability and costs, can run redundant ring configurations, which allow greater reliability but higher costs
Offshore Layout Examples

Proposed Cape Wind Layout

Layout of Horns Rev 2 Wind Farm

Differences

- Optimization
- Substation location

Source: Dong Energy. http://www.dongenergy.dk
Proposed Cape Wind Layout
Layout of Horns Rev 2 Wind Farm

Fixed Foundation Electrical Connections

a) J-tube method

b) Directional drilling method

c) Floating platform connection
Offshore AC Collector System Options

a) Single Collector Radial

b) Single Collector / Single Return

c) Single Collector / Single-Sided Ring

d) Single Collector / Double-Sided Ring

e) Single Collector / Star Clusters

f) Multi-Collector Ring
OSW Plant Cabling – Economies of Scale

• Significant cost savings can be achieved in both cabling and turbine connection costs depending on individual turbine size
• Such savings can be up to 5-6% of overall project cost depending on WPP layout and distances between turbines and rows (which is largely impacted by turbine size)
• Note – Array losses and other factors also impact plant layout and many factors impact turbine choice

3.6 MW WTGs
Area = 40 km²

5 MW WTGs
Area = 36 km²

10 MW WTGs
Area = 33 km²

Same 250 MW WPP, distance between individual turbines is kept at 8x rotor diameter
Example Offshore Layouts

Interconnection from the wind power plant to grid is the next element of the electrical interconnection, including:

- Wind plant substation and power converters (HVDC)
- Transmission (Configuration and cable)
  - HVAC, HVDC-classic, HVDC-VSC
- Cable Landing
- Grid substation and power converters (HVDC)
Critical distance is achieved when half of the reactive current produced by the cable is equal to nominal current.

Transmission Voltage (kV) | Critical Distance (km)
---|---
132 | 370
220 | 281
400 | 202
HVDC Transmission Technologies

High Voltage Direct Current (HVDC) has been used worldwide to cover long transmission distances or links between grids of different electrical characteristics (HVDC links)

- HVDC terminals have higher capital cost compared to AC substations due to the need for power conversion equipment
- Much lower line losses, decreased cable cost but higher EMF impact
- Two basic topologies of HVDC interconnection – Classic or line commutated and Voltage Source (VSC) or “light”

HVDC – Classic
- Many years of operational experience
- Point to point only
- Requires a very firm grid – sensitive to voltage fluctuations
- Dumb system, cannot provide grid support services

HVDV – VSC
- Very new – lots of products, not a lot of experience
- Multi-point configurations possible
- Allows great flexibility and can even provide expanded grid support beyond wind farm
- Slightly higher cost (but evolving rapidly)
Distance to shore is the most important factor as it impacts cable and installation cost and potential electrical line losses.

**Break-even distance**
- 400-700 km overhead
- 50-100 km submarine
Technology:
- Typically use directional drilling to go under beaches and coastal areas
- Place structure on the seafloor where cable goes underground for protection
- Onshore switchyard and grid interconnection space requirements

Permitting:
- Pass through state waters – all state permitting required
- Local zoning requirements for installation and interconnection
- FERC interconnection regulations (Same as any power plant)
Cable Landing - What not to do…

PR-Vieques cable landing point

Google earth panoramio photo
Electrical Cable

Offshore Wind Power Plant with HVDC Transmission

Fig. 5 Typical HVDC subsea cable with double layer armouring for deepwater. Voltage Source Converter Cable.

Conductor
- Aluminium or copper
- Conductor screens
  - Steel conductive plates
- Insulation
  - Dry cured HVDC polymer
- Insulation screen
  - Steel conductive polymer
- Sealing tapes
- Lead alloy sheath
- Inner jacket
  - Polyethylene
- Tensile armour
  - Two layers of tensile armour
    - One in counter-haul
  - Coloured coated wires
- Outer cover
  - Polypropylene yarn
Submarine Cable Technologies

Major submarine cable suppliers: ABB, Prysmian, Nexans, Sumitomo, Fujikura

• Type 1: Self-contained Fluid-Filled (SCFF) – 1000 kVAC, 600 kVDC
  • Vancouver Island – 525 kVAC, 1200MW circuit, 30/8 km

• Type 2: Mass-Impregnated (MI) – 69 kVAC, 500 kVDC
  • Neptune project (NJ / Long Island) – 500 kVDC, 85/20 km

• Type 3: Cross-Linked Polyethylene (XLPE) – 500 kVAC
  • Sardinia-Corsica, 150 kVAC, 150 MVA

• Type 4: Cross-Linked DC Polymer (XLDC) – +/-320 kVDC
  • Transbay, +/- 200 kVDC, 400 MW, 88 km

• Type 5: Cross-Linked Ethylene-Propylene (EPR) – 150 kVAC

Source: Prysmian Cables and Systems
Submarine Cable Selection Criteria

Source: T. Ackerman – Evaluation of electrical transmission concepts for large offshore wind farms

Courtesy of Prysmian Cables and Systems
Cable Installation and Hazards

Subsea Survey Requirements
- Determination of landing locations
- Identification of historical sites
- Identification of dump or development zones
- Competing use identification (pipelines, fishing)
- Seabed formations and levels
- Strong currents
- Sediment makeup
- Sand ripples, waves and migration

Cable Damage Hazards
- Seabed variations/mobility leading to exposure and suspensions
- Seismic activity
- Iceberg scour
- Submarine landslides
- Dredging hazard
- Fishing/trawling
- Anchor hazard
- Dropped objects/constructions

Installation equipment
- Cable lay vessels
- Burial tools
- Support vessel with crane
- Dive crews
- Anchor handing tug with survey equipment
- Shore equipment, directional digging
Potential Environmental Impacts

Installation, Maintenance and Repair
- Seabed disturbance
- Damage / disturbance of organisms
- Re-suspension of contaminants
- Visual disturbance
- Noise (vessels, laying machinery)
- Emissions and waste from vessels
- Region specific impacts (i.e. coral reefs, turtle egg-laying beaches, etc.)

Operational phase
- Introduction of artificial hard substrate (installed for cable protection)
- Electromagnetic fields (OCS Report: 2011-09 and NSL#: PC-11-03) impact on migration and behavior
- Navigational equipment impacts (HVDC using sea as a return)
- Thermal radiation - known general impact though no studies exist
Assessment of Energy Unavailability can be conducted on specific electrical system configurations and can vary between 1 and 3 percent of total energy generation.
Design Tools

Power system simulation software tools (PSCAD, DigSilent, etc.) can be used for electrical/cabling system design for both offshore and onshore applications. However:

Onshore: There are several wind farm design optimization tools that address BOS cost components

- GE WindLayout, GH/GL WindMaster, etc.
- Layout optimization, electrical loss minimization

Offshore: Only some parts of the existing tools can be applied to offshore BOS costs and in many cases key decision variables are not integrated, reducing the ability to optimize

- Offshore Wind Farm Layout Optimization project
European Offshore Super Grid Proposal

Atlantic Wind Connection Proposal

Source: www.airtricity.com

Note: Depicted routes are notional, not to scale, and for concept demonstration only.
Concepts of Advanced Offshore Collector Systems

- MVDC collector systems using MVDC wind turbines
- Removes need for turbine mounted transformers
- Reduced costs of turbine hardware, including turbine power converters which are currently required
- Lighter and less expensive cabling
Carpe Ventum

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Photo from Nebraska Public Power District, NREL 16442