Integration of offshore wind in the grid – challenges and solutions

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Contents

General challenges of offshore wind farms

Layout of offshore wind farms

Electrical systems for offshore wind farms

  High Voltage Direct Current (HVDC) transmission systems

Some other activities at dept. Energy Technology, AAU

Summary and outlook.
General Challenges

• Reduce cost and increase production in both planning and operation stages

• Improve reliability

• Meet grid code requirements and support grid operation
Two PhDs at Dept. of Energy Technology, Aalborg University

PhD Hongzhi LIU, completed, September, 2014

Grid Integration of Offshore Wind Farms via VSC-HVDC

PhD Peng HOU, to be completed in February, 2017

Offshore Wind Farm Optimization
Offshore Wind Farm Optimization

PhD Peng HOU, to be completed in February, 2017

- Wind farm configuration
- Advanced Control
- Grid Connection
- HVDC transmission
- Systems optimization
Wake Loss Model

• Jensen model

\[ V_w = V_0 + V_0 \left( \sqrt{1-C_t} - 1 \right) \left( \frac{R_0}{R(x)} \right)^2 \]

\[ R(x) = R_0 + kx \]

• Partial Wake

\[ V_w = V_0 - V_0 \left( 1 - \sqrt{1-C_t} \right) \left( \frac{R_0}{R(x)} \right)^2 \left( \frac{S_{\text{partial}}}{S_0} \right) \]

• Multiple Wakes

\[ V_{n,m} = V_0 \left[ 1 - \sqrt{\sum_{i=1}^{N_{\text{row}}} \sum_{j=1}^{N_{\text{col}}} \left[ 1 - \left( \frac{V_{ij}}{V_0} \right) \right]^2} \right] \]
Wake Loss Calculation Case

Energy Yields Comparison of Two Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Without considering wake effect</th>
<th>Considering wake effect</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case I</strong></td>
<td>4164.91 (Matlab)</td>
<td>4214.40 (WAsP)</td>
<td><strong>1.17%</strong></td>
</tr>
<tr>
<td></td>
<td>3460.70 (Matlab)</td>
<td>3394.46 (WAsP)</td>
<td><strong>2.84%</strong></td>
</tr>
<tr>
<td><strong>Case II</strong></td>
<td>4164.91 (Matlab)</td>
<td>4219.09 (WAsP)</td>
<td><strong>0.045%</strong></td>
</tr>
<tr>
<td></td>
<td>3789.00 (Matlab)</td>
<td>3926.71 (WAsP)</td>
<td><strong>3.51%</strong></td>
</tr>
</tbody>
</table>

- Validation through WAsP (Wind Atlas Analysis and Application software)
- the results is close to that obtained with WAsP
Optimized wind turbine placement

- Measured wind data in the vicinity of FINO3
- 12 sections with 30 degree per section
- 5 wind speed interval in each section (5m/s)

The optimization procedure of finding optimal wind farm layout.
Comparison of placement of WT for three layouts.

<table>
<thead>
<tr>
<th>Table I Layout Comparisons of Two Optimal Layouts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Power Losses</td>
</tr>
<tr>
<td>Energy Yields</td>
</tr>
<tr>
<td>Cable Costs</td>
</tr>
<tr>
<td>LPC</td>
</tr>
<tr>
<td>Layout</td>
</tr>
</tbody>
</table>
Substation Placement (1)

- OS location is an important factor of designing a cost-effective wind farm.
- The cable connection layout design considering the number of OSs.
- Heuristic algorithm will be used for cable connection layout design.
- The energy yields as well as power losses along the cables will be taken into consideration to evaluate the layout performance.
Substation Placement (2)

Wind farm layout comparison for regular shape wind farm

Table I
Specification of regular shaped wind farm

<table>
<thead>
<tr>
<th></th>
<th>Scenario I</th>
<th>Scenario II</th>
<th>Scenario III</th>
<th>Scenario IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cable length for CS (km)</td>
<td>73.37</td>
<td>72.96</td>
<td>49.67</td>
<td>50.95</td>
</tr>
<tr>
<td>Trenching length for CS (km)</td>
<td>73.37</td>
<td>54.78</td>
<td>49.67</td>
<td>49.75</td>
</tr>
<tr>
<td>Cable to shore (km)</td>
<td>25</td>
<td>25</td>
<td>32.21</td>
<td>31.38</td>
</tr>
<tr>
<td>Cable costs for CS (MDKK)</td>
<td>118.10</td>
<td>131.31</td>
<td>68.39</td>
<td>63.11</td>
</tr>
<tr>
<td>Cable costs for TS (MDKK)</td>
<td>103.75</td>
<td>103.75</td>
<td>133.65</td>
<td>135.91</td>
</tr>
<tr>
<td>Total Cable invest (MDKK)</td>
<td>221.85</td>
<td>235.06</td>
<td>202.04</td>
<td>199.02</td>
</tr>
<tr>
<td>Substation location</td>
<td>(2.84,-5)</td>
<td>(2.84,-5)</td>
<td>(2.84,2.2)</td>
<td>(2.84,1.38)</td>
</tr>
</tbody>
</table>
Optimization of Cable Connection Layout (1)

- Dynamic MST (DMST) algorithm to generate the cable connection layout.
- Cable current carrying limit is the main constraint.
- Uncrossed cable connection layout is desired.
- Minimized the levelised production cost (LPC) of the wind farm.
Optimization of Cable Connection Layout (2)

Case Study (I)

Table I: Specification of Cable Color

<table>
<thead>
<tr>
<th></th>
<th>Collection system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage level</td>
<td>33kV</td>
</tr>
<tr>
<td>Type</td>
<td>AC</td>
</tr>
<tr>
<td>Color</td>
<td>blue  green  purple  yellow  black</td>
</tr>
<tr>
<td>Cable Sectional area (mm²)</td>
<td>70,95, 120,150 185,24 0, 300 400,50 0 630,800 1000</td>
</tr>
</tbody>
</table>

Table II: Layout Comparisons for Irregular Shaped Wind Farm

<table>
<thead>
<tr>
<th></th>
<th>MST</th>
<th>DMST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable invest (MDKK)</td>
<td>202.47</td>
<td>200.31</td>
</tr>
<tr>
<td>Total cable length for CS (km)</td>
<td>50.4</td>
<td>50.4</td>
</tr>
<tr>
<td>Trenching length for CS (km)</td>
<td>49.77</td>
<td>49.77</td>
</tr>
</tbody>
</table>

The illustration of cable connection configuration for case I. (a) Optimized cable connection layout using MST. (b) Optimized cable connection layout using DMST.
Optimization of Cable Connection Layout (3)

Case Study (II)

Table III: Layout Comparisons for Extremely Irregular Shaped Wind Farm

<table>
<thead>
<tr>
<th></th>
<th>MST</th>
<th>DMST</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cable invest (MDKK)</strong></td>
<td>399.06</td>
<td>374.70</td>
</tr>
<tr>
<td><strong>Total cable length for CS (km)</strong></td>
<td>99.215</td>
<td>98.785</td>
</tr>
<tr>
<td><strong>Trenching length for CS (km)</strong></td>
<td>69.741</td>
<td>78.214</td>
</tr>
</tbody>
</table>

illustration of cable connection configuration for case II.
(a) Optimized cable connection layout using MST.
(b) Optimized cable connection layout using DMST.
Grid Integration of Offshore Wind Farms

*PhD Hongzhi LIU, completed, September, 2014*

- Offshore VSC
- VSC-HVDC Link
- DC Cable
- Onshore VSC
- Offshore Wind Farm
- Dynamic Stability Study
- Main AC System

- Impact investigation
- Stability enhancement of main AC system
Impact on Power System Stability

Test Power System

- Steady state voltage profile
- Dynamic voltage stability
- Transient angle stability
Impact on Power System Stability

Mode 1 - Unity power factor wind power supply

Mode 2 - Rated PCC voltage wind power supply

The wind power penetration level (WPPL) is defined as the maximum wind power injection with which the connection node voltage reaches 0.95 pu.
Impact on Power System Stability

Dynamic Voltage Stability

![Diagram of power system with various components and measurements including Bus10 voltage (pu), PCC voltage (pu), P of onshore VSC (MW), Q of onshore VSC (MVar), and Q of onshore VSC (MVAr)].
Impact on Power System Stability

Transient Angle Stability

Fault location

- L1-1 near Bus6
- L2-1 near Bus7
- L3 near Bus9
- L4-1 near Bus10

CCT (s)

- 0MW
- 270MW
- 450MW

![Diagram showing power system components](image-url)
Coordinated Frequency Regulation

Wind Turbine Ancillary Control

\[
\begin{align*}
2H \frac{df}{dt} &= P_m - P_e \\
\Delta P &= \frac{\Delta f}{R}
\end{align*}
\]

Under-frequency Controller \((f_{\text{meas}} < 49.8\text{Hz})\)

\[
\begin{align*}
\frac{1}{1+sT} \quad &\quad \frac{df}{dt} \quad &\quad K_{\text{inertia}} \\
\Delta f \quad &\quad 1/R \quad &\quad P_{\text{droop}} \\
f_{\text{meas}} \quad &\quad f_{\text{nom}} \quad &\quad P_{\text{under}} \\
\omega_{\text{gen}} \quad &\quad P_{\omega_{\text{ref}}} \quad &\quad P_{g^*}
\end{align*}
\]
Coordinated Frequency Regulation

VSC-HVDC Ancillary Control

Offshore VSC control

Onshore VSC control

Frequency signaling
Application of BESS

- Electric energy time-shift
- Load following
- Area regulation
- Wind power integration enhancement

- Power quality
- Reserve capacity
- Transmission congestion relief

![Diagram of BESS system with components labeled: AC grid, PWM converter, Current controller, Charge controller, PV controller, Frequency controller, Power management unit, Battery model, SOC, V, P, Q, and other symbols representing various electrical parameters and controls.]
Application of BESS

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Small frequency disturbance &amp; small wind power fluctuation</td>
</tr>
<tr>
<td>S2</td>
<td>Small frequency disturbance &amp; large wind power fluctuation</td>
</tr>
<tr>
<td>S3</td>
<td>Large frequency disturbance &amp; small/large wind power fluctuation</td>
</tr>
</tbody>
</table>
Application of BESS

Power Management Unit

Principle of smoothing controller

Frequency controller

\[ P_{odr} + P_{fref} \leq 1 \]

\[ P_{o\text{ max}} < 1 \]

\[ P_{f\text{ max}} = 1 - P_{odr} \]
Publications so far from the two PhD projects

Journal papers

7

Conference publications

10
Research in Wind Power Systems

- Pitch Control/Stress Reduction
- Wind turbine monitoring and fault detection
- Optimal Design of Generators
- Power Electronics Interface
- Wind Turbine Control
- Wind Farm Design and Control
- Wind Power Integration and Interaction with Grid
- Power System Stability and Economics with Large Scale Wind Farms

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Smart Energy Systems

Wind power station

Wind power station

Power Station

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Power Electronics and its Control

- Power electronic interface for wind turbines
- Optimized design of power electronic system
- Wind turbine control with Power electronics
- Modelling and simulation

Generator-side power loss distribution

Grid-side power loss distribution

![Diagram of wind turbine and power electronics system]

- Power loss distribution of grid-side converter (W)
  - On-state loss of IGBT
  - Switching loss of IGBT
  - On-state loss of FRD
  - Recovery loss of FRD

- Power loss distribution of generator-side converters (W)
  - On-state loss of IGBT
  - Switching loss of IGBT
  - On-state loss of FRD
  - Recovery loss of FRD
Wind Farm Optimal Control

\[ P_{\text{out}} = P_{\text{mec}} - P_{\text{loss \ Rotor}} - P_{\text{loss \ Stator}} - P_{\text{loss \ RSC}} - P_{\text{loss \ GSC}} - P_{\text{loss \ filter}} \]
HVDC system and DC/DC converters
Research on hybrid multi-in feed HVDC system with large scale offshore wind farms

Danish Power system

Hybrid Dual-infeed HVDC system model

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Incipient Stator Insulation Fault Detection of Permanent Magnet Synchronous Wind Generators

The comparison of Discrete wavelet transform and Hilbert-Huang Transformation on inter-turn fault detection of PMSG

- Based on Hilbert-Huang Transformation (HHT)
- The capability to detect the inter-turn short circuit fault at the minimum severity degree of 0.1488% is much better than the best record (2.78%) in the literature

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Wind Turbine Power Quality

Flicker Mitigation with reactive power control

\[ \text{In} = 0.1, \text{SCR} = 20, \psi_k = 63.4^\circ \]

\[ v = 9 \text{ m/s}, \text{SCR} = 20, \psi_k = 63.4^\circ \]

\[ v = 9 \text{ m/s}, \text{In} = 0.1, \psi_k = 63.4^\circ \]
Wind Power Integration Into Weak Power Systems

POC voltage behavior in response to SCR and X/R ratio variations

POC voltage response against in-feed wind power and grid parameters

1≤SCR≤4 and X/R≤2
Coordinative Control of Active Power and DC-link Voltage for Cascaded Converter
Harmonic Stability Analysis of Inverter-Fed Power Systems

Experimental Setup

Experimental results in unstable case ($K_{pv}=0.053, K_{pc}=8$)

Experimental results in stable case ($K_{pv}=0.04, K_{pc}=8$)

DG1 Voltage

DG2 Voltage

Bus1 phase-to-phase voltage

Bus2 phase-to-phase voltage
Wind Power in Electricity Market

Fig. 1 On-line pricing model
Oscillation Performance and Wide-area Coordination Control of Power System with Large-scale Wind Farms

- Study the influence of wind farm integration on power system oscillation
- Design a wide-area damping control strategy, coordinating PSS, FACTS damping controller and wind farm damping controller
Summary and outlook

- NORCOWE cooperation has produced some good results on
  - Grid Integration of Offshore Wind Farms via VSC-HVDC
  - Offshore Wind Farm Optimization

- ET-AAU has also been working on some technical solutions

- More challenges to be addressed, for example
  - High voltage and high capacity cables, cable joint technologies for deep sea
  - High power VSC HVDC links and multiterminal solutions
  - Fault handing of DC electrical grids
  - System reasonance and stability of power electronic integrated systems
ET-AAU welcome to develop national and internation collaboration with industry and research institutions.

Thank You!