Challenges in wind farm optimization

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Introduction … it’s all about money (COE)

• Given the large WF investments, large profit is hidden in a WF layout, where the following elements (dictating WF economics) are optimally balanced (i.e. minimizing COE):
  o Financial costs
  o WT loads … and (derived) O&M
  o WF production
Definition of the problem

• Given the ambient wind climate (measured or modeled) quantified as:
  o Wind direction distribution
  o Mean wind distribution ... conditioned on wind direction
  o Roughness/shear ... conditioned on wind direction
  o Turbulence characteristics ... conditioned on wind direction

• ... and imposed constraints (e.g. area, power quality, allowable turbine loads, etc., etc.)

determine the "optimal" WF topology ... possible including (optimal) WT and WF control
Challenges (1)

- Objective function (discharging control aspects)
  \[ \Pi(P(x,y), FC(x,y), L(x,y)) \]; with design space
  \[ x = (x_{WT1}, ..., x_{WTN}) \]
  \[ y = (y_{WT1}, ..., y_{WTN}) \]

- **Challenge n° 1** ... computational speed
  - Ex.: 100WT; 72WD (5 deg. bins); 20 WS (1m/s bins); 1000 iterations ... require
  - Aeroelastic computations: \(100 \times 72 \times 20 \times 1000 = 144 \times 10^6\) 10-min simulations
  - WF flow field computations: \(72 \times 20 \times 1000 = 1.44 \times 10^6\) (10-min) simulations
Challenges (2)

- **Challenge n° 2** ... WF flow fields
  - The WF wind climate deviates significantly from the ambient wind climate:
    - Wind resource decreased
    - Turbulence intensity increased and turbulence structure is modified
    - ... and the WF turbines interact dynamically though wakes
  - ... due to many scales, these (in-stationary) fields are not trivial to compute
Challenges (3)

- **Challenge n° 3 ... cost models**
  - To “collapse” the multi-parameter WF optimization problem into a single objective function requires cost models; e.g.
    - Reliable grid cost models ... including determination of an optimal grid layout in each iterative step of the “overall” WF optimization – an embedded opt. prob.
    - Costs of foundation
    - Cost of fatigue dictated WT degradation
    - Cost of O&M
Challenges (4)

- Challenge no 4 ... optimization strategy
  - Efficient and robust optimization strategy ensuring convergence to a global optimum ... and potentially including sensitivity considerations
What is an optimal layout?

• Examples of potential approaches
  
  o One-parameter approach: Optimizing the *power output* ... and subsequently ensuring that the loading of the individual turbines is beneath their design limit
  
  o Multi-parameter approach: Optimizing WF topology from a “holistic” *economical* point of view ... throughout the life time of the WF
Differences between power output optimization and economical optimization (1)

- **WT:**
  - Power: WT strongly simplified and described in terms of power- and thrust curves
  - Econ.: Full aeroelastic simulation of each individual WF wind turbine ... giving loads as well as production

- **WF flow field:**
  - Power: Stationary flow fields suffice for production optimization
  - Econ.: *In-stationary* characteristics of the WF flow field have to be considered to enable prediction of reliable WT dynamic loading ... considerable complication!
Differences between power output optimization and economical optimization (2)

• Cost models:
  o Power: No cost models are needed
  o Econ.: Cost models accounting for
    ▪ WF production
    ▪ WT fatigue degradation
    ▪ WT O&M
    ▪ Financial costs ... depending on interest rate!
TOPFARM … an economical opt. platform

- Vision: A “complete” wind farm topology optimization, as seen from an investors perspective, taking into account:
  - Loading- and production aspects in a realistic and coherent framework
  - Financial costs (foundation, grid infrastructure, ...)
  ... and and subjected to various constraints (area, spacing , ...)
  as seen over the lifetime of the wind farm!
TOPFARM – basic elements

Module 1: Wind farm wind climate (
*wake affected* flow field)

Module 2: Production/loads (aeroelastic modeling)

Module 3: Control strategies (WT/(WF))

Module 4: Cost models (financial costs, O&M, wind turbine degradation costs)

Module 5: Optimization (synthesis of Modules 1-4)
TOPFARM – WF flow field module (1)

- The TOPFARM multi-fidelity optimization approach requires a hierarchy of models

1. Stationary wake flow field (analytical model) + WT power curve
2. "Poor man’s LES"; i.e. DWM (Database – generic production/load cases + interpolation)
3. DWM (simulation)
TOPFARM – WF flow field module (2)

• The requested *in-stationary* flow field modeling is based on the DWM approach (... Poor man’s LES)

• The core of this model is a *split in scales* in the wake flow field, with
  - large turbulent scales being responsible for stochastic *wake meandering*, and
  - small turbulent scales being responsible for *wake attenuation* and *expansion* in the meandering frame of reference as caused by turbulent mixing

• The wake deficit is thus basically treated as a *passive tracer* in the large scale turbulent field – conveniently defined by the cut off frequency \( f_c = U/2D \)
TOPFARM – WF flow field module (3)

- Basic DWM elements:

The wake is treated as a linear perturbation on the conventional ambient turbulence field!
TOPFARM – WF flow field module (4)

- DWM – validation (1):

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TOPFARM – WF flow field module (5)
TOPFARM – WT aeroelastic module

- **HAWC2:**
  - Non-linear FE model resolving WT dynamics
    ... based on a multi-body formulation
  - Aerodynamics based on Blade Element Momentum algorithm and profile look-up tables
    ... which in turn “delivers” the boundary conditions for the quasi-steady wake deficit simulation used in the DWM model
  - WT generator model included
  - WT control algorithms included
  - Wave loading ... including floating turbine option
  - Output is power and forces/moments in arbitrary selected cross sections
TOPFARM – cost model module (1)

- Basic simplifying approach:
  - Only costs that depend on wind farm topology and control – variable costs – are of relevance in a topology optimization context ... and therefore included
TOPFARM – cost model module (2)

- Examples of cost models ... required to transform the (physical) quantity in question into an economical value for the OF synthesis:
  - Financial costs
    - Foundation costs ... e.g. depending on water depth
    - Grid infrastructure costs
  - Operational costs
    - Turbine degradation (fatigue loading/lifetime)
    - Operation and maintenance costs (O&M)
  - Electricity production
TOPFARM – cost model module (3)

- Grid costs (CF):
  - Presumes a constant price on cabling pr. running meter (including cost of cables, trenching and laying of these)
  - For **each topology iteration step**, the grid cost is defined as associated with the “shortest possible” connection between all turbines
  - “Idealized” cables able to carry all electricity produced by WTs connected to them
TOPFARM – cost model module (4)

- Grid costs (CF):
  - Approach allowing for branching:
    - Phase 1: Each turbine is connected to its closest neighbour
    - Phase 2: resulting sub-clusters are successively interconnected through their closest turbines
TOPFARM – cost model module (5)

- Cost of WT degradation (CD):
  - Only *fatigue driven degradation* considered
  - Based on writing off the investment of the turbines ... specified on main turbine components (i.e. tower, blades, main axis, gear box, generator)
  - Fatigue damage estimated using Palmgren-Miner linear damage accumulation
  - The writing off is presumed *proportional* to the *accumulated equivalent moments* (or accumulated equivalent stresses) in design critical “hot spots” on the respective components
TOPFARM – objective function (1)

- Objective function (OF):
  - The objective function represents the synthesis of all modules into an optimization problem
  - OF is formulated as a financial balance expressing the difference between
    - The wind farm income (power production (WP)) and
    - The wind farm expenses; i.e.
      - O&M expenses (CM)
      - Cost of turbine fatigue load degradation (CD)
      - Financial expenses (C)
TOPFARM – objective function (2)

- Objective function (OF) ... an example:
  - The value of the wind farm power production over the wind farm lifetime, WP, refers to year Zero
  - All operating costs (in this example CD and CM) refer to year Zero ... with the implicit assumption that the development of these expenses over time follows the inflation rate ($r_i$) ... and that the inflation rate is the natural choice for the discounting factor transforming these running costs to net present value

$$FB = WP_n - C\left(1 + \left(\frac{r_{c1} - r_i}{N_L}\right)^{XN_L}\right), \quad WP_n = WP - CD - CM$$

- C denotes the financial expenses (here including grid costs (CG) and foundation costs (CF))
TOPFARM – numeric’s (1)

- Optimization approach ... some tricks to reduce computational time:
  - Structured grids (i.e. reduction of the design space)
  - Multi-fidelity optimization approach based on 2 (3) levels of sophistication

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<td>HAWC2-DWM Database</td>
<td>HAWC2-DWM Simulations</td>
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<td>SLP or SGA+SLP</td>
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<td>Fine</td>
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<tr>
<td>Wind speed and direction bin size</td>
<td>Coarse</td>
<td>Fine</td>
<td>Fine</td>
</tr>
</tbody>
</table>
TOPFARM – numeric’s (2)

- Selected optimization algorithm is a mix of 2 algorithms:
  - Genetic Algorithm (SGA) with key characteristics
    - Structured grid – coarse resolution
    - Slow (many iterations necessary)
    - Global optimum ... usually
  - Gradient Based Search (SLP) with characteristics
    - Unstructured grid (good for refinements)
    - Fast (few iterations for converging)
    - Local minimum
  - SGA+SLP is a good combination for searching a refined global optimum
TOPFARM – example application (1)

- Middelgrunden
TOPFARM – example application (2)

- Middelgrunden

Allowed wind turbine region

Middelgrunden layout
TOPFARM – example application (3)

- Middelgrunden - ambient wind climate
TOPFARM – example application (4)

- Middelgrunden iterations: 1000 SGA + 20 SLP

Optimum wind farm layout (left) and financial balance cost distribution relative to baseline design (right).
Future activities

- More detailed and realistic cost functions - e.g. inclusion of a detailed grid layout platform developed in a collaboration between University of Bergen and University of Aarhus ... taking advantage of the “vehicle rooting problem”
- Inclusion of WF control in the optimization problem
- Inclusion of atmospheric stability effects in the WF field simulation ... using a spectral tensor including buoyancy effects
- Accounting for meso-eddy scales (l > ~10km; T > ~10 min)
- Inclusion of noise aspects
References (1)

References (2)

