Distributed Control Strategies for Wind Farms for Grid Support

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About me...

Energy Engineering at University of Rome, LA SAPIENZA

Bachelor’s Thesis:

“Numerical analysis of a moored floating structure for allocation of WEC systems”

Master Thesis:

“Modelling of wake effects for the wind-turbine fatigue-life prediction in large wind-farms”
Project Presentation

Catalonia Institute for Energy Research

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Advisor:
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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Marie Skłodowska-Curie grant agreement No 675318
Wind Energy in Europe

<table>
<thead>
<tr>
<th>Installed Capacity</th>
<th>142</th>
<th>GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Energy Produced</td>
<td>315</td>
<td>TWh</td>
</tr>
<tr>
<td>European Consumptions</td>
<td>11.4</td>
<td>%</td>
</tr>
<tr>
<td>Conventional Fuel cost saved</td>
<td>7,7bil</td>
<td>€</td>
</tr>
<tr>
<td>CO₂ Emissions avoided</td>
<td>176bil</td>
<td>tons</td>
</tr>
</tbody>
</table>

Germany  Spain  France  Italy  Sweden  Portugal

Installed capacity 28%
Wind Power Plant (WPP)

Wind turbines are located inside large wind farms

Main Advantages:
- To do the wind energy competitive with the conventional power plants
- To make it easier the grid network connections and the generated power control

Main Disadvantage:
- Changing on the inflow for the downstream turbines

*Wake effect*
Wake effect

As a result of the master thesis, a wake model was developed to predict the remaining lifetime and the power reduction, which was implemented inside HAWC2, the aerelastic software of DTU.

Values normalized by stand-alone WT AEP (operation under no wake conditions)
WPPs: participation in grid support

The WPP is organised in a hierarchical structure with two control levels

Over 90% of WTs are horizontal axis and variable speed turbines equipped with PMSG or DFIG
The control strategies can be:

- Power limitation strategy (above rated wind speed)
- Power optimization strategy (below rated wind speed)
- Track given total WF active and reactive power references
WF control level

The coordination between WFC and WTC ensures (Hansen et al., 2006)

\[ P_{wfc}^{ref} \leq \sum_{i=1}^{N_{turb}} P_{i}^{ava} \]

\[ P_i^{ref} = \frac{P_{i}^{ava}}{P_{WF}^{ava}} P_{WF}^{ref} \]

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**Power control requirements**

*Balance control ➔* active power is adjusted downwards or upwards in steps at constant levels

*Delta control ➔* constant reserve capacity in relation to its momentary power production

*Power ramp limiter ➔* how fast the WF power production can be adjusted upwards or downwards

*Frequency control ➔* must be able to produce active power in order to compensate frequency oscillations.

*Reactive power control ➔* WF produces or absorbs a constant value of reactive power

*Voltage control ➔* WF produces or consumes an amount of reactive power in order to control the voltage
Control strategies

- Maximize total WF active power
  \[ P_{WT}^i = P_{i ava} \]

- Operate the turbines at a derated power curve

- Release part of the kinetic energy stored in the wind rotor

\[ N_{turb} \]

1 degree of freedom (DFO)

- kinetic energy
- Power reserve

[Diagram showing power curve with cut-in, rated, and cut-out wind speeds.]

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How to use the additional DOF?

According to the literature, the main ways to manage this DOF aim to:

- Minimize the fatigue loads
- Reduce the energy lost in transmission lines
- Maximize the kinetic energy
- Maximize power reserve

The objective is to reallocate the power production according to the WT position and the wake effect

<table>
<thead>
<tr>
<th>Centralized control</th>
<th>Distributed control</th>
</tr>
</thead>
<tbody>
<tr>
<td>All sensors and actuators are connected to one central controller</td>
<td>WTs organised in clusters</td>
</tr>
<tr>
<td>Simple</td>
<td>Each WT communicates with its nearest neighbours</td>
</tr>
<tr>
<td>Extremely dependent on the failure of the one controller</td>
<td>In case of cluster outage the WF continue to operate</td>
</tr>
</tbody>
</table>
Optimisation of kinetic energy ($E_k$)

Objectives:
- Provide ancillary services: frequency control
- After a frequency event, the WF increases its aggregate generated power by releasing part of stored $E_k$

Shabir et al. (2016) proposed a coordinate optimization for WTs
- Consider a sub-optimal operation varying pitch angle $\beta$ and rotor speed $\omega$
- Consider the wake effect for only one row

\[
E_{k,i}(\omega, \beta, u) = u_i + k'(u_1 - u_i) - ku_1C_{t_i}
\]

\[
\begin{align*}
\omega_i &\leq \omega_i^{opt} \leq \omega_i^{sub} \leq \bar{\omega}_i \\
0 &\leq \beta_i^{opt} \leq \beta_i^{sub} \leq \bar{\beta}_i \\
p_i &\leq \bar{p}_i \\
\sum_{i=1}^{N} p_i^{sub} &= \sum_{i=1}^{N} p_i^{opt}
\end{align*}
\]
Optimisation of kinetic energy ($E_k$)

De Paola et al. (2016) proposed an optimization model to determine the power profile that maximizes the total final energy of WF

Outage event  
$t = 0$  
$T$: duration of event

Total power reference  
$P_r(t) \geq \sum_{i=1}^{N} \Pi(E_{ss}(u_i), u_i) = P_{ss}$  
$\forall t \in [0, T]$

Control problem  
$\max_{i=1}^{N} \sum_{i=1}^{N} E_i(T)$

As result a scheduling for the power profile for each WT is provided

- Allocating maximum power on WT which has the lowest variation of mechanical power respect $E_k$ ($\Pi_E$)

The turbines with lower values of $\Pi_E$ generate the maximum power, reducing their $E_k$ very rapidly and increasing the values of $\Pi_E$
Project Objectives

Propose distributed control strategies in order to

- simplify the WPP architecture in terms of communication
- increase the reliability of the whole control system
- provide grid support after avoiding disconnection of WPP (dynamic stability)

Benchmark layout: Horns Rev 1 wind farm located in Denmark

- 80 WTs NREL-5MW: reference wind turbine equipped with PMSG
Project set-up

WF controller

- Track given total WF active and reactive power references
- Participate at primary and secondary frequency control

WT controller

Gain=1
Near future activities

Starting point:

• Design a *centralized* strategy to provide primary frequency control

• Develop a *model predictive control* strategy for the WF control aimed to track a power reference and maximized power reserve (starting by the approach proposed by De Paola et al. 2016)

• A model will be developed in Matlab and tested in *SimPowerSystems* and *PowerFactory*

• *SimWindFarm* will be used to model the wake interactions among WTs, on the basis of Jensen wake model
References


Thank you....