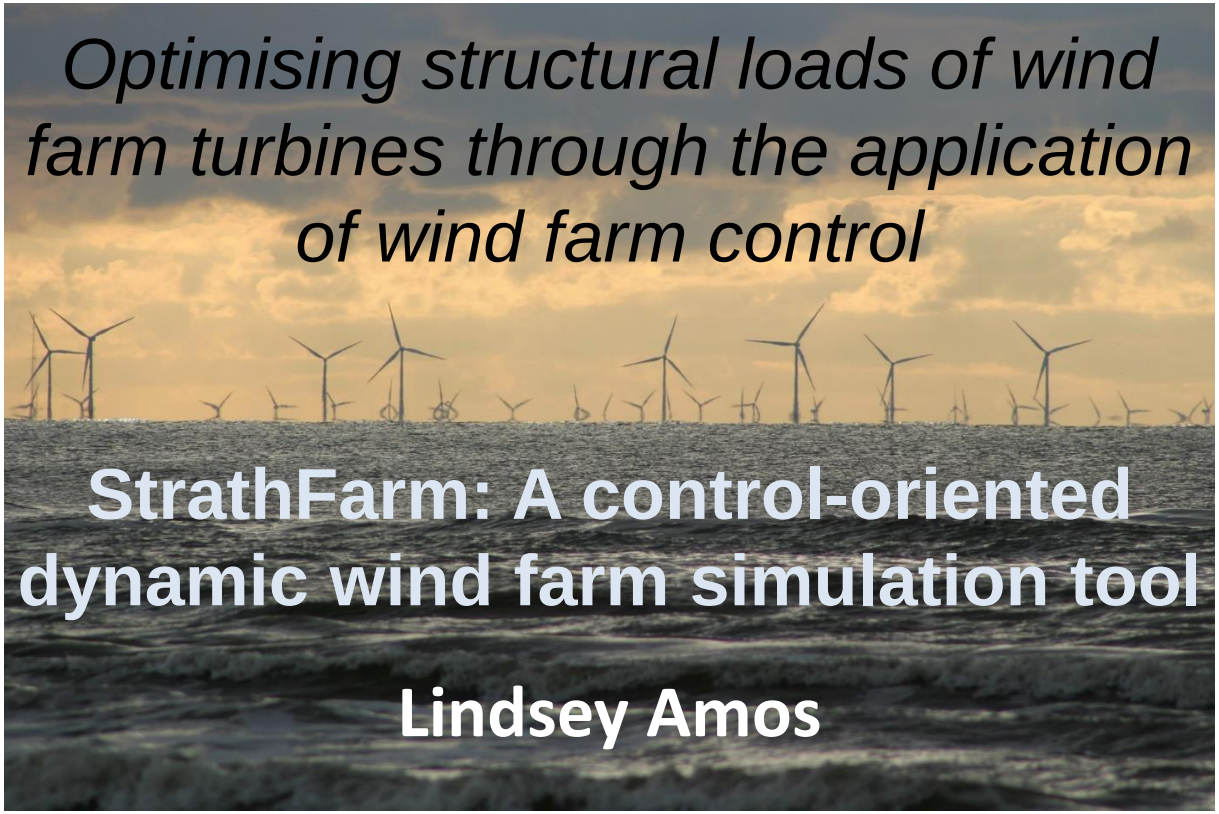
Wind & Marine Energy Systems CDT

University of Strathclyde Engineering



Optimising structural loads of wind farm turbines through the application of wind farm control

StrathFarm: A control-oriented dynamic wind farm simulation tool

Lindsey Amos

THE UNIVERSITY of EDINBURGH
School of Engineering

EPSRC
Engineering and Physical Sciences Research Council

Contents

Introduction

University of Southampton

BSc (hons) Mathematics

Imperial College London

MSc Advanced Computational Methods for Aeronautics, Flow Management and Fluid Structure Interaction

Red Bull Racing Formula One Team

7 years work experience in motorsport simulation engineering

Optimising structural loads of wind farm turbines through the application of wind farm control

Expected finish date (end of funding): **December 2019**

Supervisors: William Leithead, Hong Yue, Adam Stock

Objective is to develop wind farm control strategies and wind farm layouts to minimise the cost of energy.

THE UNIVERSITY of EDINBURGH
School of Engineering

EPSRC
Engineering and Physical Sciences Research Council

Introduction: Context & Motivation

Wind turbines are typically operated as single entities, regardless of whether they are part of a wind farm or not, a strategy that often does not lead to the most optimum performance of the wind farm.

IMAGE: http://www.greenchipstocks.com

Why specifically **offshore** wind farms?

- Large O&M costs offshore
- Larger turbines offshore – more flexible structures
- Impracticality of modelling terrain!
- Energy policy – offshore is the future
- Future flexibility with floating platforms

Wind farm control can offer a highly effective way of optimising the wind farm.

A wind farm controller designed to reduce the loads on the most at risk turbines in a wind farm could help reduce O&M costs.

Wind & Marine Energy Systems CDT

University of Strathclyde Engineering

"Wind farm control is in its infancy… much further work is required to enable widespread commercial adoption"

Ervin Bossanyi and Tiago Jorge, DNV-GL

2016 European Control Conference

IMAGE: https://www.thecrownestate.co.uk/

THE UNIVERSITY of EDINBURGH School of Engineering

EPSRC Engineering and Physical Sciences Research Council

Wind & Marine Energy Systems CDT

StrathFarm

University of Strathclyde Engineering

Requirement for an analysis and design wind farm model and simulation tool that:

- Models wakes and wake interactions.
- Models the turbines in sufficient detail that tower, blade and drive-train loads were sufficiently accurate to estimate the impact of turbine and farm controllers on loads.
- Includes commercial standard turbine controllers.
- Includes a wind farm controller.
- Provides very fast simulation of large wind farms; run in real time with 100 turbines on a standard PC.
- Flexibility of choice of farm layout, choice of turbines & controllers and wind conditions, direction, mean wind speed and turbulence intensity.

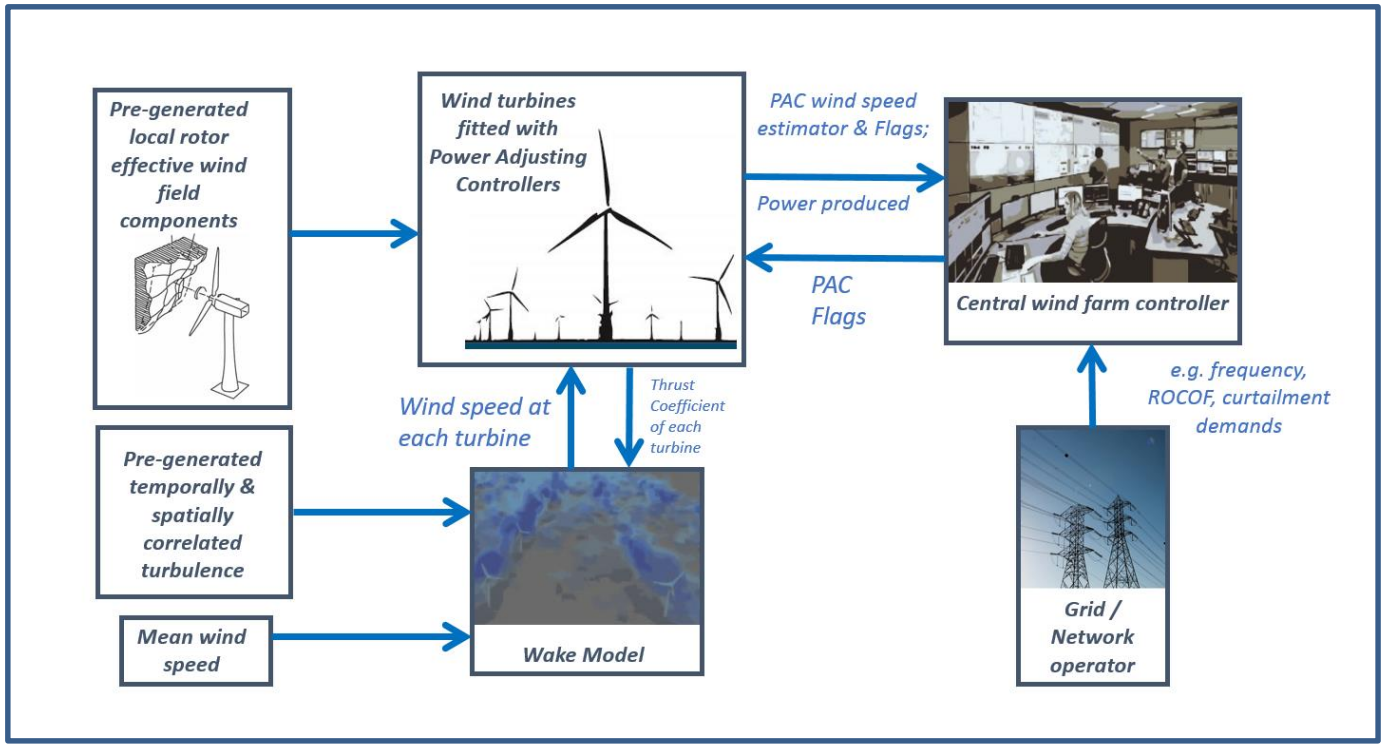
- Focus in literature on WFC for optimisation of power
- Fidelity & computational time trade-off (wake and wind turbine models)

THE UNIVERSITY of EDINBURGH
School of Engineering

EPSRC
Engineering and Physical Sciences Research Council

StrathFarm: Overview

- MATLAB / Simulink based tool
  (although most blocks are now compiled C++ dynamic link libraries).
- Generator script takes user inputs and creates wind farm model for simulation.



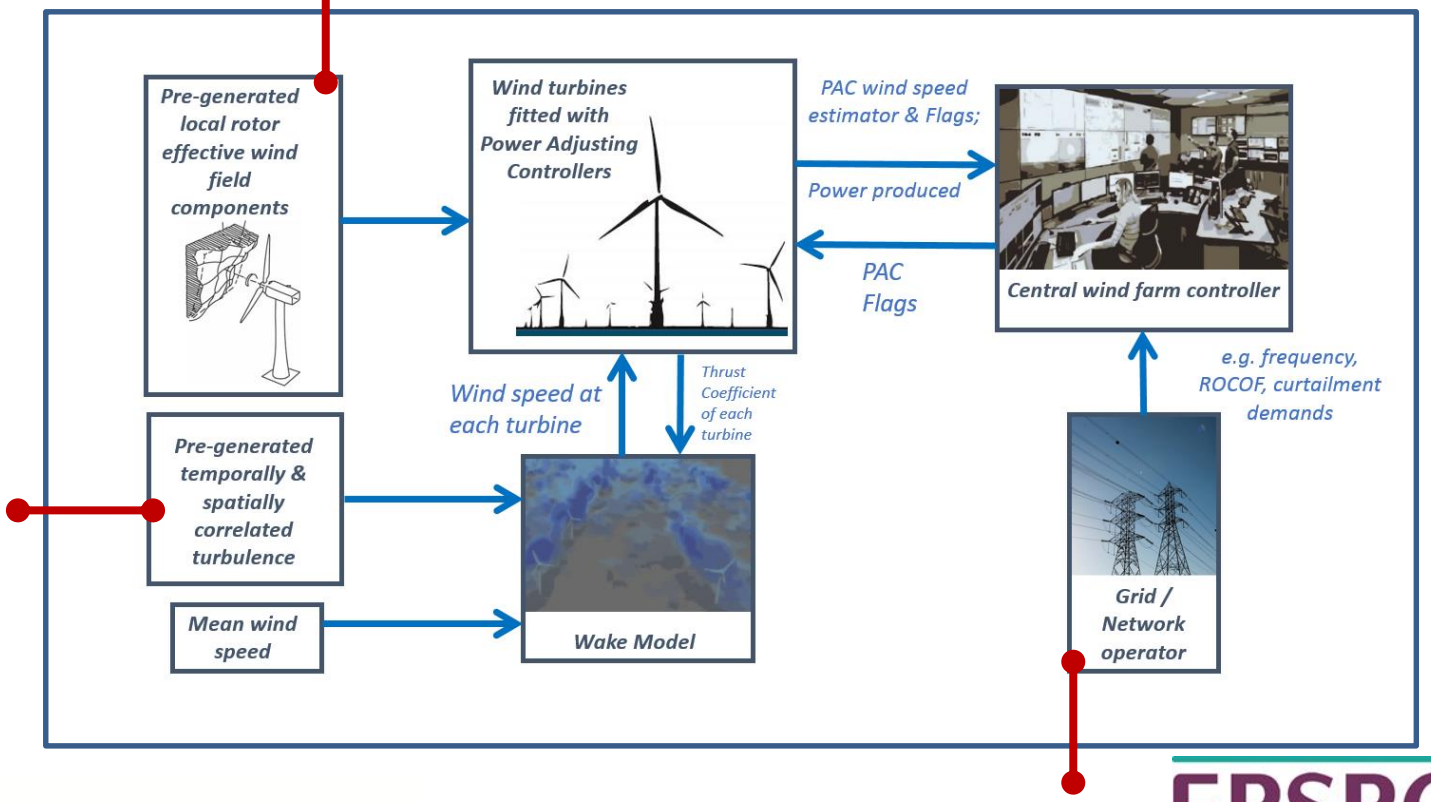
StrathFarm: Overview

Local, rotor effective, wind field model for each turbine, concerned with the higher frequency components of the wind. Deterministic (wind shear and tower shadow) and stochastic effects are modelled which induce expected in-plane & out-of-plane moments.

"Next Generation Controller Design for Large Multi-MW Wind Turbines," M. L. G. Santos, PhD Thesis, University of Strathclyde, 2017.

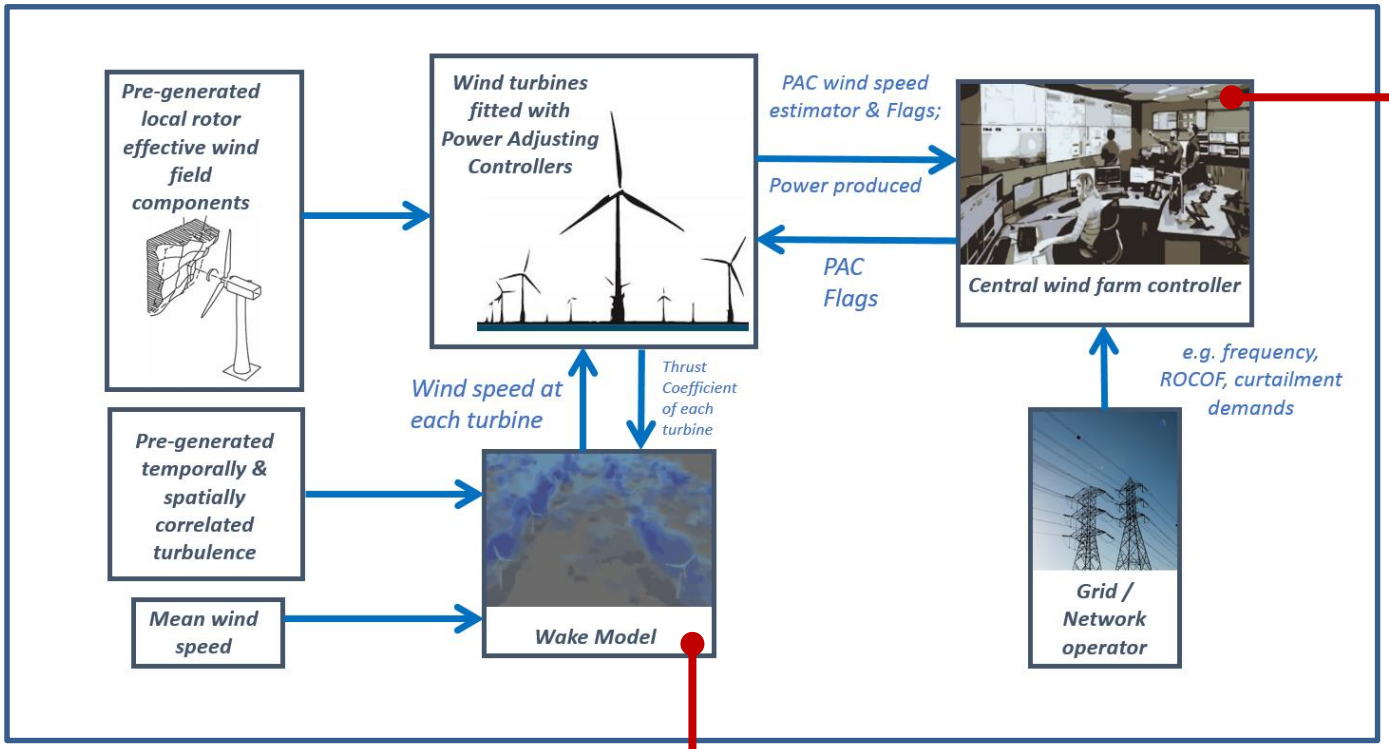
Low frequency spatially and temporally correlated wind farm wind field model. Generates longitudinal and lateral turbulence time series with required characteristics.

"Wind farm simulation modelling and control", S. Poushpas, PhD Thesis, University of Strathclyde, 2016



Inputs for power reference tracking request. Also frequency and ROCOF for droop control and synthetic inertia studies.

StrathFarm: Overview



A generic wind farm controller has been developed.

- **Hierarchical,**
- **Decentralised,**
- **Scalable.**

Power set-point adjustment avoiding feedback loops, i.e. no interference with the full envelope controller.

"Adjustment of wind farm power output through flexible turbine operation using wind farm control", S-H. Hur, W. E. Leithead, Wind Energy 19, 2016

Wake Model – provides aerodynamic coupling. Calculates wake deficit applied to mean wind speed using kinematic engineering model based on Frandsen. Currently subject of study to improve…

"Analytical modelling of wind speed deficit in large offshore wind farms", S. Frandsen et al, Wind Energy 9, 2006

StrathFarm: Overview

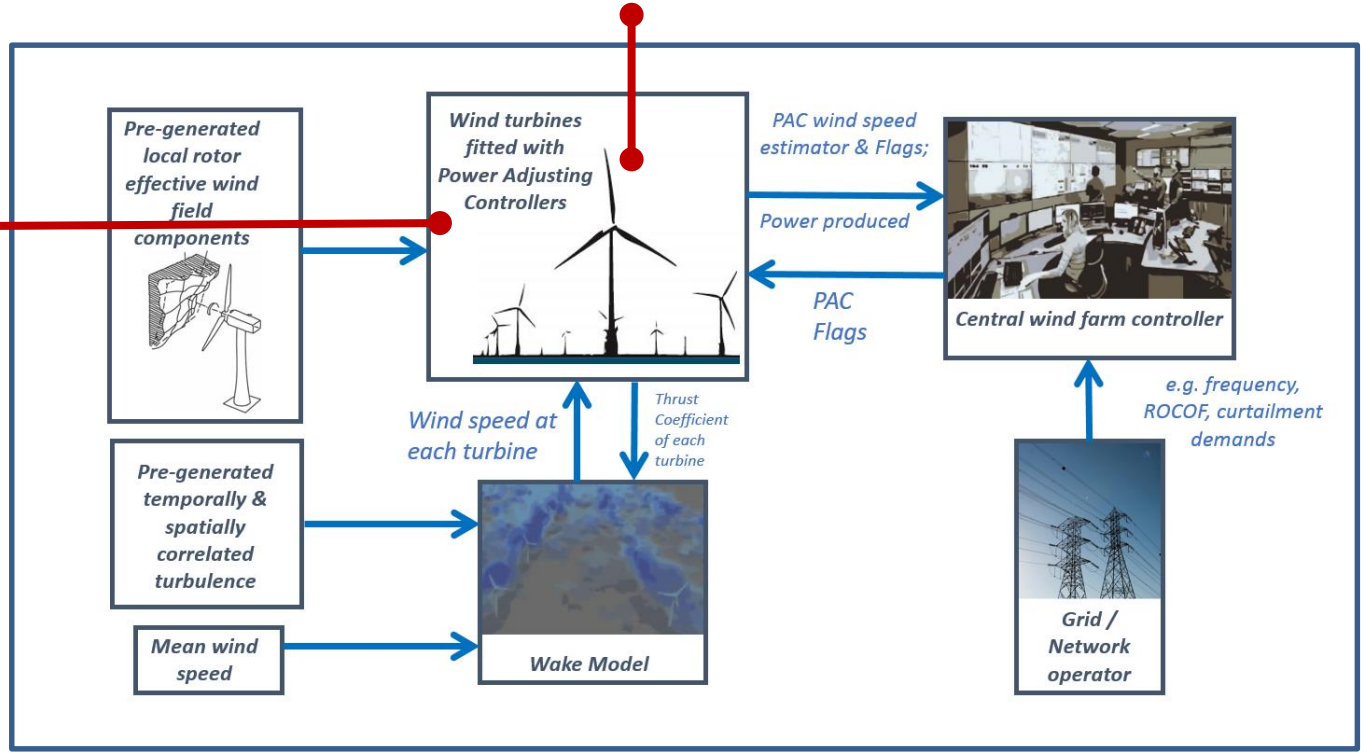
StrathTurb WT Model: Lumped parameter models used for the rotor, drivetrain and for representing blade dynamics.

"Drivetrain Characteristics of Constant Speed HAWT's: Part I - Representation by Simple Dynamic Models", W. E. Leithead and M. Rogers, Wind Engineering Vol. 20 No. 3, 1996.

"Individual Blade Control for Fatigue Load Reduction of Large-scaled Wind Turbines: Theory and Modelling," V. Neilson, PhD Thesis, University of Strathclyde, 2010.

Power Adjusting Controller (PAC): Allows a dynamic adjustment in power set-point (within limits) without interference to the full envelope controller.

"Augmented Control for Flexible Operation of Wind Turbines," A. Stock, PhD Thesis, University of Strathclyde, 2015.

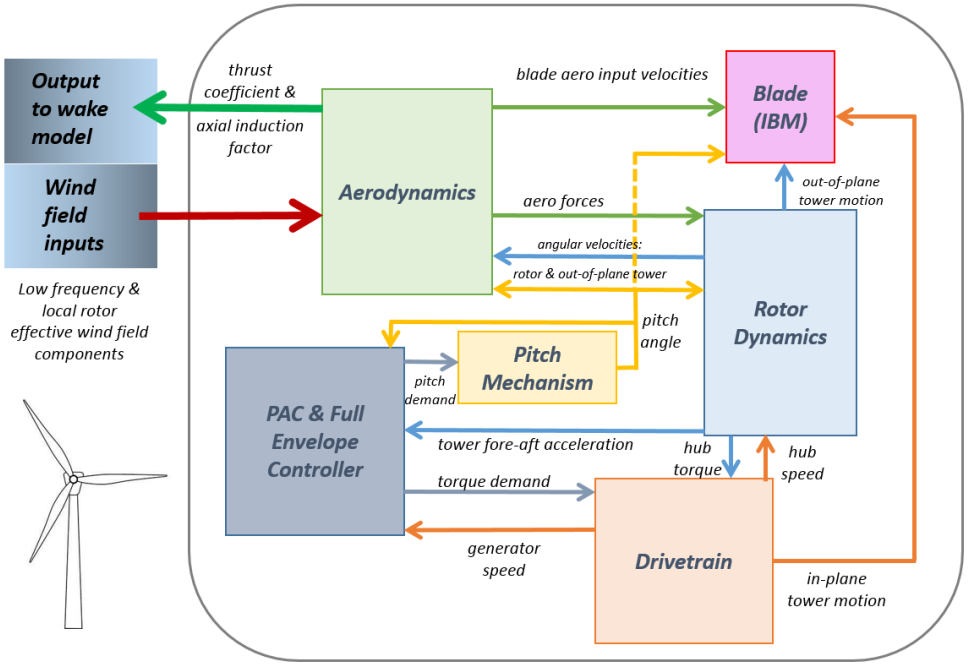


THE UNIVERSITY of EDINBURGH
School of Engineering

EPSRC
Engineering and Physical Sciences Research Council

"StrathTurb" – Wind Turbine Model

- **Supergen** *variable speed pitch regulated, 3-bladed, HAWT* exemplar turbine.
- 5MW, other sizes to be added (10MW, 1.5MW, possibly 7MW).
- Uses lumped parameter models for representing drive train, rotor and blade dynamics.
- Reformulated BEM based aerodynamic coefficient models to determine the thrust and torque at the rotor including dynamic induction lag.
- Continuous (Simulink) and Discrete (C/C++) forms available.



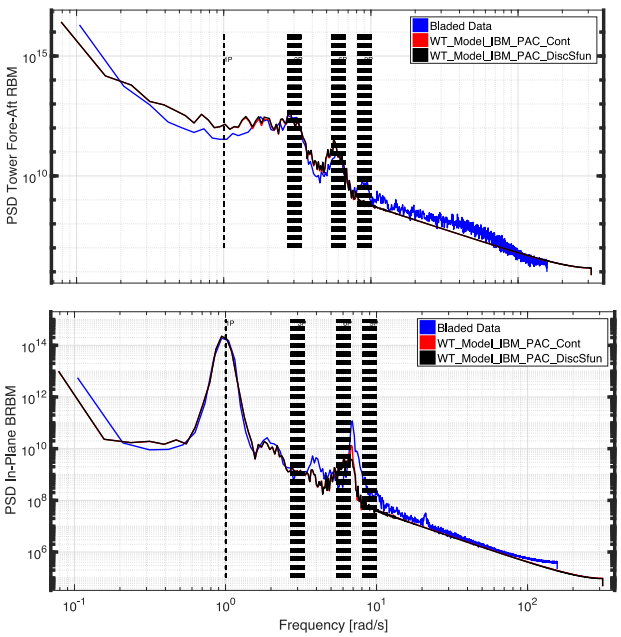
Simulation time, single WT for 600s:
Continuous = 18s
Discrete = 14s

THE UNIVERSITY of EDINBURGH
School of Engineering

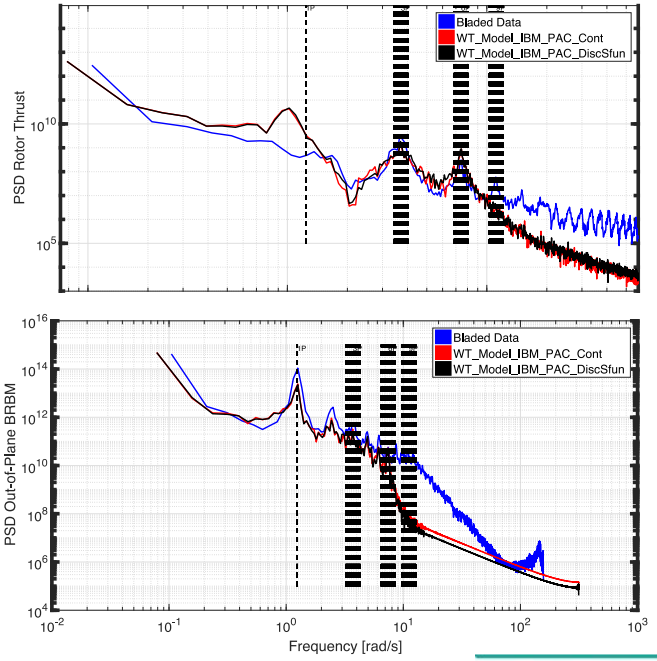
EPSRC
Engineering and Physical Sciences Research Council

StrathTurb loads compare well to DNV-GL Bladed

Mean wind speed 8m/s, 10% TI



Mean wind speed 15m/s, 10% TI



** Note: wind fields not identical comparing DNV-GL Bladed to StrathTurb*

Wake Modelling

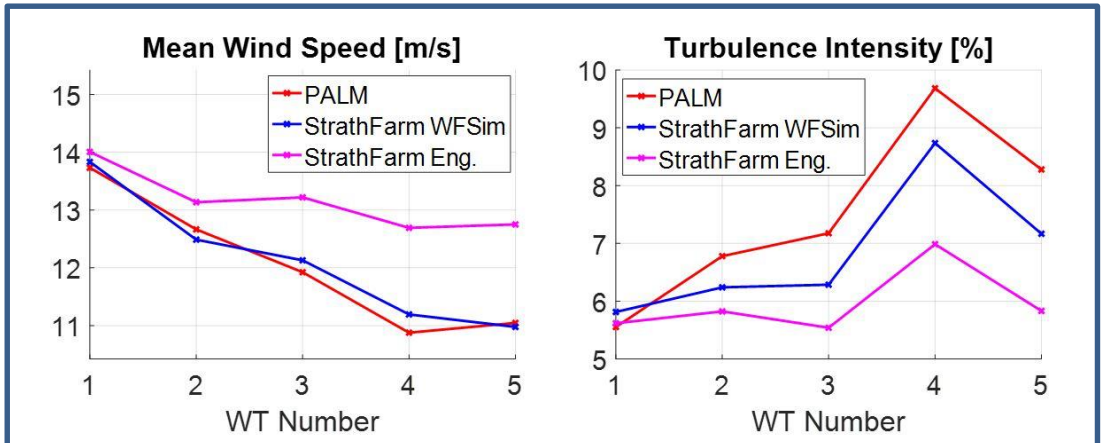
Wind & Marine Energy Systems CDT

University of Strathclyde Engineering

Current research

A) WFSim in StrathFarm

- Investigation into formulating a suitable, alternative wake model based on the RANS equations.
- Implemented in StrathFarm: ”WFSim” – DTU developed code based on modified 2D N–S equations with a correction term (continuity equation) to partially include the vertical dimension.
- Currently tuning model and validating against high-fidelity PALM datasets from DTU.



E.g. (preliminary) result: Above rated, row of 5 WTs, 7D spacing

Abstract submitted for WESC June 2019: *“Modelling and analysis of fatigue loads wind a control-oriented dynamic wind farm simulation tool: WFSim in StrathFarm”, L. Amos, S. Boersma & W. Leithead*

THE UNIVERSITY of EDINBURGH School of Engineering

EPSRC Engineering and Physical Sciences Research Council

Wake Modelling

Wind & Marine Energy Systems CDT

University of Strathclyde Engineering

Current research

A) WFSim in StrathFarm

- Investigation into formulating a suitable, alternative wake model based on the RANS equations.
- Implemented in StrathFarm: ”WFSim” – DTU developed code based on modified 2D N–S equations with a correction term (continuity equation) to partially include the vertical dimension.
- Currently tuning model and validating against PALM data from DTU.

Example StrathFarm sim times:
5 WTs / 1000s simulation

- *Engineering model : 20s*
- *WFSim model: 290s*

Abstract submitted for WESC June 2019: *“Modelling and analysis of fatigue loads wind a control-oriented dynamic wind farm simulation tool: WFSim in StrathFarm”, L. Amos, S. Boersma & W. Leithead*

B) Improvements to kinematic engineering model

- Thought / known to be “conservative” which is prudent if only considering effect WFC can have on power optimisation.
- Simplistically deals with partial wake overlap. Atm. Stability?
- Use WFSim results to tune this model?
- Study to look at applying wake deficit effects to parameters of the local rotor effective wind field.

THE UNIVERSITY of EDINBURGH
School of Engineering

EPSRC
Engineering and Physical Sciences Research Council

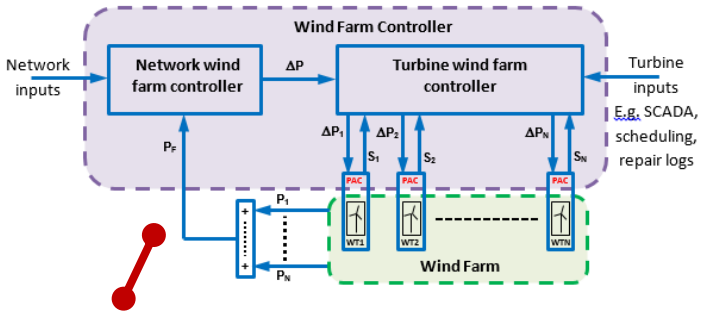
PhD Future Work

Application of Wind Farm Control for Optimisation of Wind Farm Power and Loads

- Simulation and analysis study to inform/guide design of WFC which looks to reduce farm fatigue loads;
  - Vary wind conditions, wind directions, layouts, (turbine size).

    Analyse Damage Equivalent Loads (to measure fatigue).
  - *"Effect of wind flow direction on the loads at wind farm", R. Kazacoks, L. Amos and W. Leithead*

    EERA Deepwind Trondheim, January 2019
- **Development and analysis of WFC algorithms;**
  - Smoothing power = smoothing loads?
  - Turbulence as a proxy for fatigue?
  - Upwind turbine curtailment



Wind farm controller split into two parts – a power controller and a distributed controller. The aim of the distributed controller will be to change power in such a manner as to reduce loads on the turbines – thus optimising the wind farm.

Beyond the PhD…

PRODUCE A (fairly) OPEN SOURCE RESEARCH TOOL WHICH IS MODULAR, FLEXIBLE and ENTIRELY C++ BASED

(Issues for larger number of WTs because of number of link libraries: no need to use Simulink engine now all elements are available in discrete form and coded in C/C++)

Effect of size of WT?

Further advancements in WFC algorithms for power and loads

Layout optimisation

Yaw?
Wake redirection control
vs
axial induction control

Offshore emerging technologies:
- Floating wind turbines
- Multi-rotor
- Tidal
- Wave

Additions to the model for O&M based studies… hub bearing loads, generator faults

Electrical side – ancillary services, storage

THE UNIVERSITY of EDINBURGH
School of Engineering

EPSRC
Engineering and Physical Sciences Research Council

Conclusion

- Wind farm control has potential to reduce the cost of energy, either by maximising power capture or reducing O&M costs.
- Wind farm control for optimisation of power and loads is in it's infancy.
- To develop Wind farm control strategies a wind farm model is required; which gives a good representation of the aerodynamic interactions of WTs and the loads experienced by the WTs. StrathFarm is being developed to this end.
- Future work on this PhD will complete the wake modelling study and then development and analysis of wind farm control algorithms.
- The tool has great potential to be further developed and added to.
- Validation: real world data would be incredibly useful!

Thank you for listening

Acknowledgements:

With thanks to the contributions of Adam Stock, Victoria Neilson, Lourdes Gala Santos, Saman Poushpas, Sung-Ho Hur, Giorgio Zorzi and Velissarios Kourkoulis from the University of Strathclyde.

The work has been funded by *EPSRC EP/G037728/1 DTC Wind Energy Systems; EPSRC EP/L016680/1 DTC Wind and Marine Energy Systems; EPSRC EP/H018662/1 Supergen Wind Phas2; EPSRC EP/N006224/1 MAXFARM; FP-ENERGY-2013.10.1.6: 609795 IRPWind*

lindsey.amos@strath.ac.uk

University of
Strathclyde
Glasgow