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Knudsen, Torben; Bak, Thomas; Soltani, Mohsen

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Distributed Control of Large-Scale Offshore Wind Farms *

Torben Knudsen, Thomas Bak, Mohsen Soltani
Aalborg University
Department of Electronic Systems
Automation and Control
Fredrik Bajers Vej 7
DK-9220 Aalborg Ø, Denmark
Fax, +45 98 15 17 39
e-mail, tk@es.aau.dk

Summary

This paper describes the idea, approach, and preliminary results in the EU-FP7 project with the above title and the acronym Aeolus. The partners in the project are: Aalborg University Denmark, Industrial Systems and Control Ltd UK, Lund University Sweden, University of Zagreb Croatia, Energy research Centre of the Netherlands, Vestas Wind Systems A/S Denmark.

The control of wind turbine farms can be separated in two levels. The first level is the network operator giving a set point for active and reactive power for the whole farm. This project focuses on the next level of the wind farm control where the farm set point are distributed into single turbine set points. Currently, this is done in a basic manner where all turbines essentially are treated the same disregarding the present local wind field and turbine status.

The aim with this project is to exploit information from all turbines in the control of individual turbines in the farm.

This paper first discussed the above problem in more details. Then the five work packages included in the project are described. Finally preliminary work on the simulation model included in one of the work packages is presented.

1 Introduction

Developing the potential for wind energy relies on access to the fundamental resource - wind. Wind energy systems are hence being developed for offshore deployment and large-scale distributed systems with more than 80 individual turbines (e.g. Horns rev offshore wind farm) are currently in operation. These installations are expected to operate similar to conventional power plants and provide quality power (stable, safe, predictable and controllable) at the lowest possible cost.

From a control perspective, the complexity of large-scale farms has historically been handled by separating the control into control on single wind turbine level and control on the wind farm level [11, 23, 22]. The farm level controller serves the demands from the network operator that gives a set point for active and reactive power for the whole farm combined with one of several operational modes, e.g. maximum energy production, rate limiting, balancing, frequency control, voltages control, or delta control. The farm level controls typically measure the wind with a few masts and select appropriate operational strategies, manually or semi-automatic. Set-points for single turbines are generated based on maps and longer term predictions of the wind field and may include trade offs between load and energy performance. At the Horns rev offshore wind farm [13], power set points are generated by a transmission system control and sent to the wind farm through the SCADA-system (Supervisory Control And Data Acquisition system) on a regular basis. The wind farm power set-point is converted to turbine set points for the individual turbines with regard to their power capability and state using a PI type controller.

However, from the point of view of efficient, robust, predictable operation, there is a serious lack of understanding of how the wind resource dynamically may be shared among the individual wind turbines to

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increase the energy performance and reduce the mechanical loads. There is a need to enhance models and controls to exploit the interdependency of the turbines though the wind and move from single turbine control to optimal and dynamic farm level control.

An understanding of the wind is fundamental to control that aim at optimizing power production while minimizing load and providing quality power. Previous attempts have been made to use "upstream" wind information actively in farm level control [19] under the assumption that the turbulence or wind speed variations move downwind with the mean wind speed. This simplified turbulence hypothesis is, however, relatively uncertain for typical distances in most large-scale wind farms, and the attempt to use wind speed predictions, to improve the control was abandoned.

Several methods exist for the calculation of wake effects and the corresponding power production and fatigue loads. The core of these methods is formed by a wake model, which calculates the wake properties from a given free stream wind field. A large variety of wake models exists, ranging from very simple engineering methods [15, 21] to advanced but very time-consuming Computational Fluid Dynamics (CFD) methods as addressed in the EU project Upwind [5]. The high cost in computing time does not allow for advanced CFD simulations of whole wind farms at present. Recently also wakes resulting from several upwind turbines in a farm have been modelled with some success [20, 18]. However the uncertainty increases downwind and most important these studies have been based on static models. Consequently they cannot be used to exploit dynamic behaviour as gusts move though the farm.

A representation of the wind resource and the interconnection between individual turbines through the wind resource, could potentially be exploited by the farm level control to increase the energy performance and reduce the mechanical loads. Optimization based approaches such as model-based predictive control, has been so successful in the chemical and petrochemical industries [12, 17] and may then be applied to wind farm power and load optimisation. The result would be a centralized farm level approach that would allow a model based optimization relative to relevant parameters.

This centralized paradigm has conceptual advantages, but also inherent limitations. In particular, industrial practice in the wind industry relies on distributed control structures and there is a strong need for more systematic approaches to design of such controllers, taking the distributed information into account.

During the last few years, some very encouraging progress has been reported in the area of distributed control [3, 4]. A closely related development is the literature on distributed Kalman filtering. In a distributed Kalman filter, nodes exchange estimates of the quantity of interest possibly together with their local measurements. Among the earlier references is [8] where a decentralized Kalman filter was proposed and more recently, a two step procedure for distributed Kalman filtering [2].

This paper describes the idea, approach, and preliminary results in the EU-FP7 project *Distributed Control of Large-Scale Offshore Wind Farms* that address the problems outlined above and was initiated in May 2008. The partners in the project are: Aalborg University Denmark, Industrial Systems and Control Ltd UK, Lund University Sweden, University of Zagreb Croatia, Energy research Centre of the Netherlands, Vestas Wind Systems A/S Denmark.

The project objective is to exploit information from all turbines in the control of individual turbines in the farm. The improvements will be in two areas. By combining turbine information such as fatigue load and a model which relates the power set point changes to wind field changes the total park power set point will be obtained with the smallest possible fatigue load in the whole farm. Secondly, when wind turbines in the upwind row are hit by a large or extreme gust the downwind travel of this gust will be predicted and the downwind turbines will be protected by appropriate control action.

To pursue the above objectives, the project aims to develop models for the wind field and the relation to the power set points and resulting fatigue loads. These models are decomposed into a quasi static model origination largely from physics and a large scale turbulence model which will be based on measurement from the individual turbines in the wind farm. In addition a centralized controller paradigm is derived based on "model predictive control" in parallel with a distributed controller paradigm where the turbines essentially only communicate with their neighbours. The ideas will be tested in wind farm simulations and through full scale tests.

The remaining of the paper first describes the five work packages which the project is organised in. Then preliminary work on the simulation model included in one of the work packages are presented. Finally some conclusions are drawn.

2 Methods and work packages

This section explains the methods chosen and the resulting organisation of the project into work packages.

2.1 Overall organisation

Basically this is a control engineering project and it is therefore based on control engineering methods. A block diagram illustrating the control problem is shown in figure 1.

Classical control design methods are cheap, robust and works well for simpler single input single output (SISO). However, they are not optimal and for multiple input multiple output (MIMO) systems they do not work. Optimal control of MIMO systems as the wind farm calls for modern model based control design methods. These methods can in general be divided into the following steps.

1. Specify the control task. What are the system input. Which can be manipulated and which can be measured. What are the system outputs. Which should be controlled and which can just be measured. What are the cost function.
2. Develop a model for the system to be controlled.
3. Verify the model.
4. Design a controller.
5. Verify the controlled system.

One possible approach to the above procedure is to finish or at least try to finish one step at a time. In practice this is extremely difficult. Thus, the above procedure will always be iterative. Therefore, the approach chosen in this project is first to go fast through all the steps in a rapid prototyping fashion. This hopefully shades some light on the obstacles along the way. Then the different steps are taken again and the necessary improvements are implemented.

2.2 Work packages descriptions

The following work packages descriptions relates to the above control design procedure. Therefore the names might seem a little odd as the WP's covers more than what is in focus here. Because of the "rapid prototyping" approach the WP numbers are not quit consecutive. Table 1 gives and overview of the WP's and their relation to the control procedure.

2.2.1 WP5 - Case study, dissemination and exploitation

The first part of this WP is the prototype approach. First the control task is specified, then simple prototype models are developed and connected with simple controllers. The validation part is mostly based on a qualitative and simple quantitative assessment of the principal behavior. This forms a good basis for the project partners to review the overall approach.

The above model is then adjusted and improved where necessary and then programmed into a Matlab/Simulink simulation model to be used by the control design WP's to verify and compare the control designs. This simulation model is not supposed to match reality perfectly on a quantitative scale but to correspond to the correct behavior.

2.2.2 WP1 - Quasi-static flow models

In the first part of this WP the static or slow part (e.g. 10 min. sampling time) of the model relating all turbine power set points to the total wind speed field is developed. The model output should also include fatigue and power production from all turbines which in principle can be obtained from the total wind field.

In the second part of the WP the designed controllers are tested on a real but down scaled wind farm at the ECN test site EWTW.

2.2.3 WP2 - Dynamic flow models

This WP is the dynamic supplement to WP1 i.e. flow models for frequencies above 1/10 min. The objective is to estimate and predict the total wind field i.e. the wind speed at all turbines from measurement of wind speed, power, pitch and rotational speed at all turbines. The effective wind speed at the turbines can be estimated based on power, pitch and rotational speed or it can be based on nacelle wind speed sensors or a combination of both.

There are no simple physical models available as simplification to the complex Navier-Stokes equations. Therefore the plan is to use more data driven modelling system identification methods [16].

2.2.4 WP3 - Principles for supervisory farm power/load optimisation

Based on the models from WP1, 2 and 5 a centralized control design is developed in this WP. Centralized controller in the sense that the controller at each

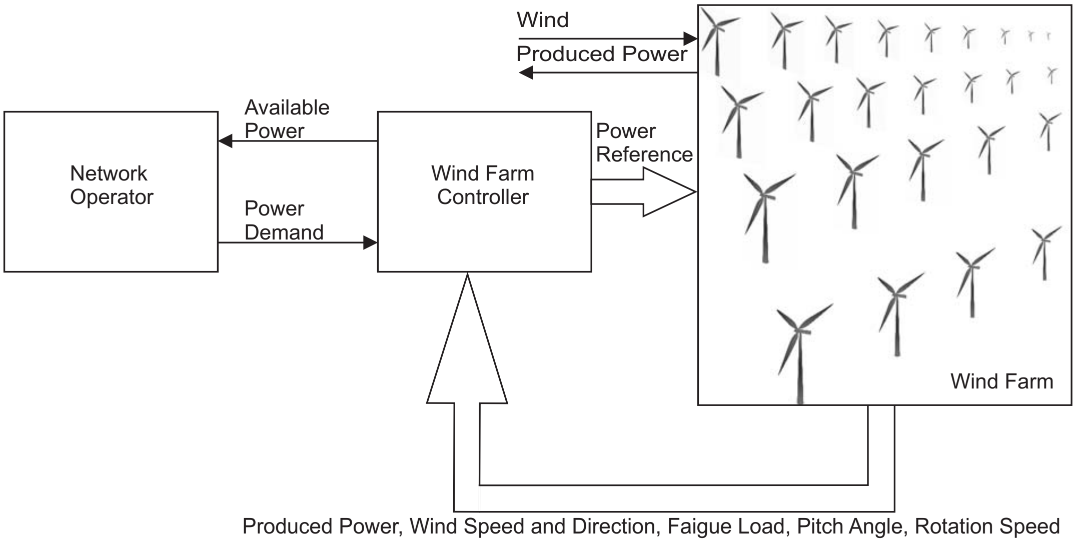

Figure 1: Block diagram illustrating the control problem.

Control procedure step	WP5	WP1	WP2	WP3	WP4
Specify control task	Prototype				
Develop model	Simulation model	Static wind	Dynamic wind		
Verify model	Simple verification of simulation model	Static wind, Provide data	Dynamic wind		
Design controller	Prototype			Centralised	Decentralised
Verify controlled system	By simulation	Full scale test		Centralised	Decentralised

Table 1: Work packages relation to the control design procedure

sampling time gets inputs from all available measurement from *all* turbines and outputs power set points to *all* turbines. The centralized control paradigm is extended to deal with abnormal situations such as the unavailability of some turbines, and possibly other large disturbances such as wind gusts.

2.2.5 WP4 - Principles for decentralized control

This WP develops a controller. It is however structurally different from the above WP3 controller as it is decentralized in the sense that the controller is placed in each wind turbine and it only communicates with the neighboring turbines. Notice that information can go from turbine to turbine in the whole farm just not in one sampling time. This decentralised controller will be designed to handle neighboring turbines not communicating. The advantage with this decentralised control concept is that it is very modular and flexible. For example, it is very easy to add turbines or take some out off operation. Also it is robust to communication problems as only few turbines will be affected if one communication channel fails. These advantages are in favour of the decentralised compared to the centralized controller. However, performance optimality is in favor of the centralized controller as you can never do worse with all information compared to only local information.

2.2.6 WP0

This is the management WP which is not described further in this paper.

3 Preliminary results

This section gives a brief description of the wind farm simulation model.

3.1 Wind farm simulation model

This model includes four major components: wind turbines, wind field, wind farm controller, and network operator.

Figure 2 represents the connections of the components. In this figure, stat is the status of the wind turbine (simply 0/1 when the wind turbine is on/off), C_t is the thrust coefficient, V_h is the wind field, Fatigue is an estimate for the fatigue load, V_meas is the measured wind speed at hub-high, P_e is the produced power, beta is the blade pitch angle, w_g is the rotational speed, P_avail is the available farm power, P_dem is the farm power demand, and P_ref are all the power references for the wind turbines.

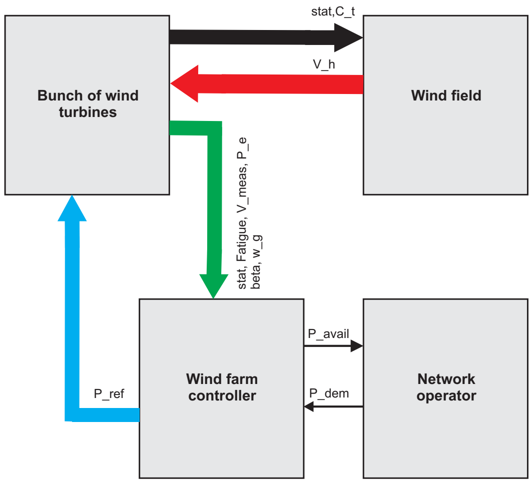

Figure 2: The first level of the wind farm simulation model.

The electro-mechanical model of the wind turbine together with the individual wind turbine controller is used. The wind turbine itself is an energy transformer with wind energy as input and the produced power as output. The wind turbine also affects the downstream wind which is experienced by other wind turbines in the wind farm (depending on how much energy is absorbed by the wind turbine).

Moreover, one of the objectives of Aeolus [1] is to reduce fatigue loads experienced by wind turbines. The fatigue load is estimated by measurement of the wind speed cycles and its effect on the wind turbine [7]. This estimation data has to be used in the wind farm controller and will effect the distribution of the power references on the wind turbines.

The working wind turbines in a wind farm influence each other through the wind field. These effects are mainly due to the wakes after every wind turbine. The wake model is then used in a wind farm and it is explained what are the cross-correlations of these wakes in a large grid of wind turbines. An analytical methodology, however crude, is used as an initial point for wind field model in Aeolus. The related works on the wake deficit [9] is used together with a wake meandering model [14] to achieve the position and deficit of the wakes on all wind turbines. An algorithm regarding the calculations for a computer-based model is given. Finally, the wind speed at each wind turbine (hub-high wind speed) is achieved.

The wind farm controller is the interface between the network operator and individual wind turbine controllers. Its main objective is to provide outputs in two directions; toward the operator and toward the wind farm. The first output is a prediction of the available power at the wind farm. This means that by analyzing the inputs from the wind turbines the controller must provide an estimate of the available power in the wind farm to the operator. This is done by simply summing up the available electrical power at each wind turbine which is predicted from the hub-high wind speed. The second output is the power references for each individual wind turbine controller. This power reference will be produced for each wind turbine by analysing the fatigue load and produced power regarding the power demand from the network operator.

The network operator provides the power demand for the wind farm controller. This demand could be categorized in different modes [6, 11].

Full Power Mode: In the full power mode, the network operator asks the wind farm controller to produce the maximum available power. A prediction of the maximum available power is a feedback from the wind farm controller to the network operator. The prediction is based on the information that the wind farm controller receives from the wind turbines as measurement feedback.

Delta Mode: In the delta mode, the operator asks the wind farm controller to reserve Δ amount of available power as given by the prediction of the available power from the wind farm controller. This actually means that the operator requests a power reserve. In [10] it is mentioned that the reserve power is also available for frequency control action.

Balance Mode: The wind farm production can be adjusted upwards or downwards in steps at constant levels in this mode.

Power Ramp Rate Limiter Mode: Determines how fast the wind farm power production can be adjusted upwards or downwards.

Automatic Voltage/Frequency Control Mode: The wind farm has to be able to produce reactive/active power in order to help the grid for adjusting the frequency.

3.2 Simulation example

The simulation program is for testing wind farm controllers. However, these has not yet been developed. Therefore only a small open loop example is show here. Figure 3 shows a example from the simulation model. The figure shows 5 minutes of nacelle wind speed and produced turbine power for 3 V90-3MW turbines in a row in the wind direction whit a separation of 300 m. The ambient mean wind speed is 10 m/s and in this example the wind farm controller gives a constant set point of 1.2, 2 and 1.2 MW for the three turbines respectively.

As seen the second and third turbine starts in wake but around time 140 sec. the first get out of wake for approximately 30 sec. The same happens to the third turbine some 30 sec. later. The first turbine reaches its reference power which the two next newer do.

4 Conclusion

This paper gives a description of the ideas and organisation of the EU-FP7 project Aeolus which focus on coordinated control of all single turbines in a farm such that farm level set point are obtained whit the lowest possible fatigue loads. A brief presentation of the simulation model is also included.

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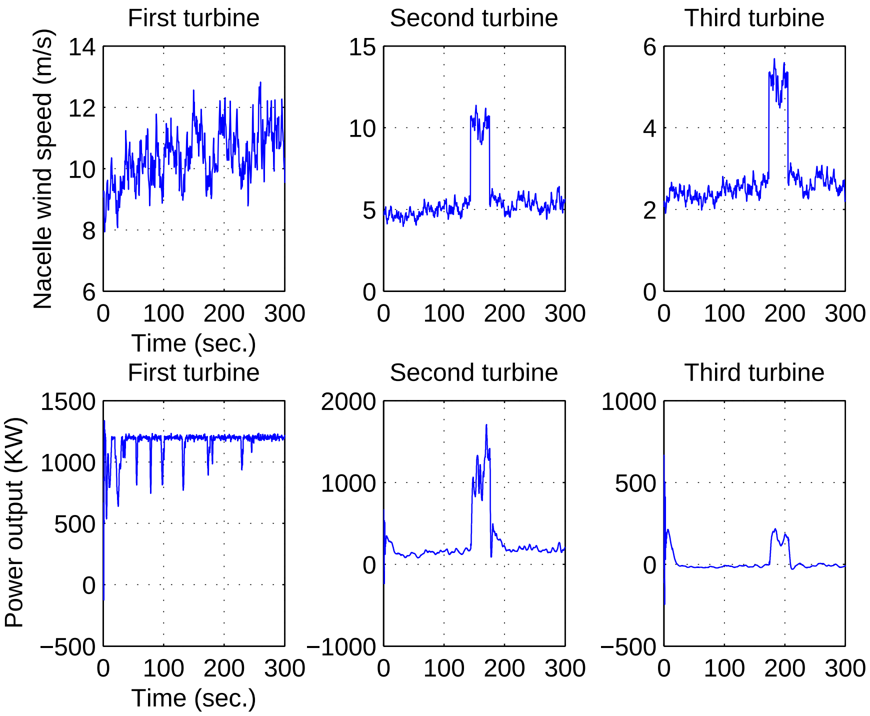

Figure 3: Simulation example with 3 V90-3MW in a row with the mean wind in the row direction from the left in the figure.

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