A Quasi-Steady Wind Farm Control Model

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A QUASI-STEADY WIND FARM CONTROL MODEL

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Summary An overview of wind farm control approaches is presented which recognize that wind turbines in a wind farm are coupled through their wakes. Four of these approaches are demonstrated for a common wind farm. Two wind farm control objectives are considered (not to exceed and to track a given power demand) and compared to the uncontrolled situation. For an ambient wind speed lower than the nominal wind speed two approaches are found to provide power references for the individual turbines that track total power demand. For ambient wind speed higher than nominal this is achieved by three approaches. The fourth approach, which has control objective not to exceed rather than to track given power demand, redistributes power references over the more upstream wind turbines.

1 Introduction

Wind farms are expected to operate similar to other power plants and to provide quality power at the lowest cost [1, 2]. This is achieved by control objectives at farm level, e.g. to track power reference while minimizing fatigue loading. These objectives have been addressed at wind turbine level for several years [3], but studies at wind farm level are few to date [4, 5, 6].

In this paper first an overview is given of wind farm control approaches which consider a wind farm as control object. These approaches include a decentralized dynamic state-space model [7], a model based on the control strategy of a variable speed variable pitch wind turbine [8], a supervisory/reconfigurable model [9, 10] and a stationary wind turbine interaction model [11].

Subsequently, another approach is introduced: the inverse mode of a quasi-steady wind farm flow model. The quasi-steady wind farm flow model relates external conditions of a wind farm (wind speed, wind direction, turbulence intensity) to state (rotor speed, pitch angle) and output (power production, mechanical loading) of all turbines in the wind farm [12]. In inverse mode, power reference is input variable whereas the other quantities are output variables.

The paper concludes with a demonstration of several control approaches. To this end a common wind farm is studied. The simulations are performed with four of the described wind farm control approaches.

2 Wind farm control approaches

In this section an overview is presented of wind farm control approaches which consider a wind farm as control object. In these approaches it is recognized that wind turbines in a wind farm are coupled through their wakes.

Johnson and Thomas describe a wind farm simulation model to be used in testing of wind farm controllers and discuss control strategies to maximize power production of wind farms [5]. Their simulation model calculates power production of each wind turbine given turbine positions, ambient wind speed, and wind speed deficit in the (overlapping) wakes. A combination of

iterative learning control an iterative feedback tuning is proposed in order to reduce wind farm losses. To this end a control objective is proposed which maximizes the total wind farm power for a given ambient wind speed by using two individual turbine control variables: blade pitch angle and tip-speed ratio.

The wind farm simulation model of Soltani et al. includes sub-models for the wind turbines, the wind field, the wind farm controller, and the grid operator [7]. The wind farm controller is the interface between the grid operator and the individual wind turbine controllers. It provides output to the grid operator and to the wind farm. Output to the grid operator consists of prediction of available power in the wind farm on basis of prediction of available power of the individual wind turbines. (Available power is the maximum power that can be extracted given the ambient wind.) Output to the wind farm consists of power references for the controllers of the individual wind turbines. These power references are determined from the total demanded power by proportional distribution. (Total demanded power is power requested by the grid operator.)

The wind farm controller of Soleimanzadeh and Wisniewsky is based on the wind turbine control strategy of a variable speed variable pitch wind turbine [8].

If wind speed is higher than the nominal wind speed, the wind farm controller provides power reference and blade pitch angle reference for the control system of each individual wind turbine in the wind farm. The collective turbine power references track the total demanded power. In addition the turbine blade pitch angle references minimize total fatigue loading. (Total fatigue loading is sum of fatigue loading of the individual wind turbines.)

If wind speed is lower than the nominal wind speed, there are two options to control a wind farm: to track the total demanded power if this is less than the available power, or, otherwise, to extract the available power. If demanded power is less than available power, the wind farm controller provides power references and blade pitch angle references for the individual turbines in such a way that total demanded power is tracked and collective turbine loading is minimized. If on the other hand available power is to be extracted, the wind farm controller provides rotor speed references for the individual turbines.

Spudić et al. and Savvidis and Van der Molen recognize that wind farm dynamics are decoupled through different time scales [9, 10]. This concept is the basis of a two-level wind farm control concept.

The high level of control acts on the mean flow in a wind farm and for that reason accounts for coupling of turbines via their wakes. This control level sets the optimal operating point for each individual wind turbine in a wind farm. It works at a relatively slow sampling rate that scales with the mean wind speed and the size of the wind farm. Savvidis and Van der Molen describe a high-level controller which is based on model-based predictive control employing a cost function [10]. The reference for this controller is the total demanded power. In addition, an objective of this controller is to minimize the fatigue loads of the individual wind turbines. The available powers of the individual turbines are used as constraints (upper limits) for the power references of the individual turbines.

The low level of control, on the other hand, reacts to disturbances like cut-outs or gusts. This control level adjusts the operating point in such a way that as soon as possible the total demanded power is tracked again. It works at a relatively fast sampling rate. Spudić et al. introduce a solution for the low-level control problem which is based on multi-parametric solution of the constrained finite time optimal control problem for each wind turbine [9]. Here optimal control action and cost are obtained as explicit expressions in parameters representing measurements, references and constraints.

The stationary wind farm control model of Madjidian and Rantzer consists of a sub-model for the ambient wind, a sub-model for the turbines, and a sub-model for the interaction between the turbines in a farm [11]. Ambient wind is modeled as a mean wind speed superimposed with fluctuations. A turbine is modeled by its power and thrust curves, and has a control variable which is generator torque and/or blade pitch angle for an uncontrolled turbine or power reference for a controlled turbine. Wind turbine interaction is modeled in such a way that wind speed at a turbine can be determined from mean and standard deviation of wind speed at its closest neighbors.
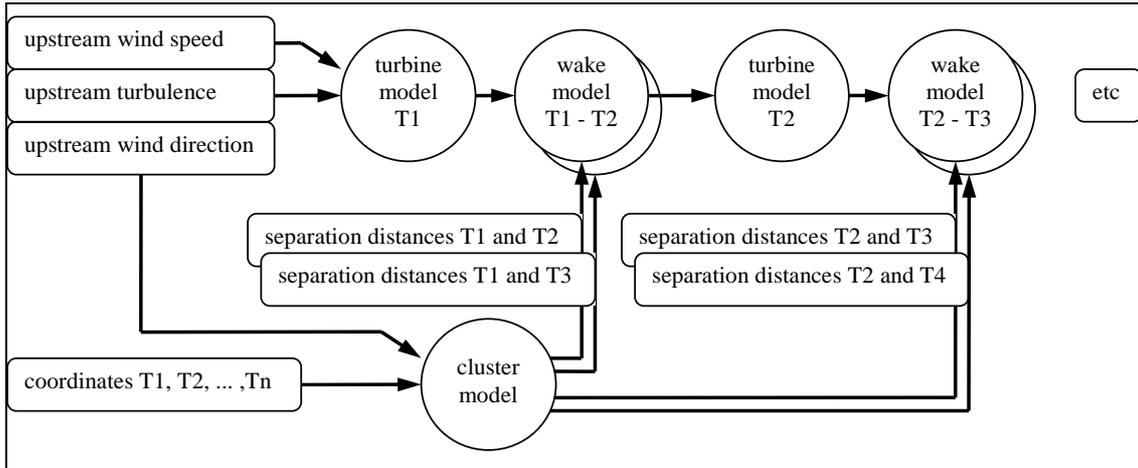
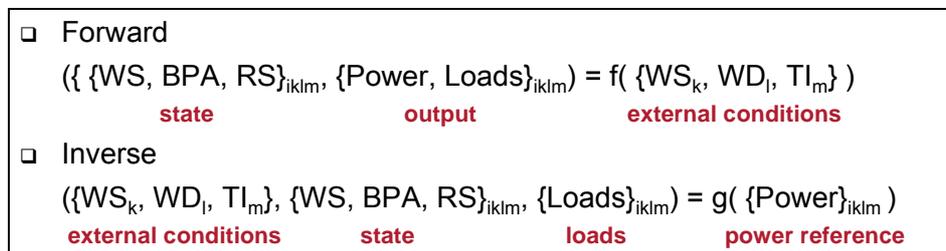Figure 1 Sub-model structure of the quasi-steady wind farm model

> ❑ Forward
>
> $(\{ \{WS, BPA, RS\}_{iklm}, \{Power, Loads\}_{iklm}) = f(\{WS_k, WD_l, TI_m\})$
>
>   **state**   **output**   **external conditions**
>
> ❑ Inverse
>
> $(\{WS_k, WD_l, TI_m\}, \{WS, BPA, RS\}_{iklm}, \{Loads\}_{iklm}) = g(\{Power\}_{iklm})$
>
> **external conditions**   **state**   **loads**   **power reference**

Figure 2 Description of forward and inverse mode of the quasi-steady wind farm model. The model relates external conditions of a wind farm (wind speed WS, wind direction WD, turbulence intensity TI) to state (rotor speed RS, pitch angle BPA) and output (power production Power, mechanical loading Loads) of all turbines in the wind farm

The control model based on the control strategy of a variable speed variable pitch wind turbine [8], the supervisory part of the supervisory/reconfigurable control model [10] and the stationary wind farm control model [11] are demonstrated in section 4 of this paper.

3 Quasi-steady wind farm control model

The quasi-steady wind farm model relates external conditions of a wind farm (wind speed, wind direction, turbulence intensity) to state (rotor speed, pitch angle) and output (power production, mechanical loading) of all turbines in the wind farm [12]. This model consists of a sub-model of the wind turbine, a sub-model of the wind turbine wake, and a sub-model of the cluster of wind turbines (figure 1).

    The model parameters include coordinates of the wind turbines in the wind farm and the following turbine parameters: hub height and rotor diameter, thrust coefficient as a function of tip-speed ratio and blade pitch angle, and rotor speed and blade pitch angle as a function of wind speed.

    The model output consists of a look-up table with external conditions, and state and output of all wind turbines in the wind farm.

    The model is computationally fast and cheap because it is gridless and because it is based on momentum theory.

The quasi-steady wind farm model can be operated in two modes: forward or inverse (figure 2).

    In forward mode, external conditions are input variables whereas state and output of all wind turbines are output variables. A typical application of the forward mode is prediction of

power production of a wind farm for a given wind speed, wind direction and turbulence intensity. Another application of the forward mode is validating and tuning the wind turbine wake sub-model.

In inverse mode, on the other hand, power is input variable whereas all other quantities are output variables. A typical application of the inverse mode is the calculation of the distribution of power references over the turbines in a wind farm if a given power demand is not to be exceeded. The inverse mode is demonstrated in section 4 of this paper.

4 Demonstration of wind farm control approaches

In this section four of the wind farm control approaches presented in the sections 2 and 3 are demonstrated for a common wind farm comprising a row of 10 NREL 5 MW wind turbines separated 5 rotor diameters [13]. The wind flow is parallel to the row of turbines and turbulence intensity is 10%.Two ambient wind speed cases are addressed: 8 m/s (halfway cut-in and nominal wind speed) and 11 m/s (just below nominal wind speed). Independently, two control cases are considered: uncontrolled and controlled. The controlled cases differ in control objective: either not to exceed a given power production (quasi-steady flow modelling approach), or to track an externally issued power production (the other approaches).

The power references of the individual wind turbines in the wind farm are shown in the figures 3 and 4. Note that power reference for a wind turbine is not the same as power produced by that wind turbine as the actual production is left to the decision of the wind turbine controller.

The left-hand side of figure 3 shows the power references of the individual turbines as functions of position in the row in the case of an uncontrolled wind farm operating at the lower than nominal wind speed of 8 m/s. There is a clear loss of production, with a maximum loss for the second turbine in the row. Total available power, equal to sum of individual power references, is 12.7% of wind farm nominal power.

The right-hand side of figure 3 presents the same information, but for a controlled wind farm with a total power demand of 33.0% of the wind farm nominal power. The controller with the objective not to exceed the power demand is able to provide the wind farm with individual power references that add up to 13.2% of wind farm nominal power while at the same time reducing power loss of the second turbine. The other controllers, apart from one, provide individual power references that almost track total power demand.

The same kind of information is displayed in figure 4 for the wind farm operating at the higher than nominal wind speed of 11 m/s.

If not controlled, individual power references add up to 34.9% of wind farm nominal power. Loss of production evidently is enormous: 60% of nominal power at second turbine, and another 20% at next turbines up to the fifth.

For this wind speed total power demand of 62.0% of wind farm nominal power is considered. The controller with the objective not to exceed the power demand provides the wind farm with individual power references that add up to 37.0% of wind farm nominal power and essentially redistributes power references over the first three turbines. The other controllers almost track total power demand.
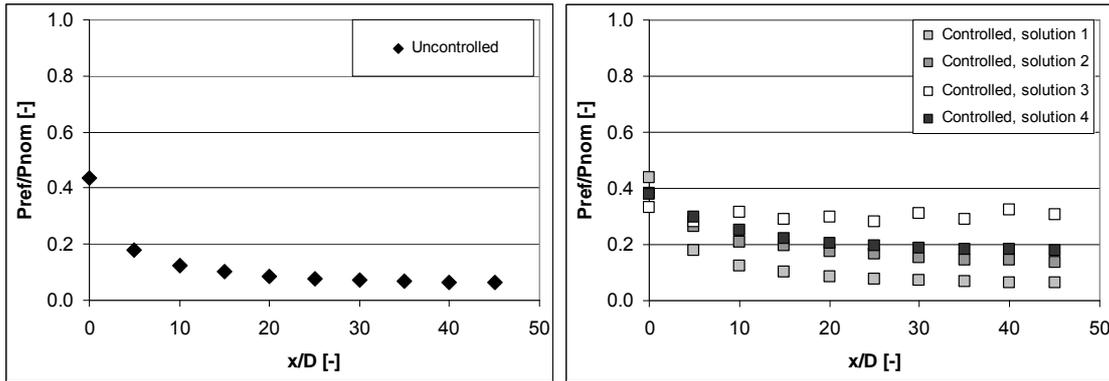
Figure 3 Wind turbine power reference P_{ref} normalized with wind turbine nominal power P_{nom} as a function of normalized position x/D in a row of wind turbines operating in a lower than nominal wind speed which is directed parallel to the row; uncontrolled wind farm (left) and controlled wind farm (right)
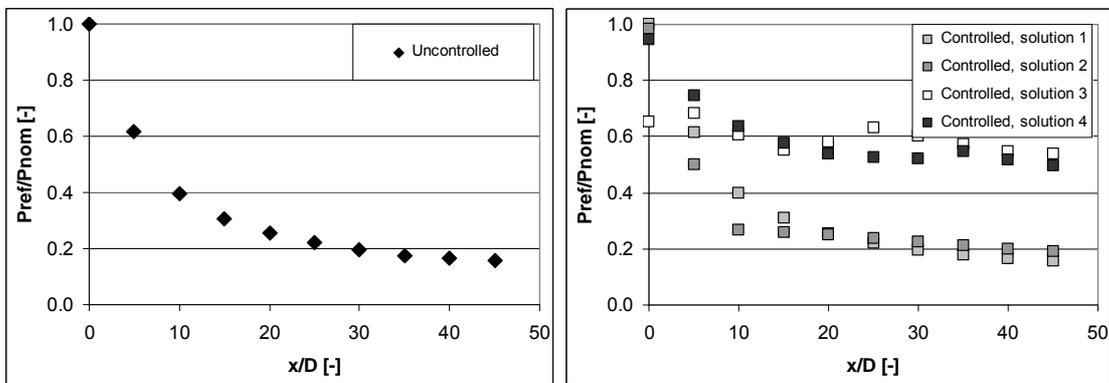

Figure 4 As figure 3 but for a higher than nominal wind speed

5 Conclusion

An overview of several wind farm control approaches, all recognizing that wind turbines in a wind farm are coupled through their wakes, has been presented, and four of these have been demonstrated for a common wind farm. Two wind farm control objectives were considered (to track and not to exceed a given power demand) and compared to the uncontrolled situation.

For an ambient wind speed lower than the nominal wind speed two approaches provide power references for the individual turbines that track total power demand. For ambient wind speed higher than nominal this is achieved by three approaches. The fourth approach, which has control objective not to exceed rather than to track given power demand, redistributes power references over the more upstream wind turbines.

Acknowledgement

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9. Spudić V, Jelavić M, Baotić M, Perić N. Hierarchical wind farm control for power/load optimization. Torque 2010. 2010
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13. Jonkman J et al. Definition of a 5-MW reference wind turbine for offshore system development. NREL, Technical Report NREL/TP-500-38060. 2009
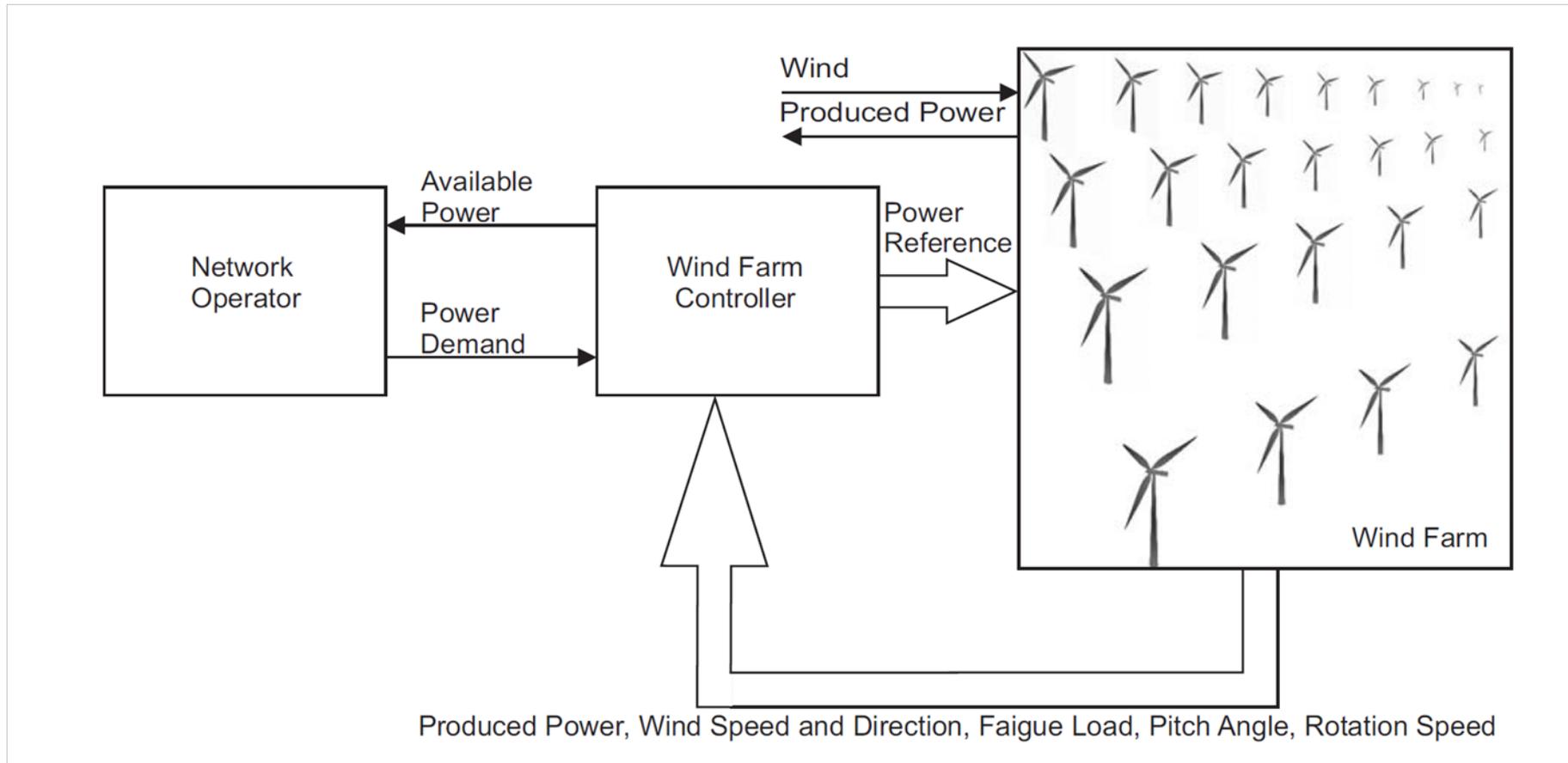
Quasi-steady Wind Farm Control Models

Arno Brand
Thomas Bak
Torben Knudsen et al.
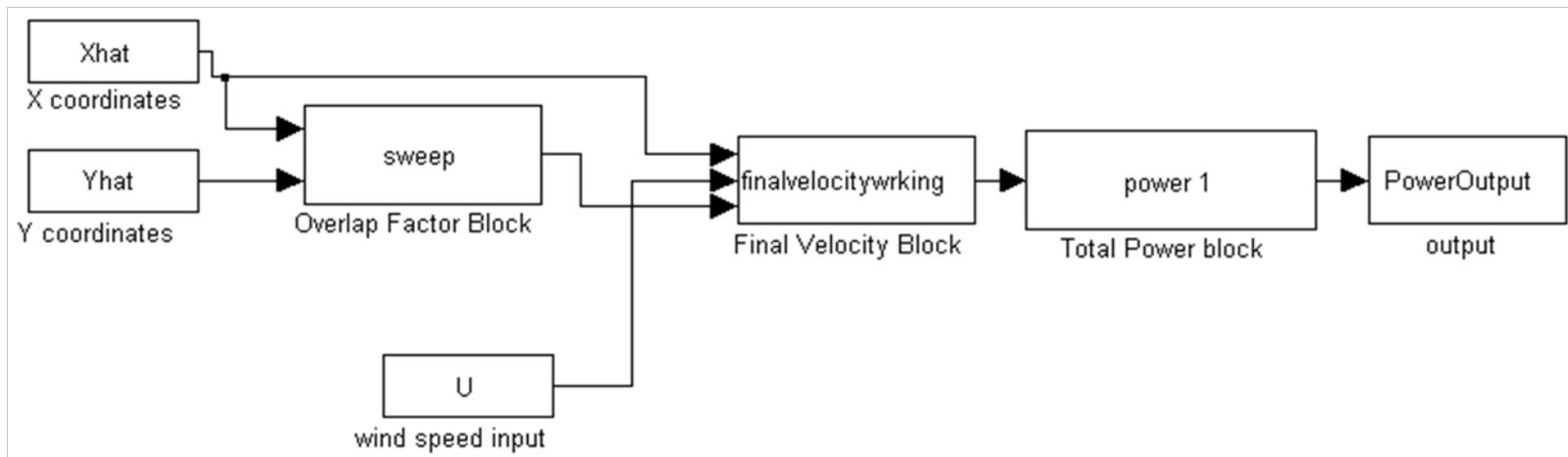**Gerrit van de Molen et al.**
Mato Baotić et al.
Anders Rantzer et al.

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ict-aeolus.eu
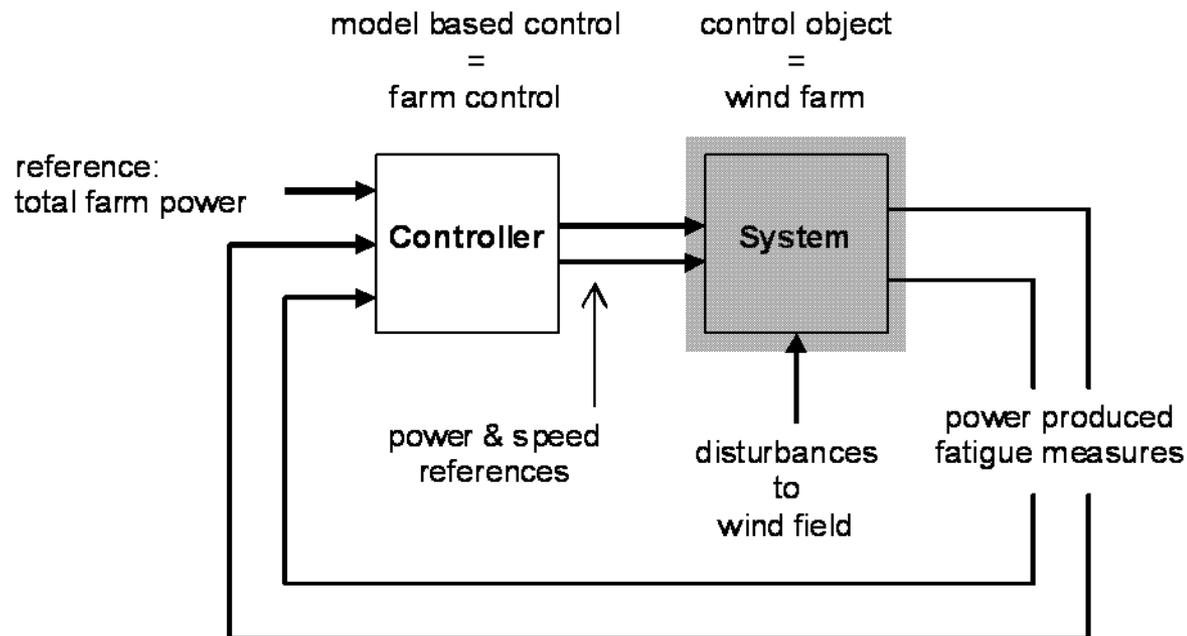
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❑ **Motivation & History**

❑ **Developments**

❑ **Another model**

❑ **Comparison**

❑ **Summary & Outlook**
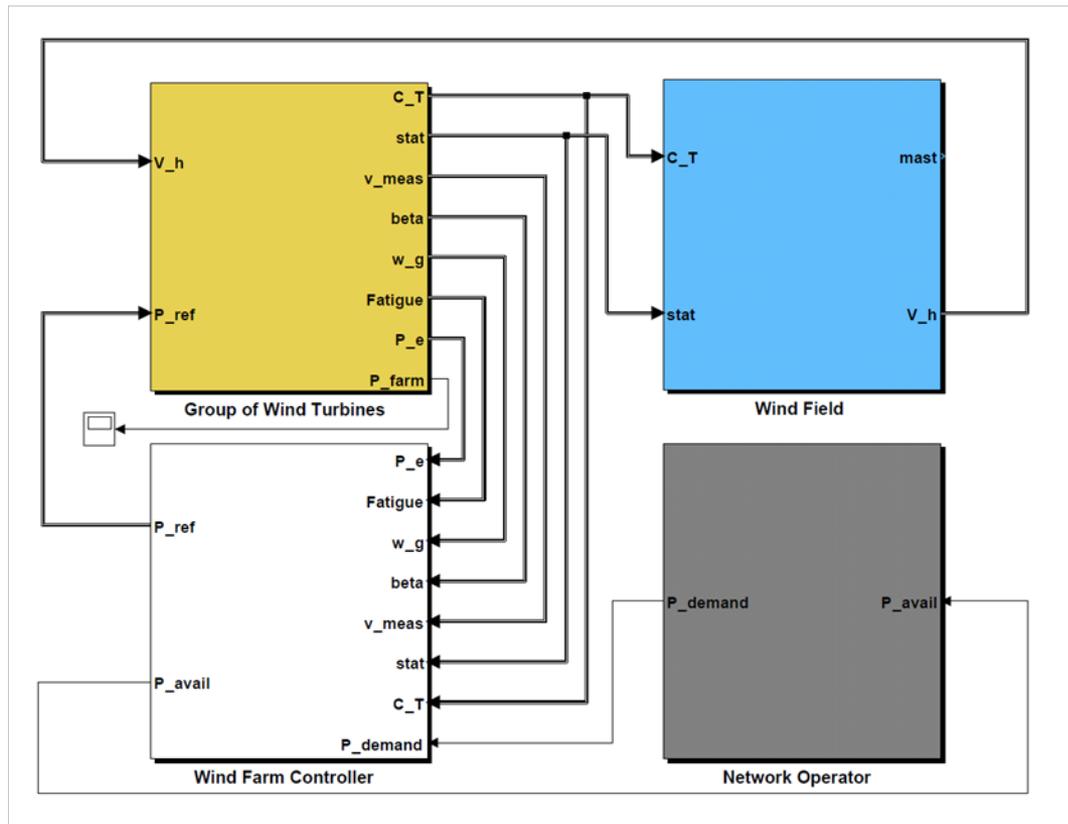
Source: Knudsen et al., Euromech 508, 2009

Source: Johnson & Thomas, 2009 ACC, 2009

model based control
=
farm control

control object
=
wind farm

reference:
total farm power

Controller

System

power & speed
references

disturbances
to
wind field

power produced
fatigue measures

Decentralized Dynamic State-space Controller

Torben Knudsen, Mohsen Soltani, Thomas Bak

Dynamic Wind Flow Model

Maryam Soleimanzadeh, Rafael Wisniewski

$$\nabla^2 U + \frac{1}{\Gamma}\frac{\partial U}{\partial t} + S = 0$$

$$\rho\frac{\partial U_{P_i}}{\partial t} + a_P U_{P_i} - a_E U_{E_i} - a_W U_{W_i} - a_N U_{N_i} - a_S U_{S_i} = b_i$$

$$\dot{X} = A(t, u)X + B(t, u)$$
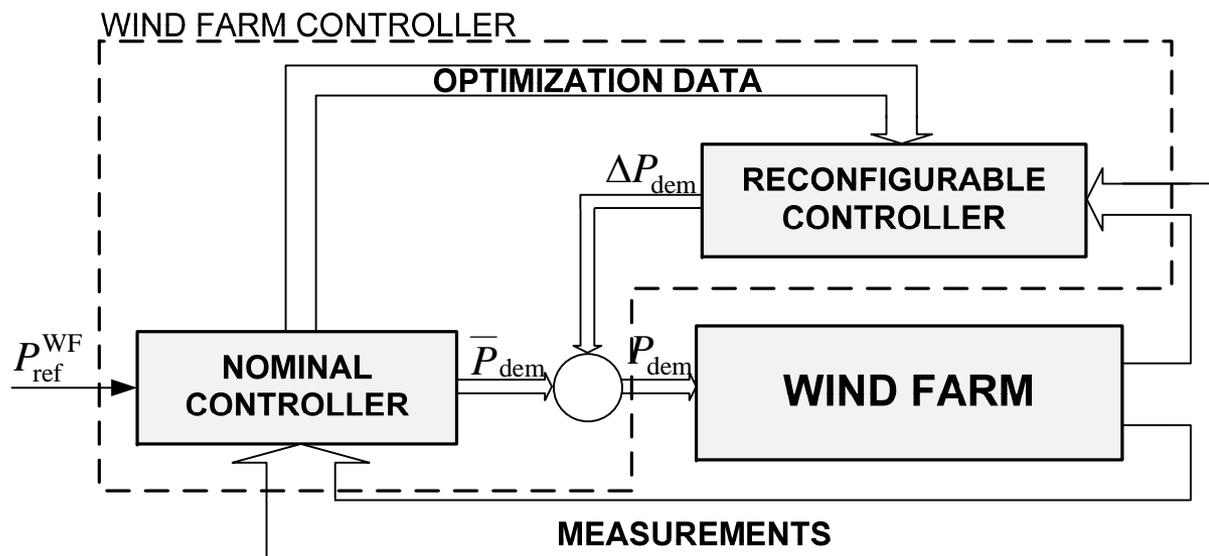
State-space representation

Wind Speed

Thrust Coefficient
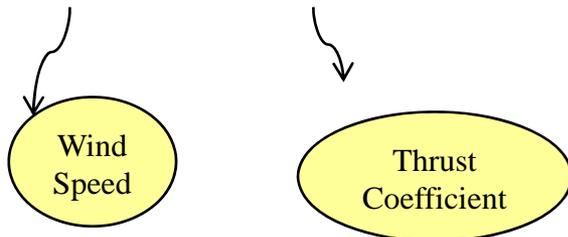
Nominal Supervisory Control with MPC

Gerrit van der Molen, Petros Savvidis, Mike Grimble
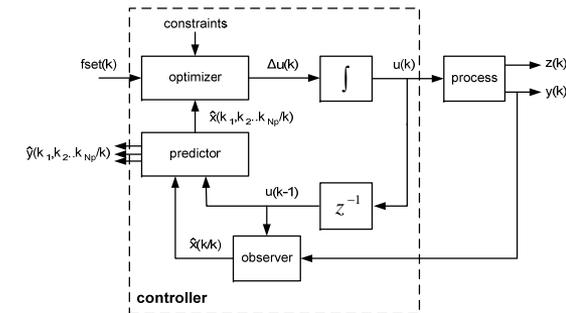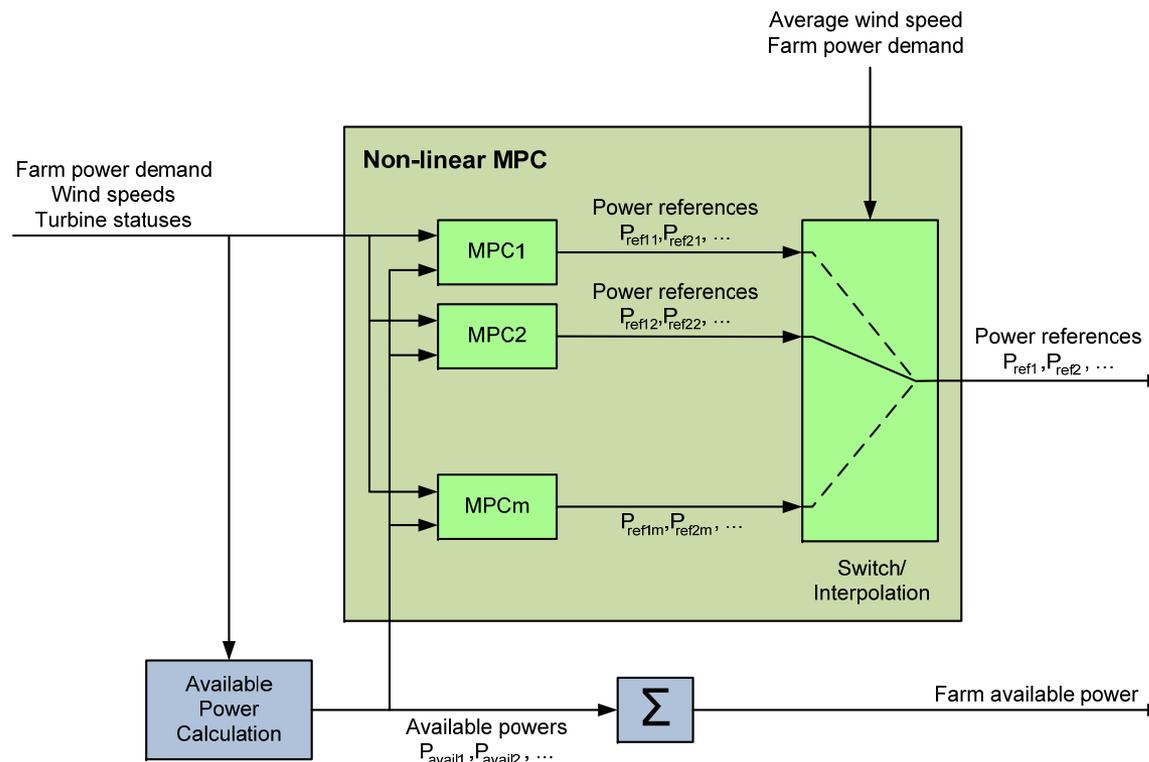
Supervisory Controller

Mato Baotić, Mate Jelavić, Vedrana Spudić, Ned Perić

Requirements: Model-based optimal controller, 1 Hz refresh rate

Stationary Wind Field Interaction Model
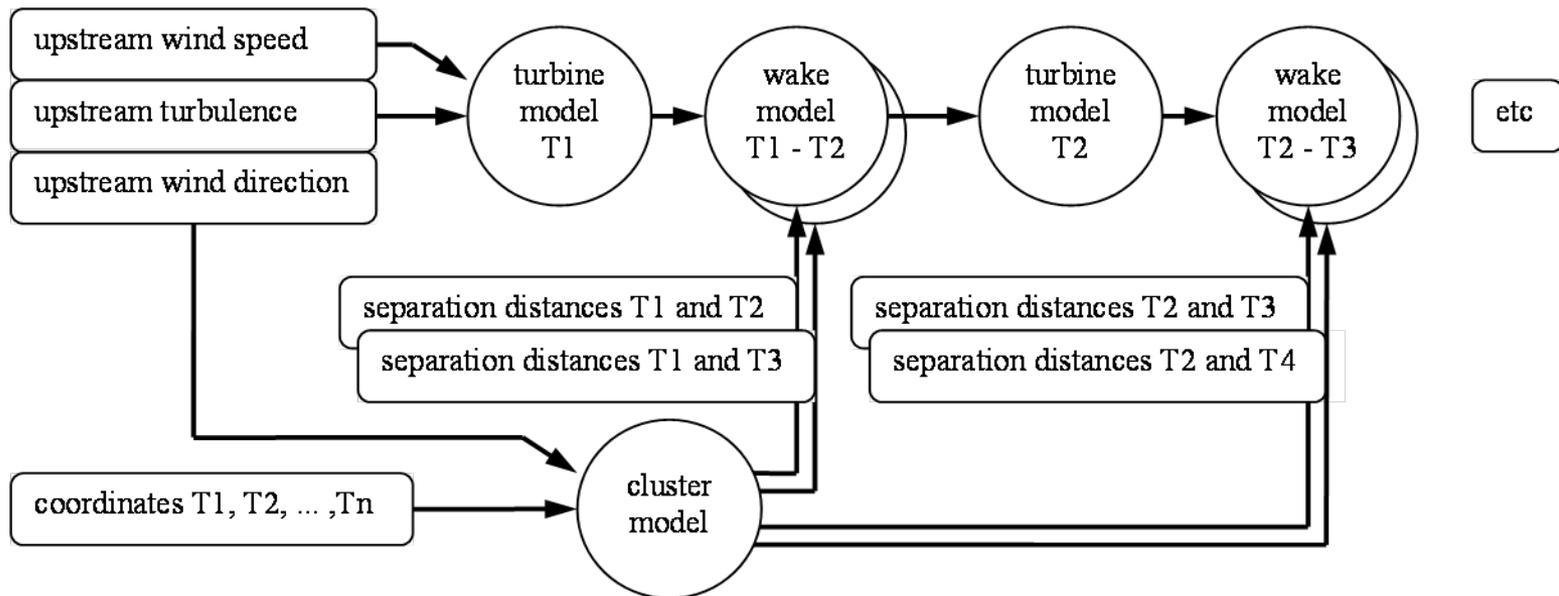
Daria Madjidian, Anders Rantzer

Wind speed model

$$
\begin{aligned}
v_{n+1}(t) \quad = \quad & \overbrace{(1 - kC_{T_n}(t-\tau))v(t-n\tau)}^{\text{deficit from n}} + \overbrace{kC_{T_n}(t-\tau)w_n(t-\tau)}^{\text{induced turbulence from n}} \\
& \underbrace{-k(v(t-n\tau) - v_n(t-\tau))}_{\text{effect from other upwind turbines}}
\end{aligned}
$$

Wind farm model

$$
\begin{aligned}
\dot{z}_n \quad = \quad & A_n^c z_n + B_n^c u_n + B_{v_n}^c v_n \\
v_n(t) \quad = \quad & -k\bar{v}C_{T_{n-1}}(t-\tau) \\
& + (1 - k\bar{C}_{T_{n-1}} - k)w(t - (n-1)\tau) \\
& + kv_{n-1}(t-\tau) + w_n'(t)
\end{aligned}
$$

Quasi-steady Wind Farm Flow Model

Arno Brand, Jan Willem Wagenaar

Model Output qsWFFM

❑ Forward

$$(\{\ \{WS, BPA, RS\}_{iklm}, \{Power, Loads\}_{iklm}) = f(\ \{WS_k, WD_l, TI_m\}\ )$$

          state   **output**   **external conditions**

❑ Inverse

$$(\{WS_k, WD_l, TI_m\}, \{WS, BPA, RS\}_{iklm}, \{Loads\}_{iklm}) = g(\ \{Power\}_{iklm}\ )$$

   external conditions   **state**   **loads**   **power reference**

WS = Ambient wind speed

WD = Ambient wind direction

TI = Turbulence intensity

BPA = Blade pitch angle

RS = Rotor speed

Motivation & History - Developments - Another Model - Comparison - Summary & Outlook

12   **FP7-ICT STREP 224548 / Aeolus**

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SEVENTH FRAMEWORK
PROGRAMME
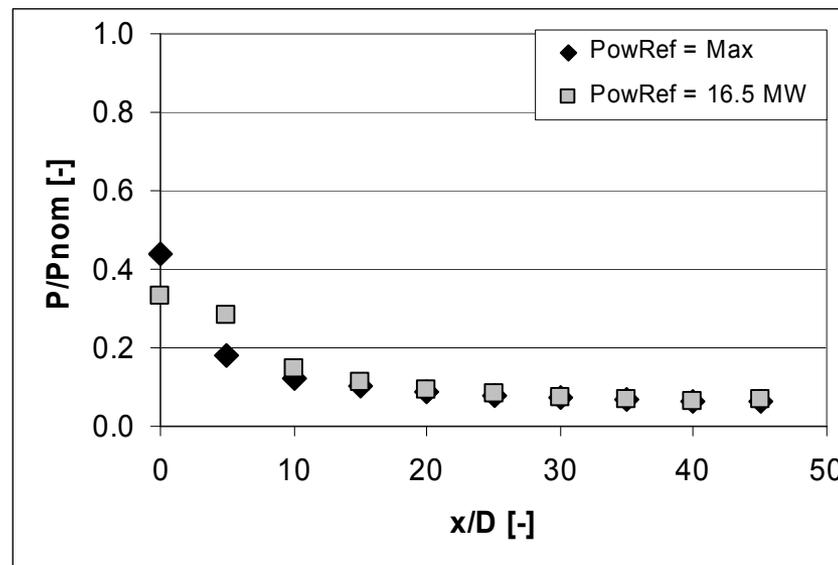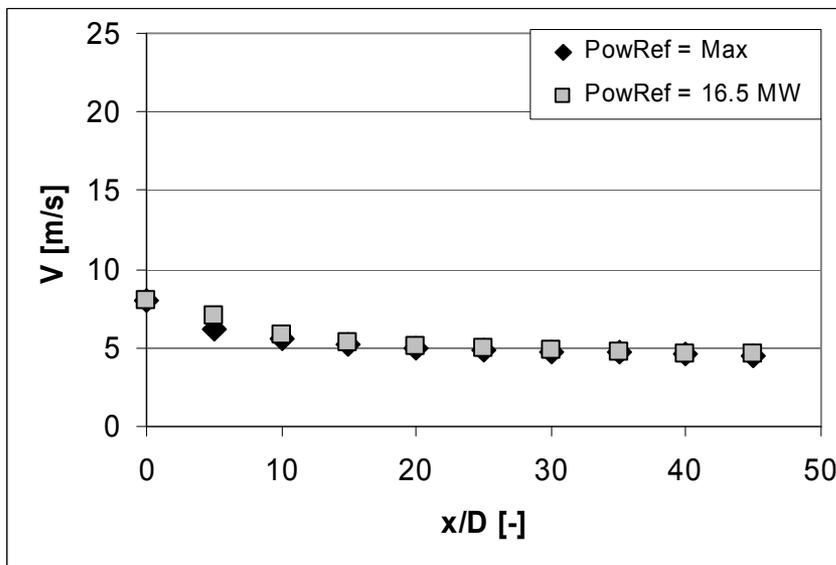
Row with 10 NREL 5 MW wind turbines

Turbine separation: 5D
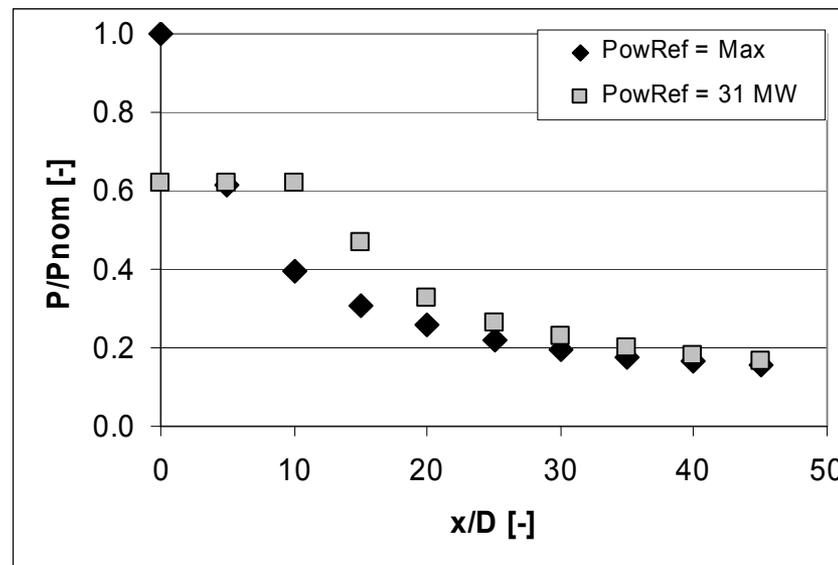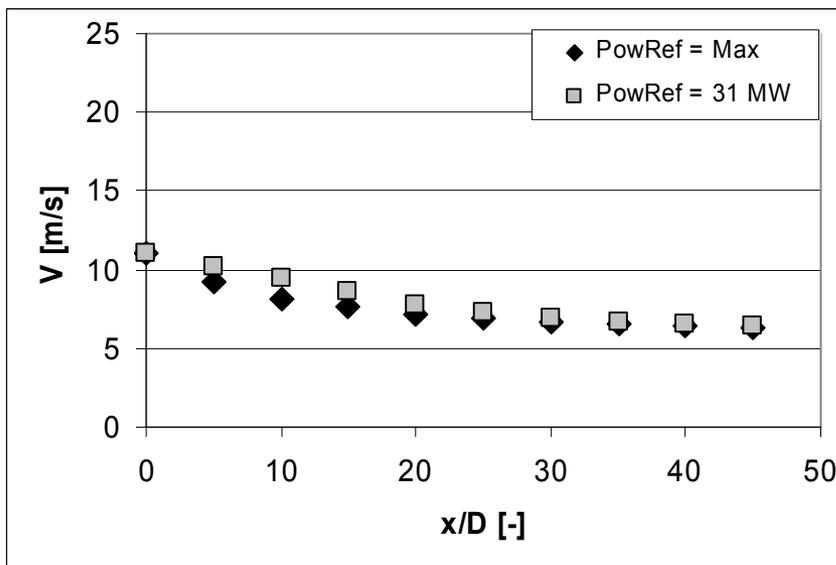Wind speed: 8 m/s
Power references: 10 x 5.0 MW and 10 x 1.65 MW

Row with 10 NREL 5 MW wind turbines

Turbine separation: 5D
Wind speed: 11 m/s
Power references: 10 x 5.0 MW and 10 x 3.1 MW

Wind farm control strategies in order to

❑ Track power reference

❑ Minimize mechanical loading

Quasi-steady wind farm control models

Demonstration of wind farm control solutions

Arno J. Brand

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Wind turbine rotor and Wind farm Aerodynamics

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