Energy research Centre of the Netherlands

TWO CONTROL SOLUTIONS FOR WIND FARM MANAGEMENT AND OPERATION ON THE GRID

A.J. Brand
M. Soleimanzadeh

Presented at: EWEA Offshore 2011, 29 November – 1 December 2011, Amsterdam, The Netherlands

December 2011
ECN-M--11-109

TWO CONTROL SOLUTIONS FOR WIND FARM MANAGEMENT AND OPERATION ON THE GRID

A.J. Brand
ECN Wind Energy, P.O. Box 1, NL 1755 ZG Petten, Netherlands
E: brand@ecn.nl, T: +31 224 56 4775, F: +31 224 56 8214

M. Soleimanzadeh
Automation and Control, Dept Electronic Systems, Aalborg University, 9220 Aalborg, Denmark
E: mas@es.aau.dk, T: +45 9940 9889, F: +45 9815 1739

Summary Two different wind farm flow models are presented: the quasi-steady wind farm flow model (qsWFFM) and a model based on the linearized Navier-Stokes equations (AAUWFM). Validation of these models reveals that the performance of both the qsWFFM and the AAUWFM is good for control purposes. Next, an interpretation of the concept of wind farm management and operation on the grid, plus the minimum requirement for a wind farm controller working on the basis of this concept are given. Subsequently, a control objective and a test case are identified, and two control solutions, one from the qsWFFM and the other from the AAUWFM, are presented. Since both models meet the minimum requirement, it is concluded that the qsWFFM and the AAUWFM can give control solutions to be used in wind farm management and operation on the grid.

1 Introduction

Wind farms are expected to operate similar to conventional power plants [1, 2]. During operation this is achieved by addressing control objectives at the wind farm level, for example to track or not to exceed an externally issued power demand. To this end control solutions at the wind farm level are needed.

In wind farm control it is recognized that the wind turbines in a wind farm are coupled through their wakes. Based on this principle several dedicated wind farm flow models have been developed [3]. These include the inverse mode of a quasi-steady wind farm flow model [4], a decentralized dynamic state-space model [5], a model based on the control strategy of a variable speed variable pitch wind turbine [6], a supervisory/reconfigurable model [7, 8], and a stationary wind turbine interaction model [9].

In this paper the focus is on two of these models: the inverse mode of the quasi-steady wind farm flow model (referred to as qsWFFM) [4] and the model based on the control strategy of a variable speed variable pitch wind turbine (referred to as AAUWFM) [6]. The objective of the study is to show the ability of the qsWFFM and the AAUWFM to give control solutions that can be used in wind farm management and operation on the grid. First, concise descriptions of the models and the model validation are given (section 2). Next follow an interpretation of the concept of wind farm management and operation on the grid, the definition of the control objective to be addressed in this paper, and the presentation of two control solutions that meet this objective (section 3). Finally, the conclusions are presented (section 4).

2 Model descriptions

2.1 Quasi-steady wind farm flow model

The purpose of the quasi-steady wind farm flow model (qsWFFM) is to model the control object wind farm. The qsWFFM relates the external conditions of a wind farm to the state and the output all wind turbines in that wind farm, provided the yaw misalignment of the wind turbines is small. The external conditions are the speed, the direction and the turbulence intensity of the wind at some distance upstream of the wind farm. The state of the wind farm comprises the rotor speed and the blade pitch angle of all wind turbines in that wind farm, whereas the output consists of the aerodynamic power and the mechanical loading of these wind turbines. In the following the model is briefly described; a detailed description is available separately [4].

The qsWFFM is steady in the sense that is valid over averaging periods of several minutes. It is quasi-steady as it takes into account the effect of variations on the average values. (This is in contrast to a dynamical model which takes care of the instantaneous deviations from the averages.) The model provides flow information for large-scale wind farms and calculates the expected electrical power output and the expected mechanical loads.

The qsWFFM 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. The model parameters include the coordinates of the wind turbines in a wind farm plus the following turbine parameters: the hub height and the rotor diameter, the thrust coefficient as a function of the tip-speed ratio and the blade pitch angle, and the rotor speed and the blade pitch angle as a function of the wind speed. The model output consists of a look-up table with the external conditions, and the state and the output of all wind turbines in the wind farm.

Apart from the sub-models based on the classic momentum theory the model includes newly developed sub-models that handle the length of the near wake, the creation and the decay of the velocity deficit, the creation and the decay of the added turbulence, the impact of turbulence on the average values, and the standard deviation of all quantities that are considered.

Using momentum theory the aerodynamic state of a wind turbine is expressed in terms of the axial induction factor a:

$$a = \frac{1}{2}\left(1 - \sqrt{1 - C_T(\lambda, \theta)}\right),$$

where C_T is the thrust coefficient of the rotor with λ the tip-speed ratio and θ is the pitch angle of the rotor blade.

Relations for the mean and the standard deviation of the axial induction factor bring the effect of turbulence into account. Subsequently the aerodynamic power Pow, the tower bending moment M_{tb}, the blade bending moment M_{bb} and the rotor shaft torque q are calculated:

$$Pow = \frac{\pi}{2} a(1-a)^2 \rho W^3 D^2 ,$$

$$M_{tb} \approx \frac{\pi}{2} a(1-a)\rho W^2 D^2 ,$$

$$M_{bb}^2 = \frac{\pi^2}{36 N_b^2} a^2 (1-a)^2 \rho^2 W^4 D^6 + \frac{25}{1152} m_b^2 g^2 D^2 ,$$

$$q = \frac{P}{\Omega} ;$$

where ρ is the air density, W is the wind speed at hub height, D is the diameter of the rotor, N_b is the number of rotor blades, m_b is the mass of a rotor blade, g is the acceleration of gravity, and Ω is the rotor speed. Note that the approximation in M_{tb} comes from neglecting the moments due to the aerodynamic force on the turbine tower, the deflection of the tower and the eccentricity of the nacelle. Also, note that the expression for M_{bb} includes the contributions from the aerodynamic force and the gravity force.

- Forward

  ({WS, BPA, RS}$_{iklm}$, {Power, Loads}$_{iklm}$) = f({WS$_k$, WD$_l$, TI$_m$})

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

- Inverse

  ({WS, BPA, RS}$_{iklm}$, {Loads}$_{iklm}$) | {WS$_k$, WD$_l$, TI$_m$} = g({Power}$_{iklm}$)

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

Figure 1 The operating modes of the quasi-steady wind farm flow model. Legend: wind speed (WS), wind direction (WD), turbulence intensity (TI), blade pitch angle (BPA) and rotor speed (RS)

In addition, for a given downstream position x and spanwise position r in the wake of a wind turbine, the wind speed deficit Δμ and the extra turbulence σ_{add} due to that wind turbine are calculated:

$$\frac{\Delta\mu(r,x)}{\Delta\mu_{ini}} = \left(\frac{x}{x_0}\right)^n \exp\left\{\ \ \alpha_1 \frac{r^2}{\beta^2(x)}\right\} \text{ and } \sigma^2_{add}(r,x) = \sigma^2_{add,1}(r,x) + \sigma^2_{add,2}(r,x).$$

The extra turbulence originates from the two edges of the rotor disk in the rx-plane:

$$\sigma_{add,i} = f_i(r,x)\ \sigma_{add,x}(x) \text{ with } f_i(r,x) = \frac{1}{2}\exp\left\{-\alpha_2\left(\frac{r-R_i(x)}{R}\right)^2\right\} \text{ and } \sigma^2_{add,x}(x) = \sigma^2_{add,ini}\left(\frac{x}{x_0}\right)^m,$$

where i indicates a rotor disk edge and R is the radius of the rotor. In addition to that, $\Delta\mu_{ini} = 2a\mu_0$ is the initial wind speed deficit, μ_0 is upstream wind speed, and $\sigma^2_{add,ini}/\mu^2_0 = c_{GCL}a$ gives the initial value of the added turbulence.

Turbine clustering is addressed by linking the individual wind turbines via their wakes. For a given wind direction, for all wind turbines in the cluster the streamwise and the spanwise distance downstream of each wind turbine are determined. Subsequently, this information is employed in order to calculate all local values of the wind speed deficit and the added turbulence by using decay laws.

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

The qsWFFM can be operated either to predict the output of a wind farm for given external conditions (referred to as the forward mode), or to calculate the state of all turbines needed to track a given output for given external conditions (the inverse mode); see figure 1.

In the forward mode the qsWFFM is a quasi-steady wind farm design method. The tuning of the forward mode of the model involved measured data from a row of eight wind turbines in a wind farm whose identity cannot be disclosed because of confidentiality reasons. The validation of this mode is addressed in section 2.3 of this paper.

The inverse mode of the qsWFFM is a quasi-steady wind farm control approach. Note this is an open-loop approach because the controller uses only the current state and the model of the object wind farm. Control solutions obtained with this mode are addressed in section 3.

2.2 Aalborg University wind farm flow model

The basic purpose of developing the Aalborg University wind farm flow model (AAUWFM) is to produce a spatial dynamic model for the wind flow in a wind farm, and to present the model in the form of ordinary differential equations which are easy to implement in classic control algorithms. The AAUWFM relates the external conditions (the wind speed and the wind direction) of a wind farm to the state (the rotor speed and the blade pitch angle) of all wind turbines in that wind farm. It is based on the linearized Navier-Stokes equation for incompressible viscous flow. The wind turbines are modeled by means of their thrust coefficient employing the vortex cylinder theory in order to model turbine yaw. The AAUWFM provides a structured model suitable for control algorithms, but can only predict the output of a wind farm if the turbulence intensity is low. In the following the procedure of developing the model is presented very briefly; details are available separately [6, 10, 11, 12].

In the AAUWFM the wind in a wind farm is expressed with the Navier-Stokes equation for viscous flow. The two wind speed components u and v in the horizontal plane are governed by a system of linearized equations [13]:

$$\hat{u}_t + p_x = (\hat{u}_{xx} + \hat{u}_{yy})/Re - U\hat{u}_x - V\hat{u}_y + F_1$$
$$\hat{v}_t + p_y = (\hat{v}_{xx} + \hat{v}_{yy})/Re - U\hat{v}_x - V\hat{v}_y + F_2$$
$$\hat{u}_x + \hat{v}_y = 0$$

Here U and V are the components of the mean wind speed in the x and the y direction, and $\hat{u}$ and $\hat{v}$ indicate the deviation from these mean wind speeds. The symbols F_1 and F_2 denote the components of the thrust force on the wind turbines, as produced by U and V. In absence of a wind turbine these force components are zero, but in the location of a wind turbine they are given by:

$$F_1 = \frac{\pi}{2}\rho R^2 U^2 C_T \text{ and } F_2 = \frac{\pi}{2}\rho R^2 V^2 C_T,$$

where R is the radius and C_T is the thrust coefficient of the turbine rotor.

If the wind direction is exactly perpendicular to the rotor plane, the effect of the wind turbines on the wind flow can be dealt with by means of the momentum theory [14]. However, usually, the wind direction makes an angle γ with the normal to the rotor plane. This angle is called the yaw angle. Then the pressure drop at the wind turbine position is modeled by the vortex cylinder model [15], and the thrust coefficient C_T is given by

$$C_T = 4a\left(\cos\gamma + \tan(0.5(1+0.6a)\gamma)\sin\gamma - a\sec^2(0.5(1+0.6a)\gamma)\right),$$

with a the axial induction factor of that turbine. Note unyawed inflow $\gamma = 0$ gives the classic result from the momentum theory $C_T = 4a(1-a)$.

In the model a wind farm is subdivided into non-overlapping square cells called a staggered grid, and the spatial discretization is performed using the finite difference method. The resulting semi-discretized equations are:

$$\frac{d}{dt}\begin{pmatrix} U \\ V \end{pmatrix} + \begin{pmatrix} G & 0 \\ 0 & \tilde{G} \end{pmatrix}\begin{pmatrix} U \\ V \end{pmatrix} + \begin{pmatrix} D \\ \tilde{D} \end{pmatrix} P = \begin{pmatrix} F_1 \\ F_2 \end{pmatrix},$$

where G and $\tilde{G}$ are the coefficient matrices of the mean wind speed components U and V, and D and $\tilde{D}$ are the coefficient matrices of the pressure drop P. (The effect of the wind turbines in the equations is observed in the pressure drop P.) Moreover, the wind turbine effect is considered to be in the far wake region.

The AAUWFM model provides an approximation of the behavior of the flow in a wind farm, and obtains the wind speed in the vicinity of each wind turbine in that wind farm. The validation of this model is addressed in section 2.3.

To control a wind farm by using the AAUWFM, the wind speed is obtained. Then, the power references for the individual wind turbines are calculated such that the power demand from the wind farm is followed. To this end the wind speed is defined as the state variable $\underline{x}$ and the power (as obtained from the thrust coefficient C_T) is defined as the system input u:

$$\underline{x} = \begin{pmatrix} U \\ V \end{pmatrix} \quad \text{and} \quad u = Pow \quad \text{so that} \quad \dot{\underline{x}} = \underline{\underline{A}}\,\underline{x} + f(\underline{x},u) \quad \text{with} \quad f(\underline{x},u) = -\begin{pmatrix} D \\ \tilde{D} \end{pmatrix} P + \begin{pmatrix} F_1 \\ F_2 \end{pmatrix}.$$

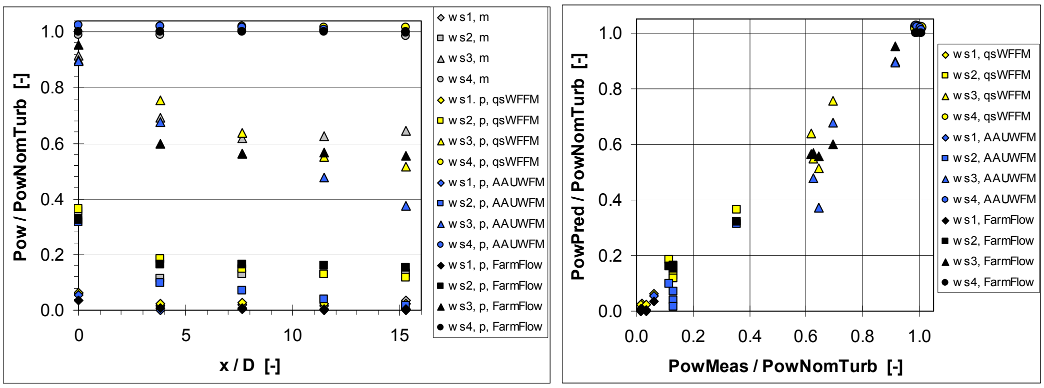


Figure 2 Measured normalized power $Pow/Pow_{nom,turb}$ (symbols labelled m) and predicted normalized power $Pow/Pow_{nom,turb}$ (symbols labelled p) as a function of the normalized position x/D in a row of five wind turbines for the following external wind speeds: near the cut-in wind speed of the wind turbine (ws1), halfway the cut-in and the nominal wind speed (ws2), near the nominal wind speed (ws3), and between the nominal and the cut-out wind speed (ws4). The power and the position are relative to the nominal power $Pow_{nom,turb}$ and the rotor diameter D of the wind turbine, respectively

The optimal control problem is solved such that the total demanded power from the wind farm is satisfied while the structural loads are minimized. The structural loads which are considered in this paper are the tower and the blade bending moments as obtained from the thrust coefficient. The control methodology is closed loop. Control solutions obtained with this mode are addressed in section 3.

2.3 Model validation

The qsWFFM and the AAUWFM are validated on the basis of the measured and the predicted wind at and the power of the wind turbines in the ECN Wind turbine Test site Wieringermeer (EWTW). The EWTW consists of a row of five 2.5 MW wind turbines separated 3.8 rotor diameter of 80 m. The measured wind and power originate from ECN's EWTW database [16, 17], whereas the predicted data are calculated by using the ECN wind farm design code FarmFlow [18].

As to validation on the basis of the wind speed it was concluded that the comparison results are very satisfactory, in particular if the measured yaw angle and the measured turbulence intensity are taken into account [10]. Recall that neither the qsWFFM nor the AAUWFM does both.

In this section the turbine power is addressed. Four values of the ambient wind speed are considered; the wind direction is parallel to the row of wind turbines.

Figure 2 shows the measured and the predicted turbine powers as a function of the position in the row together with the powers calculated by the qsWFFM and the AAUWFM.

For the high wind speed case the wind powers from the qsWFFM and the AAUWFM are correct in the sense that these correspond to the measured and the predicted powers.

For the near-nominal wind speed case the wind powers from the qsWFFM and the AAUWFM are too high, whereas for the other wind speed cases these are within a hundred kW from the measured values.

In general the difference is large if the wind speed is near the nominal wind speed or if a wind turbine's position is deep in the row. The reasons are the poor quality of the turbine model (i.e. the $C_T(\lambda,\theta)$ data) near the nominal wind speed and the inability of the analytical and the numerical wake models to handle multiple wakes.

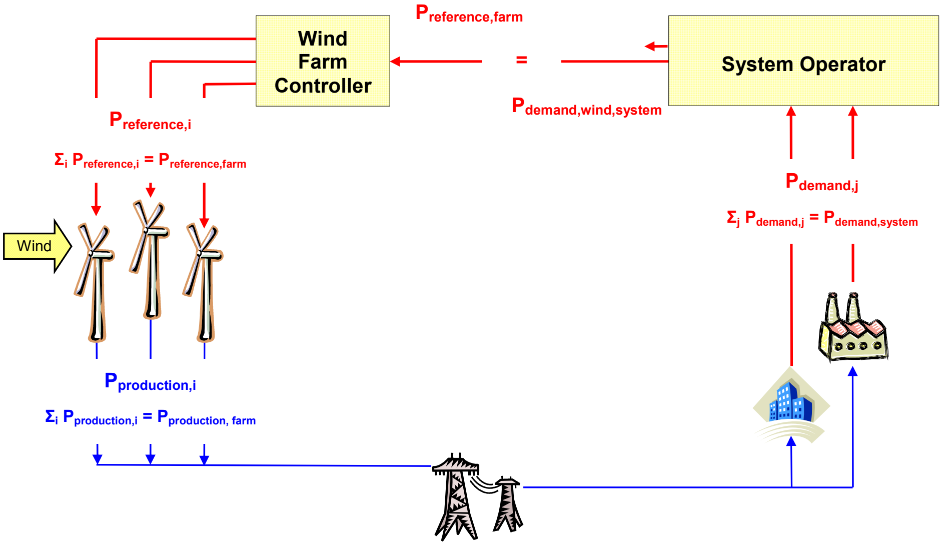


Figure 3 Sketch of wind farm management and control as considered in this paper

May the performance of the qsWFFM and the AAUWFM be insufficient for wind farm design purposes, where the power of a wind turbine is to be predicted up to a kilowatt, it is concluded that it is good for control purposes because these require a rough estimate of the power reference only.

3 Demonstration of wind farm control solutions

3.1 An interpretation of the concept of wind farm management and operation on the grid

In order to be able and perhaps also to be allowed to operate on the grid, the output of a wind farm has to be managed and controlled. Apart from straightforward issues like the scheduling of maintenance and new issues like delivering ancillary services, wind farm management includes the issue of controlling the active power and minimizing the structural loads of the wind turbines in a wind farm. (In this paragraph active power is used in order to distinguish from reactive power. In the rest of the paper power is a synonym for active power.)

In this paper the scope of wind farm management is limited to controlling the active power output of a wind farm on basis of an externally issued demand of active power. In this context the operator of the electricity system accumulates the power demands of the various consumers of electricity, and subsequently distributes the individual demands over the various producers of electricity. The objective of a wind farm controller now is to ensure that the power production of the wind farm tracks or does not exceed the allotted power demand. The wind farm controller tries to achieve this by distributing power references (i.e. set points) over the individual wind turbines in the farm in such a way that the sum of the turbine power references is less than or equal to the power reference of the wind farm being the power demand of the system. This scope is sketched in figure 3.

On the basis of this interpretation the minimum requirements of a wind farm control method, which is to give control solutions that can be used in wind farm management and operation on the grid, can be identified: To issue individual turbine power references in such a way that their sum is less than or equal to the wind farm power reference.

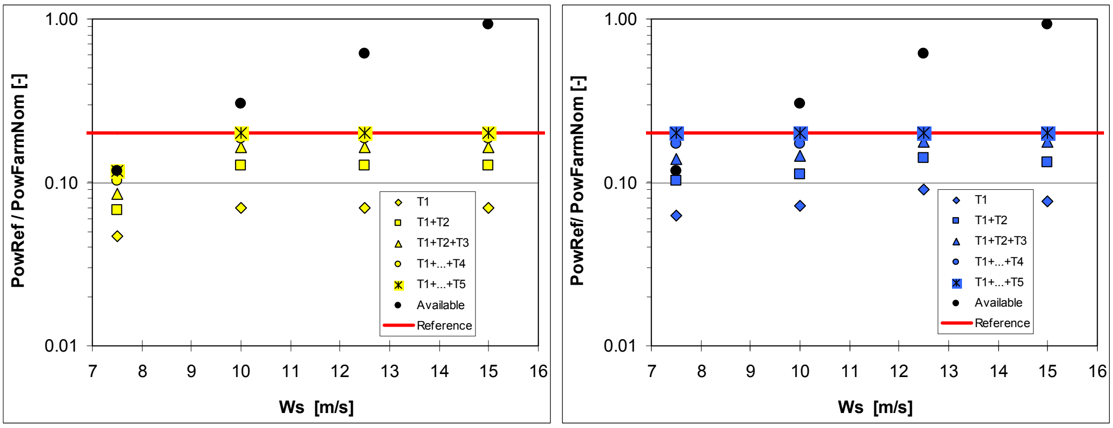


Figure 4 The distributions of the power references PowRef over the individual wind turbines for a given value of the power reference of the wind farm and different values of the ambient wind speed; qsWFFM (left) and AAUWFM (right). PowFarmNom is the nominal power of the wind farm. Also indicated is the power that is available in the wind farm for a given wind speed

3.2 Definition of the control objective

Now consider a wind farm that is connected to the grid. In addition, consider as the control objective to track, for given values of the ambient wind speed, the power demand of the grid while reducing the structural loads of the wind turbines. As explained, this is achieved by distributing the power references over the individual wind turbines in that wind farm. These distributions of the power references are the control solutions. Note that the power reference of a wind turbine is not the same as the power produced by that wind turbine as the actual production is left to the decision of the wind turbine controller.

3.3 Two control solutions for the same control objective

In the following two control solutions are presented, one obtained by using the qsWFFM and the other by using the AAUWFM. The test case is the row of five wind turbines in the ECN Wind turbine Test site Wieringermeer (EWTW). Note this test case is a simulation only.

The figure 4 shows the control solutions for four ambient wind speeds in combination with an external power demand equal to twenty percent of the wind farm nominal power.

The qsWFFM and the AAUWFM give solutions that meet the power control objective for three of the four wind speeds (10.0 m/s, 12.5 m/s and 15.0 m/s), but give different distributions of the turbine power reference. In fact the qsWFFM gives a fixed distribution whereas the AAUWFM distributions depend on the wind speed. The reason is that the two models differ in the way they reduce the structural loading: The AAUWFM aims to minimize the tower acceleration whereas the qsWFFM does not.

At the other wind speed (7.5 m/s) the models issue different values of the turbine power references. The qsWFFM urges the wind turbines to produce the power which is available at that wind speed whereas the AAUWFM asks for the maximum possible power. Again the difference is due to way the models reduce the structural loading.

Regarding the wind turbines, assuming that the control options of the wind turbine are modelled correctly, different control solutions at the same wind speed will result in different values of the operating points of the rotor speed and/or the blade pitch angle.

As far as the grid is concerned, under the same assumption, the production of the wind farm will be equal to the demand of the grid for the wind speeds of 10.0 m/s, 12.5 m/s and 15.0 m/s. At 7.5 m/s, on the other hand, the two different control solutions will result in the same production because the power which is available at that wind speed is equal to the maximum possible power at that wind speed. Evidently, at 7.5 m/s the production of the wind farm will be lower than the demand of the grid.

Since the sum of the power references of the individual wind turbines is less than or equal to the power reference of the wind farm, it is concluded that the qsWFFM and the AAUWFM can give control solutions that can be used in wind farm management and operation on the grid.

4 Conclusion

Concise descriptions of two wind farm flow models and the validation of these models have been presented. These models are the quasi-steady wind farm flow model (qsWFFM) and a model based on the linearized Navier-Stokes equations (AAUWFM). The performance of the qsWFFM and the AAUWFM is good for control purposes because these require a rough estimate of the power reference only.

An interpretation of the concept of wind farm management and operation on the grid has been given. In addition the minimum requirement for a wind farm controller working on basis of this concept has been given: the sum of the power references of the individual wind turbines is less than or equal to the power reference of the wind farm.

A control objective and a test case have been identified, and two control solutions, one form the qsWFFM and the other from the AAUWFM, have been presented. Since both models meet the minimum requirement, it is concluded that the qsWFFM and the AAUWFM can give control solutions to be used in wind farm management and operation on the grid.

References

1. Ackermann Th (ed.). *Wind power in power systems*. John Wiley & Sons. 2005
2. Freris L, Infield D. *Renewable energy in power systems*. John Wiley & Sons. 2008
3. Brand AJ, Quasi-steady wind farm control models, EWEA Annual Event 2011. 2011
4. Brand AJ, Wagenaar JW. A quasi-steady wind farm flow model in the context of distributed control of the wind farm. European Wind Energy Conference 2010. 2010
5. Soltani M, Knudsen T, Bak Th. Modeling and simulation of offshore wind farms for farm level control. European Offshore Wind Conference 2009. 2009
6. Soleimanzadeh M, Wisniewski R. Controller design for a wind farm considering both power and load aspects. *Mechatronics*, vol. 21, no. 4, pp. 720-727. 2011
7. Spudić V, Jelavić M, Baotić M, Perić N. Hierarchical wind farm control for power/load optimization. Torque 2010. 2010
8. Savvidis P, Van der Molen GM. Supervisory and reconfigurable control strategies - Part 1: Supervisory predictive control. Deliverable 3.4 Project Aeolus, Report ISC_311210_Deliverable_D3.4_0001(1)_CO (confidential). 2010
9. Madjidian D, Rantzer A. A stationary turbine interaction model for control of wind farms. IFAC 18th World Congress. 2011
10. Soleimanzadeh M, Wisniewski R, Brand AJ. State-space representation of the flow model for a wind farm. *Wind Energy* (submitted)
11. Soleimanzadeh M, Brand A, Wisniewski R. A wind farm controller for load and power optimization in a wind farm, 2011 IEEE Multi-Conference on Systems and Control. 2011
12. Soleimanzadeh M, Wisniewski R. An optimization framework for load and power distribution in wind farms - Low wind speed. IFAC 18th World Congress. 2011
13. Kress W, Nilsson J. Boundary conditions and estimates for the linearized Navier-Stokes equations on staggered grids. *Computers & Fluids*, vol. 32, no. 8, pp. 1093-1112. 2003
14. Bianchi F, De Battista H, Mantz R. *Wind turbine control systems: principles, modelling and gain scheduling design*. Springer Verlag. 2006
15. Burton T, Sharpe D, Jenkins N, Bossanyi E. *Wind Energy Handbook*. John Wiley and Sons. 2001
16. Eecen PJ, Machielse LAH, Braam H, Verhoef JP. LTVM statistics database. Report ECN-CX--05-084. 2005
17. Eecen PJ, Verhoef JP. EWTW meteorological database - Description June 2003 - May 2007. Report ECN-E--07-041. 2007

18. Eecen PJ, Bot ETG. Improvements to the ECN wind farm optimisation software 'FarmFlow'. European Wind Energy Conference 2010. 2010

Two Control Solutions for Wind Farm Management and Operation on the Grid

PO. 227

A.J. Brand and M. Soleimanzadeh
ECN Wind Energy, P.O. Box 1, NL 1755 ZG Petten, Netherlands
Automation and Control, Dept Electronic Systems, Aalborg University, Aalborg, Denmark

Background and Objective

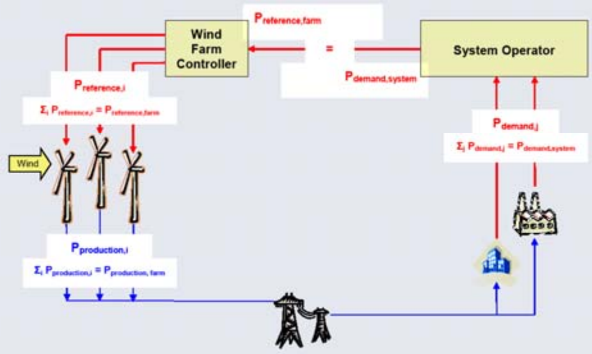
Wind farms are expected to operate similar to conventional power plants. During operation this is achieved by addressing control objectives at the wind farm level, for example to track or not to exceed an externally issued power demand. To this end control solutions at the wind farm level are needed.

In wind farm control it is recognized that the wind turbines in a wind farm are coupled through their wakes. Based on this principle several dedicated wind farm flow models have been developed. Here the focus is on two of these models: the quasi-steady wind farm flow model (qsWFFM) and the AAU wind farm model (AAUWFM).

The objective of this study is to show their ability to give control solutions that can be used in wind farm management and operation on the grid.

This poster presents different control solutions for the same control objective. In addition, concise descriptions of the models and the model validation are given.

Sketch of Wind Farm Control



Demonstration of the Wind Farm Control Solutions

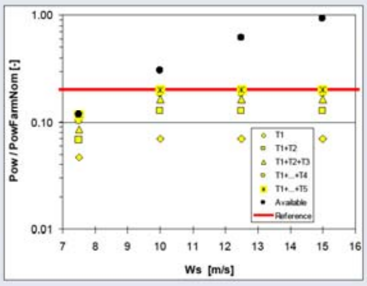
Consider a wind farm that is connected to the grid. The control objective is to track, for given values of the ambient wind speed, the power demand of the grid while reducing the structural loads of the wind turbines. This is achieved by distributing power references over the individual wind turbines in that wind farm.

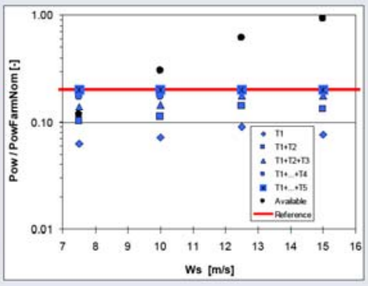
The test case is the row of 5 wind turbines in the ECN Wind turbine Test site Wieringermeer (EWTW). Note this test case is a simulation only.

The control solutions are shown for 4 values of the ambient wind speed in combination with an external power demand equal to 20% of the wind farm nominal power.

Note that the power reference of a wind turbine is not the same as the power produced by that wind turbine as the actual production is left to the decision of the wind turbine controller.

The figures show the control solutions - distributions of the power references over the wind turbines - for 4 ambient wind speeds; qsWFFM (left) and AAUWFM (right).





Both models give solutions that meet the power control objective for 3 of the 4 wind speeds, but give different power reference distributions. In fact the qsWFFM gives a fixed distribution whereas the AAUWFM distributions depend on the wind speed.

At 7.5 m/s the models issue different values of the power references. The qsWFFM urges the wind turbines to produce the power which is available at that wind speed whereas the AAUWFM asks for the maximum possible power.

Conclusion of this demo: The qsWFFM and the AAUWFM can give control solutions to be used in wind farm management and operation on the grid.

References

Brand A.J., Quasi-steady wind farm control models, EWEA Annual Event 2011, Brussels, March 2011

Brand A.J., A quasi-steady wind farm flow model, Tutorial Training Workshop on Improved Control of Wind Farms, Glasgow, May 2011

Soleimanzadeh M. et al., State-space representation of the flow model for a wind farm, submitted to Wind Energy

Soleimanzadeh M. and Wisniewski R., Controller design for a wind farm considering both power and load aspects, Mechatronics 21.4, 720-727, 2011

Soleimanzadeh M. et al., A wind farm controller for load and power optimization in a wind farm, 2011 MSC, Denver, September 2011

Description of the qsWFFM

The qsWFFM is based on the classic momentum theory.

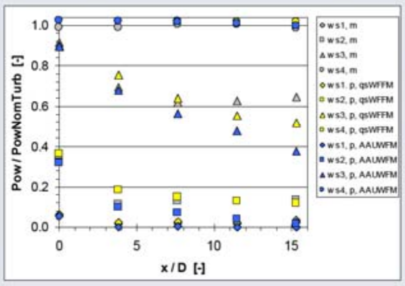
It relates the external conditions (the wind speed, the wind direction and the turbulence intensity) of a wind farm to the state (the rotor speed and the blade pitch angle) and the output (the aerodynamic power and the mechanical loading) of all wind turbines in the wind farm, provided the yaw misalignment of the wind turbines is small.

The qsWFFM can be operated either to calculate the state of all turbines needed to track a given output for given external conditions, or to predict the output of a wind farm for given external conditions.

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

Validation of the qsWFFM and the AAUWFM

The qsWFFM and the AAUWFM are validated on basis of the measured power of the wind turbines in the EWTW. Four values of the ambient wind speed are considered; the wind direction is parallel to the row of wind turbines.



For the high wind speed case the predicted powers are correct. For the near-nominal wind speed case the predicted wind powers are too high, whereas for the other wind speed cases the predicted powers are within a hundred kilowatt.

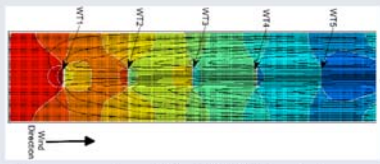
May these results be insufficient for design purposes where the power is to be predicted up to a kilowatt, it is concluded that they are good for control purposes because these require a rough estimate of the power reference only.

Description of the AAUWFM

The AAUWFM is based on linearized Navier-Stokes equations combined with a vortex cylinder model.

It relates the external conditions (the wind speed and the wind direction) of a wind farm to the state (the rotor speed and the blade pitch angle) of all wind turbines in the wind farm.

The AAUWFM provides a structured model suitable for control algorithms, but can only predict the output of a wind farm if the turbulence intensity is low.



Pressure contour of the AAUWFM output

EWEA OFFSHORE 2011, 29 November – 1 December 2011, Amsterdam, Netherlands