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Summary:

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**Distributed Control of Large-Scale Offshore Wind Farms
(AEOLUS)**

**Deliverable 1.6:
Plan for validation of control strategies**

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Abstract

This deliverable defines the case studies for testing of the wind farm controllers developed in Aeolus project. The case studies are defined so that they can be run/tested with the previously developed SimWindFarm toolbox, which runs under Matlab/Simulink programming environment. A subset of the case studies that respects the implementation constraints, and has a viable chance for occurrence at the Barrow wind farm, is defined.

List of symbols

\bar{V}	mean wind speed, [m/s]
Θ	wind direction, [°]
I	turbulence intensity, [%]
P_{wf}^{nom}	nominal wind farm power, [MW]
P_{wf}^{ref}	wind farm power reference, [MW]
$P_{wf}^{available}$	available wind farm power, [MW]
WT	wind turbine
WF	wind farm
CS	case study

1. Introduction

The aim of the Aeolus project is to develop the controller for the wind farm based on the model of the physical phenomena that occur in the wind farm [1]. Two control approaches are studied:

- centralized (supervisory) controller structure, comprising nominal controller [2] and reconfigurable controller [3], and
- decentralized controller [4].

For validation of the proposed control concepts in simulation the SimWindFarm toolbox for Matlab was developed [5].

The cost functions that should be used for evaluation and comparison between different controllers are presented in [6]. The cost function evaluation takes into account the tracking error of the produced wind farm power (in relation to the wind farm power reference), the mean loads and the oscillating loads experienced by the wind turbines. The oscillating loads are evaluated in two different ways: i) as standard deviation, and ii) as damage equivalent loads of load histories.

In Section 2 the interface between the wind farm controllers, which are being designed within Work Package 3 and Work Package 4, and the controlled system is determined. This interface is driven by the availability of measurements on the Barrow wind farm.

In Section 3 the definition of case studies is elaborated. The aims are to define the case studies that: i) demonstrate the abilities of the wind farm controllers, and ii) are viable for testing on the test site.

In Section 4 10 case studies are singled out and defined. These case studies will be used for validation in simulation and/or on the Barrow test site.

2. Wind farm controller interface

The controller interface is defined by the available signals at Barrow wind farm. Typically, the available wind turbine measurements from a V90 wind turbine:

1. Produced electrical power, P [W],
2. Wind speed measured by the anemometer at the nacelle, V_{meas} [m/s],
3. Generator speed, ω_{gen} [rad/s],
4. Pitch angle, β [°],
5. Rotor speed, w_{rot} [rad/s],
6. Tower acceleration, \dot{v}_{tow} [m/s²], and
7. Wind direction (that is not synchronized with the compass), θ [°].

Figure 1 shows the interfaces in (the model of) a controlled wind farm. The blocks for modeling the wind farm system are taken from SimWindFarm toolbox. The wind farm control system consists of the wind farm estimator and the wind farm controller.

The wind farm estimator uses the system measurements and inputs to estimate the effective wind speed and the available power at each wind turbine. The design of this block is to be delivered by Work Package 2.

The wind farm controller uses the wind farm power demand, the wind farm measurements and the estimates of the effective wind speed and available power to compute the wind farm control signals, i.e. power demands for individual wind turbines. This block is to be delivered separately by Work Package 3 (centralized controller) and Work Package 4 (decentralized controller).

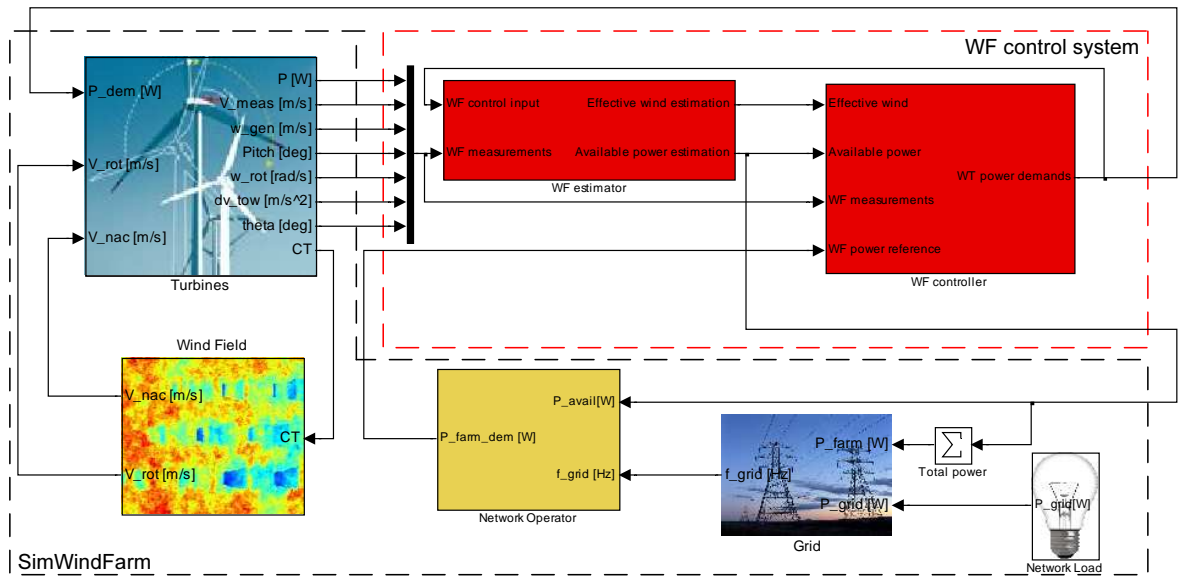


Figure 1: Wind farm controller interface

3. Case studies

The main aim of the simulation case studies is to demonstrate performance of the developed controllers. Furthermore, simulation case studies are an essential preparation step for validation of the controllers on the real wind farm. The case studies, i.e., a subset of those case studies, should match as close as possible the environment that will be encountered at the Barrow wind farm.

The SimWindFarm toolbox allows simulation of the wind farm of an arbitrary configuration and wind direction. However, a drawback of the approach taken for simulating the wind field in SimWindFarm is that the mean wind speed as well as the wind direction remain constant during the entire simulation. This limitation is unduly inhibiting the evaluation of

controllers. Namely, the controllers can not demonstrate the ability to adapt to changes in the mean wind speed and direction.

To define a case study for implementation in Simulink with the SimWindFarm toolbox one needs to set the following parameters:

1. Wind turbine type,
2. Wind farm configuration (geometry),
3. Average wind speed, direction and turbulence intensity,
4. Network operator requirement, and
5. Operational status of wind turbines.

3.1. Wind turbine type

There are two types of wind turbines currently available in SimWindFarm. The first is the Vestas V90 wind turbine, which is the wind turbine type that is likely to be found at the test site. The second wind turbine type is the NREL model, a publicly available (unlike V90) wind turbine model that serves as a benchmark in the wind turbine control community.

Those case studies that are considered as a preparation for implementation at the test site must use V90 wind turbine model. Unfortunately, at the time of this report, the V90 model used in SimWindFarm toolbox suffers from implementation problems. Consequently, all current controller designs are derived and/or tested with the NREL model. For this reason, and also to enable the public dissemination of achieved results, we also consider several case studies with the NREL wind turbine model.

3.2. Wind farm configuration

The choice of wind farm configuration is primarily driven by the layout of the test site. All scenarios that are aimed for testing at the test site will be tested in simulation first. Additionally, the configurations are defined that will be tested in simulation only, due to restricting limitations of the test site. These configurations are included because they demonstrate important abilities of the developed controllers.

3.2.1. Wind farm configurations based on Barrow wind farm layout

The layout of Barrow is shown in Figure 2. This wind farm consists of 30 wind turbines in a diamond-shaped layout. The three configurations of wind turbines that will be used in the case studies are also depicted in Figure 2. Note that the wind farm control system available at Barrow allows the maximum of 8 wind turbines for wind farm control. The separations and directions denoted at Figure 2 are the average values for separations and directions in the corresponding row of wind turbines.

The smallest separation between wind turbines in a row is 493 meters. The subset of 8 wind turbines that contains the longest line of wind turbines with the smallest separation is denoted as *Configuration 1* in Figure 2. The wind blows parallel to this line for wind directions 132° and 312° . Here, the wind direction 0° denotes the wind from north and the angle increases in the clock-wise manner (the wind from east is 90° , from south 180° and from west 270°).

The set of wind turbines denoted as *Configuration 2* in Figure 2 consists of two rows of 4 wind turbines. The smallest distance between wind turbines from the two rows is 805 meters. For the wind directions 132° and 312° the wind is blowing parallel to the rows of wind turbines, while for 60° and 240° the wind is blowing perpendicular to the rows.

Figure 11 depicts the wind rose for the Barrow wind farm site. The wind directions of interest are also denoted. One can see that the most interesting wind directions for Configuration 1 and 2 have relatively low expectation. Also, the measurements available from Barrow for the months in which the experiments should take place show rather low occurrence rate of these wind directions. Available measurements from Barrow for last three years for the April and May can be seen in the Appendix.

Taking into account the site statistics, the *Configuration 3* was selected, see Figure 2. This configuration consists of two rows of four wind turbines. The separation inside the row is 805.5 meters and the separation between the rows is 493 meters. The wind directions in line with the rows of wind turbines are 24° and 204° . One should note that for wind directions 24° and 204° the rows D5-D4, C5-C4, B6-B5 and A6-A5 are not parallel to the wind front, see Figure 2. This is also true for other configurations, however due to closeness of the rows for this configuration this fact might increase the complexity of wind field model.

The wind farm configurations for case studies listed above are all driven by the layout of Barrow and the limited to 8 wind turbines (due to limitation of Barrow wind farm controller).

3.2.2. Generic configuration

However, the aim of the Aeolus project is the control of large-scale offshore wind farms. In that respect the case studies should not be limited to configurations with only 8 wind turbines. Furthermore, the full effectiveness of distributed control strategy will be shown when dealing with a larger scale wind farm. Therefore, we introduce *Configuration 4* that consists of a row (direction North - South) of 25 wind turbines with the separation of 500 meters.

3.3. Average wind speed, wind direction and turbulence intensity

In this project we aim mainly at wind farm control above the nominal wind speed. The nominal wind speed is 15 m/s for the V90 turbine [7] and 12 m/s for NREL [8]. For the purpose of validation of control algorithms it would be the best to use one wind speed that is far above the nominal wind speed and one below the nominal wind speed. For the first one we could test the behavior of controllers when the constraints are not limiting its performance much. The second test would show how the wind farm controller handles the constraints. However, since we aim to transfer some of the case studies to the Barrow wind farm it is

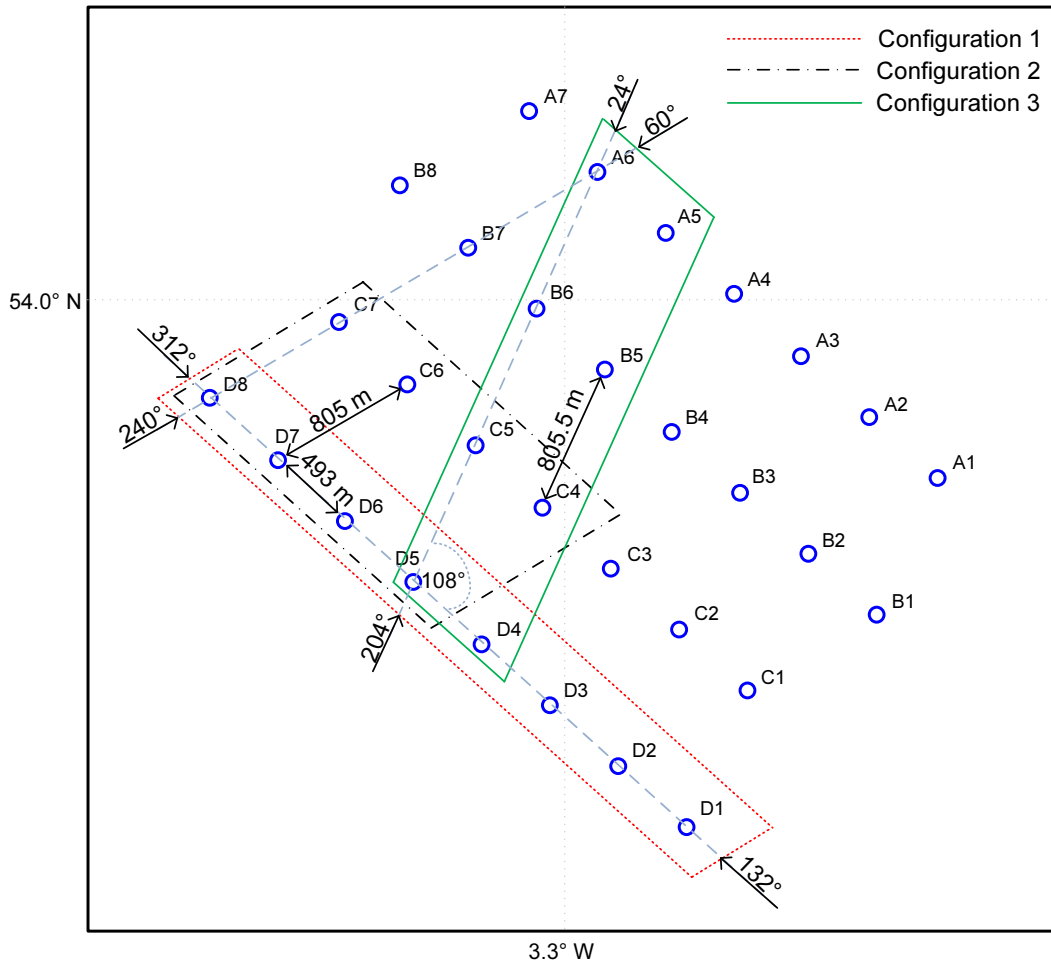


Figure 2: Barrow wind farm layout. Wind directions are defined according to Figure 11.

necessary to define case studies that have a viable chance of occurrence. Our experiments on the Barrow wind farm are planned for spring and summer of 2011. These seasons are, unfortunately, known for low wind speeds. Therefore, we will use lower wind for the case studies and achieve the desired controller environment by adapting the wind farm power reference.

For the case studies at V90 the wind speeds of 10 m/s and 14 m/s will be used.

The case studies that use the NREL wind turbine will be run only in simulation, therefore the wind speeds of 12 m/s (below nominal) and 18 m/s (above nominal) will be used.

The wind direction used in the case studies will be the direction with the strongest coupling of the wind turbines. The wind directions with larger likelihood of appearance at the Barrow wind farm are preferred.

The turbulence intensities used in the case studies will be 7 % (normal) and 10 %

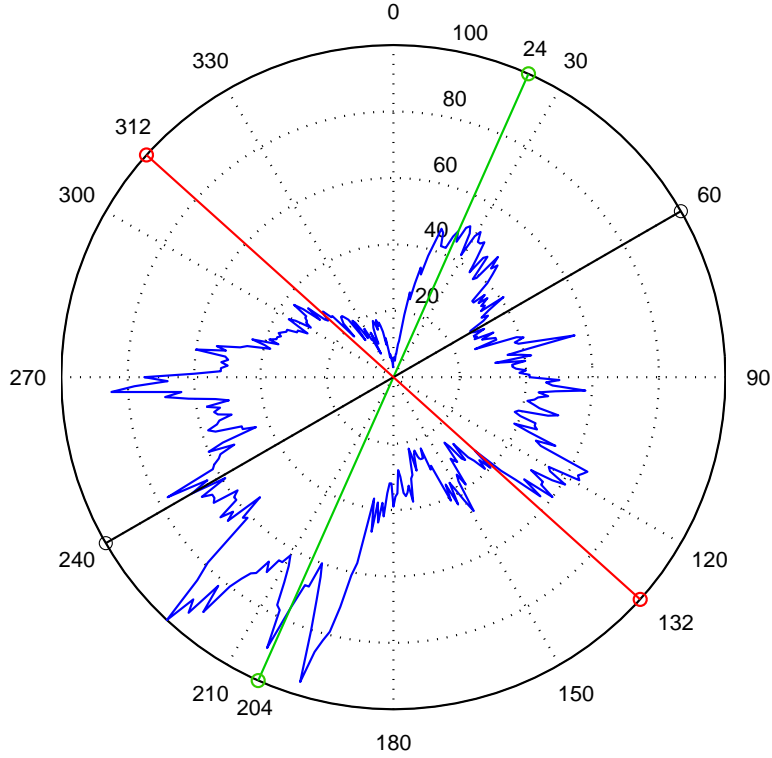


Figure 3: Wind rose for Barrow wind farm

(high). These turbulence intensities were chosen arbitrarily, because there is no statistics from Barrow available to authors that could steer the decision.

3.4. Network operator requirement

Two types of network operator requirements will be tested: absolute power requirement and delta mode.

The absolute power requirement is the operating mode where the network operator issues the absolute wind farm power reference (in Megawatts). Such power reference is held constant for a longer period in time (i.e. the reference is constant until the network operator issues a new requirement).

The delta mode is the operating mode in which the network operator issues the requirement for power reserve. The wind farm power reference is $P_{wf}^{ref} = P_{wf}^{available} - P_{WF}^{\Delta}$, where P_{WF}^{Δ} is issued by the network operator. Since the wind farm available power changes with the wind speed experienced at different ind turbines, the wind farm power reference changes accordingly. From the perspective of the wind farm control system, this is the requirement for reference tracking, while the absolute power requirement is the set-point control.

These scenarios resemble two possible situations that can happen in real grid control. The first is curtailment of wind farm production due to excessive power in the grid that

can happen during windy nights or weekend days. The second scenario occurs when the network operator demands an operating reserve that can be used for fast compensations of the discrepancy between power production and consumption on the grid.

As it is mentioned in Section 3.3 we will use the choice of wind farm power reference to obtain two different behaviors of the wind farm controller. At low wind speed we will use the wind farm reference that is approximately equal to the available wind farm power at that wind speed. The effect of this choice is that approximately 50% of the time it will be required to curtail the wind farm power, while other 50% of the time the constraint that describes the limit of power production will be active. At higher wind speed we will use the wind farm power reference that is equal to 80% of the available power at that wind speed. The effect of this is that for the most of the time the wind farm power will need to be curtailed, which will allow the wind field optimization effect of the controllers to be demonstrated more clearly.

For the mean wind speed of 10 m/s the available power of the V90 wind turbine is approximately 1.8 MW [7]. Therefore, the wind farm power reference at this wind speed will be $8 \times 1.8 = 14.4$ MW. At the mean wind speed of 14 m/s the available power of the V90 is approximately 2.95 MW. For the case studies that use this wind speed the power reference will be $80\%(8 \times 2.95) = 18.88$ MW.

It should be noted that V90 wind turbines have a lower limit for power references that can be provided to them. For wind speeds lower than 17 m/s this limit is 25% of wind turbines nominal power, i.e. 0.75 MW. For the defined power references this limit will not be an issue.

The delta mode will be tested for the mean wind speed of 14 m/s, with $P_{wf}^{\Delta} = 4.72$ MW.

The same approach is used to compute the power references for case studies that use the NREL wind turbine.

3.5. Operational status of wind turbines

A case study will be formulated that simulates the sudden turn off of one wind turbine. Such a scenario can be caused by wind turbine fault or a strong wind gust, and it is a common scenario in wind farm operation. It can also easily be simulated at Barrow wind farm.

4. Tables of case studies

In Tables 2–6 we define 10 case studies, CS1 – CS10. Each case study will be carried out as a 1000 second long simulation in Matlab Simulink. For the computation of costs according to [6] one will use the histories of relevant variables from 400th to 1000th second of the simulation. This will allow the warm-up of simulator and controllers and leave the 10-minute of time-marching data for analysis.

Table 2, Table 3, Table 4 and Table 5 recount the scenarios that are aimed for testing on the Barrow wind farm. Tables 2 and 3 contain the case studies with absolute power requirement, the Table 4 contains the case studies with delta power requirement and the Table 5 contains case studies with the change in operational status of wind turbines. Table 6

recounts the additional scenarios that will be tested only in simulation. These case studies use the NREL model.

Each experiment is attributed a priority between 1 and 10, which denotes the priority of the scenario for on-site testing. The priorities are given in the bottom row of the tables.

Table 1: CS1: case study for implementation on Barrow

CS1	
Configuration 1	
V90	
CS1 a)	CS1 b)
$\bar{V} = 10$ m/s $I = 7$ % $\Theta = 132^\circ$	$\bar{V} = 14$ m/s $I = 10$ % $\Theta = 132^\circ$
Absolute $P_{wf}^{ref} = \begin{cases} 14.4 \text{ MW}, t < 700 \text{ s} \\ 14 \text{ MW}, t \geq 700 \text{ s} \end{cases}$	Absolute $P_{wf}^{ref} = \begin{cases} 18.88 \text{ MW}, t < 700 \text{ s} \\ 18 \text{ MW}, t \geq 700 \text{ s} \end{cases}$
All WTs operational	
Priority 5	Priority 6

Table 2: CS2: case study for implementation on Barrow

CS2	
Configuration 2	
V90	
CS2 a)	CS2 b)
$\bar{V} = 10$ m/s $I = 7$ % $\Theta = 312^\circ$	$\bar{V} = 14$ m/s $I = 10$ % $\Theta = 312^\circ$
Absolute $P_{\text{wf}}^{\text{ref}} = \begin{cases} 14.4 \text{ MW}, t < 700 \text{ s} \\ 14 \text{ MW}, t \geq 700 \text{ s} \end{cases}$	Absolute $P_{\text{wf}}^{\text{ref}} = \begin{cases} 18.88 \text{ MW}, t < 700 \text{ s} \\ 18 \text{ MW}, t \geq 700 \text{ s} \end{cases}$
All WTs operational	
Priority 9	Priority 10

Table 3: CS3: case study for implementation on Barrow

CS3	
Configuration 3	
V90	
CS3 a)	CS3 b)
$\bar{V} = 10$ m/s $I = 7$ % $\Theta = 204^\circ$	$\bar{V} = 14$ m/s $I = 10$ % $\Theta = 204^\circ$
Absolute $P_{\text{wf}}^{\text{ref}} = \begin{cases} 14.4 \text{ MW}, t < 700 \text{ s} \\ 14 \text{ MW}, t \geq 700 \text{ s} \end{cases}$	Absolute $P_{\text{wf}}^{\text{ref}} = \begin{cases} 18.88 \text{ MW}, t < 700 \text{ s} \\ 18 \text{ MW}, t \geq 700 \text{ s} \end{cases}$
All WTs operational	
Priority 1	Priority 2

Table 4: CS4 – CS5: case studies for implementation on Barrow

CS4	CS5
V90	V90
Configuration 1	Configuration 3
$\bar{V} = 14$ m/s $I = 7$ % $\Theta = 132^\circ$	$\bar{V} = 14$ m/s $I = 7$ % $\Theta = 204^\circ$
Delta mode $P_{wf}^\Delta = 4.72$ MW	Delta mode $P_{wf}^\Delta = 4.72$ MW
All WTs operational	All WTs operational
Priority 8	Priority 4

Table 5: CS6 – CS7: case studies for implementation on Barrow

CS6	CS7
V90	V90
Configuration 1	Configuration 3
$\bar{V} = 14$ m/s $I = 10$ % $\Theta = 132^\circ$	$\bar{V} = 14$ m/s $I = 10$ % $\Theta = 204^\circ$
Absolute $P_{wf}^{\text{ref}} = 15$ MW	Absolute $P_{wf}^{\text{ref}} = 15$ MW
D4 turns off at 500th second	C4 turns off at 500th second
Priority 7	Priority 3

Table 6: CS8 – CS10: case studies on NREL

CS8		CS9		CS10	
NREL		NREL		NREL	
Configuration 1		Configuration 2		Configuration 4	
CS8 a)	CS8 b)	CS9 a)	CS9 b)	CS10 a)	CS10 b)
$\bar{V} = 12 \text{ m/s}$	$\bar{V} = 18 \text{ m/s}$	$\bar{V} = 12 \text{ m/s}$	$\bar{V} = 18 \text{ m/s}$	$\bar{V} = 12 \text{ m/s}$	$\bar{V} = 18 \text{ m/s}$
$I = 7 \%$	$I = 10 \%$	$I = 7 \%$	$I = 10 \%$	$I = 7 \%$	$I = 10 \%$
$\Theta = 132^\circ$	$\Theta = 132^\circ$	$\Theta = 312^\circ$	$\Theta = 312^\circ$	$\Theta = 0^\circ$	$\Theta = 0^\circ$
Absolute $P_{\text{wf}}^{\text{pref}} = \begin{cases} 32 \text{ MW}, t < 700 \text{ s} \\ 30 \text{ MW}, t \geq 700 \text{ s} \end{cases}$		Absolute $P_{\text{wf}}^{\text{pref}} = \begin{cases} 32 \text{ MW}, t < 700 \text{ s} \\ 30 \text{ MW}, t \geq 700 \text{ s} \end{cases}$		Absolute $P_{\text{wf}}^{\text{pref}} = \begin{cases} 100 \text{ MW}, t < 700 \text{ s} \\ 95 \text{ MW}, t \geq 700 \text{ s} \end{cases}$	
All WTs operational		All WTs operational		All WTs operational	

References

- [1] Distributed Control of Large-Scale Offshore Wind Farms (Aeolus). Grant agreement Annex I - "Description of Work", October 2010.
- [2] Industrial Systems and Control Ltd. Aeolus Deliverable 3.2 Supervisory Control Paradigm, Part 3 Nonlinear Predictive Control using State Dependant and Linear Parameter Varying Models for Wind Turbine Supervisory Control. Project report, 2010.
- [3] V. Spudić, M. Jelavić, M. Baotić, M. Vašak, and N. Perić. Aeolus Deliverable 3.3 Reconfigurable Control Extension. Project report, University of Zagreb, Faculty of Electrical Engineering and Computing, 2010.
- [4] Daria Madjidian, Ahmed H. El-Shaer, and Anders Rantzer. Aeolus Deliverable 4.3 Preliminary Distributed Control Strategy. Project report, Automatic Control LTH, Lund University, 2010.
- [5] Mohsen Soltani, Torben Knudsen, and Thomas Bak. Aeolus Deliverable 5.4 Simulation models for case study. Project report, Aalborg University, 2009.
- [6] Vestas. Aeolus Deliverable 5.5 Plan for performance assessment. Project report, 2010.
- [7] Vestas Wind Systems A/S. V90 3 MW. Product brochure. <http://nozebra.ipapercms.dk/Vestas/Communication/Productbrochure/V9030MW/V9030MWUK/>.

- [8] J. Jonkman, S. Butterfield, W. Musial, and G. Scott. Definition of a 5-MW Reference Wind Turbine for Offshore System Development. Technical report, National Renewable Energy Laboratory, February 2009.

Appendix

Barrow statistics

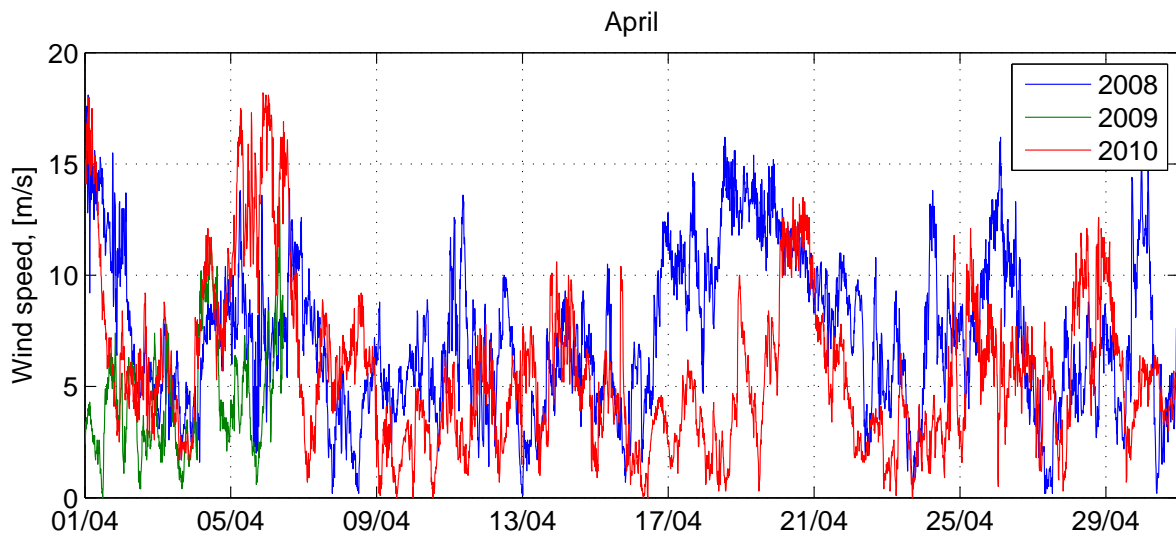


Figure 4: Measured 10 minute average wind speed in April

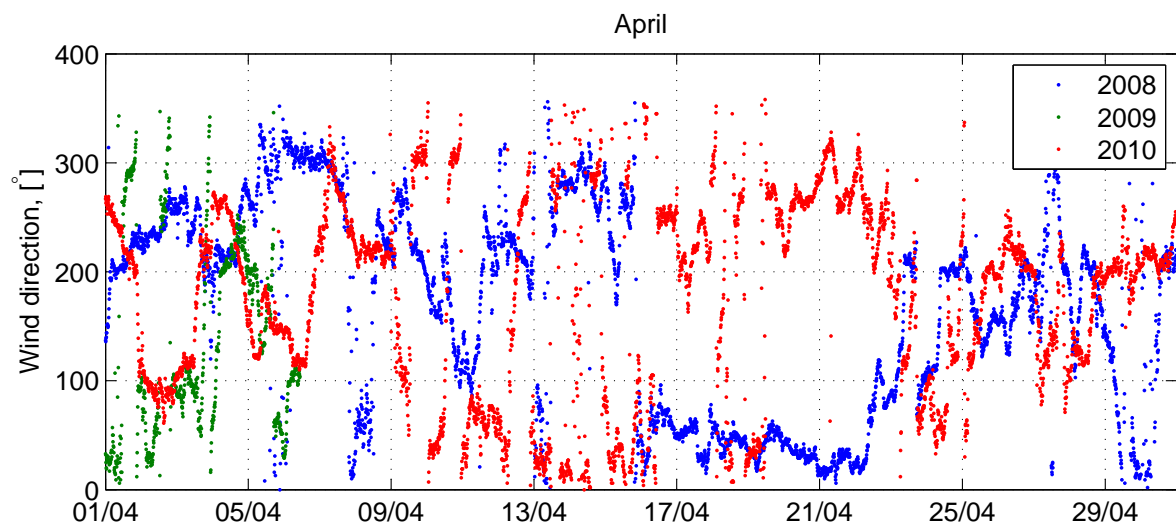


Figure 5: Measured 10 minute average wind direction in April

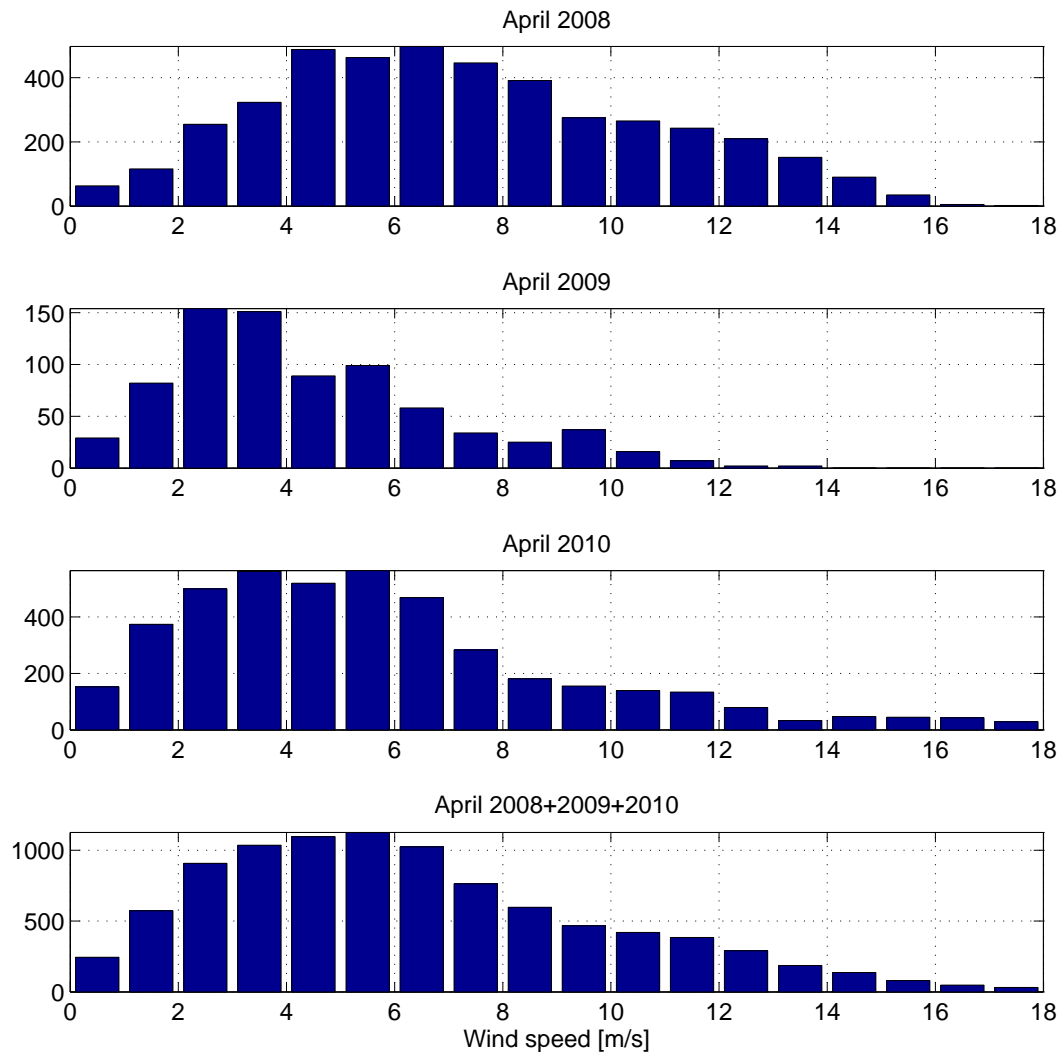


Figure 6: Distribution of 10 minute average wind speed in April

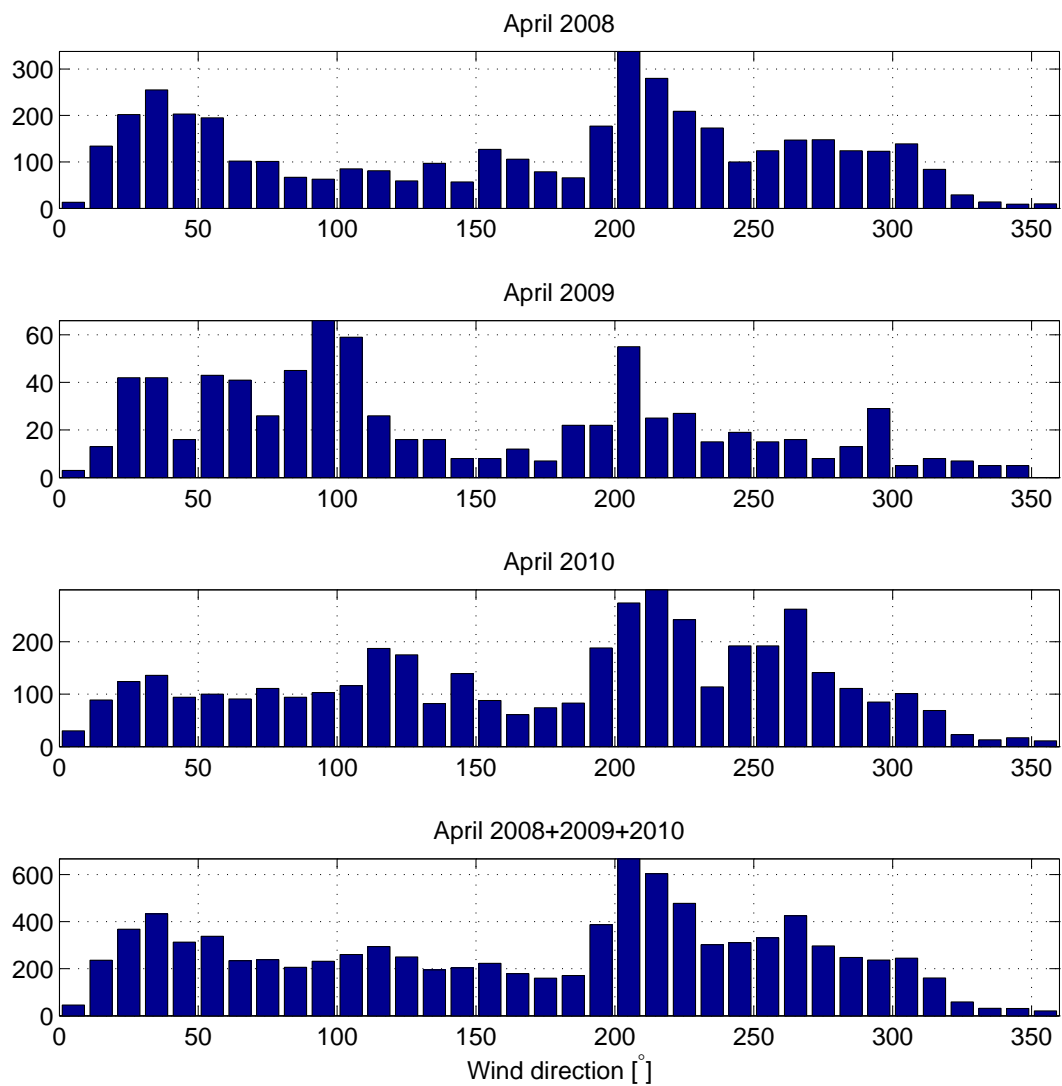


Figure 7: Distribution of 10 minute average wind direction in April

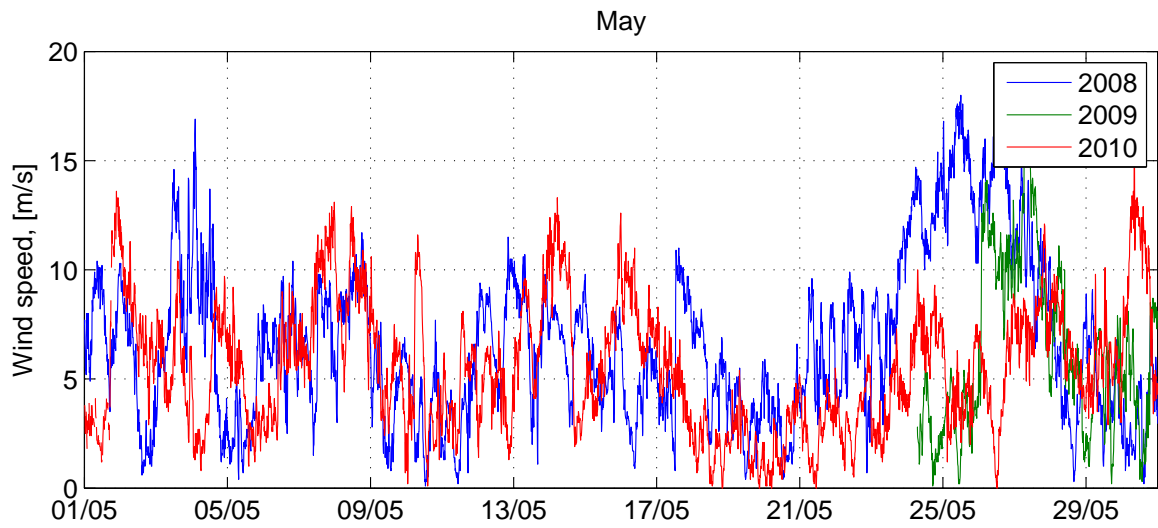


Figure 8: Measured 10 minute average wind speed in May

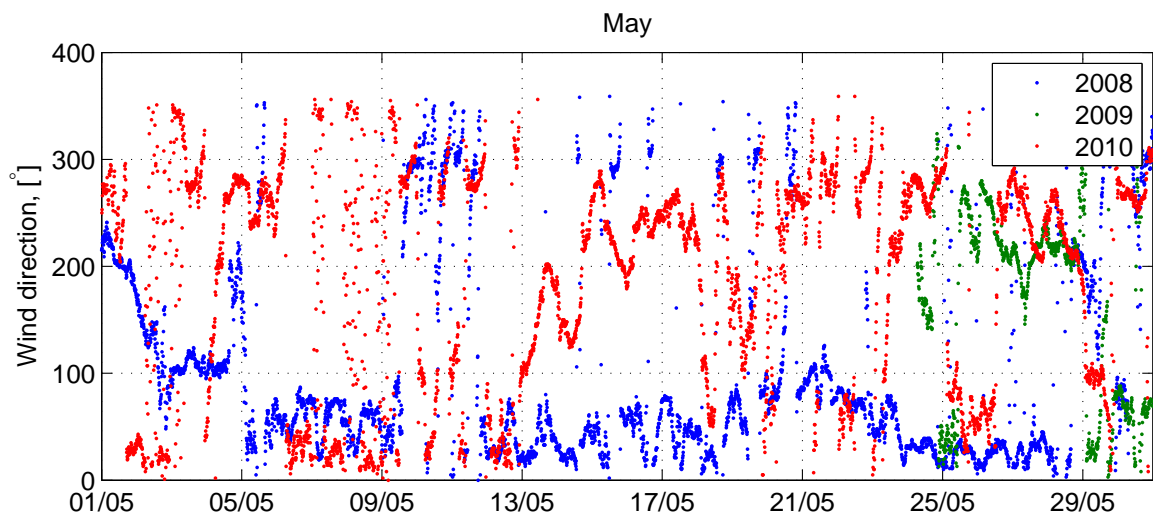


Figure 9: Measured 10 minute average wind direction in May

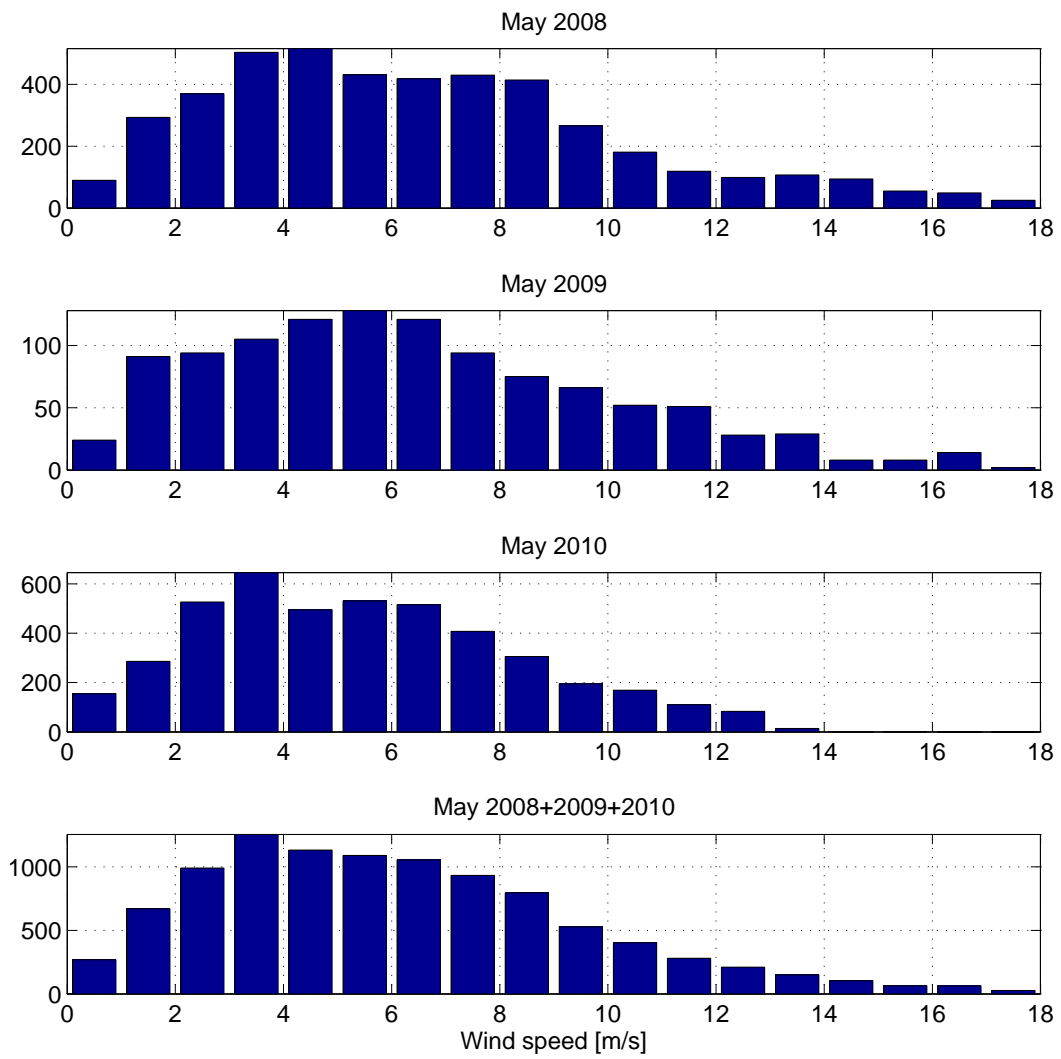


Figure 10: Distribution of 10 minute average wind speed in May

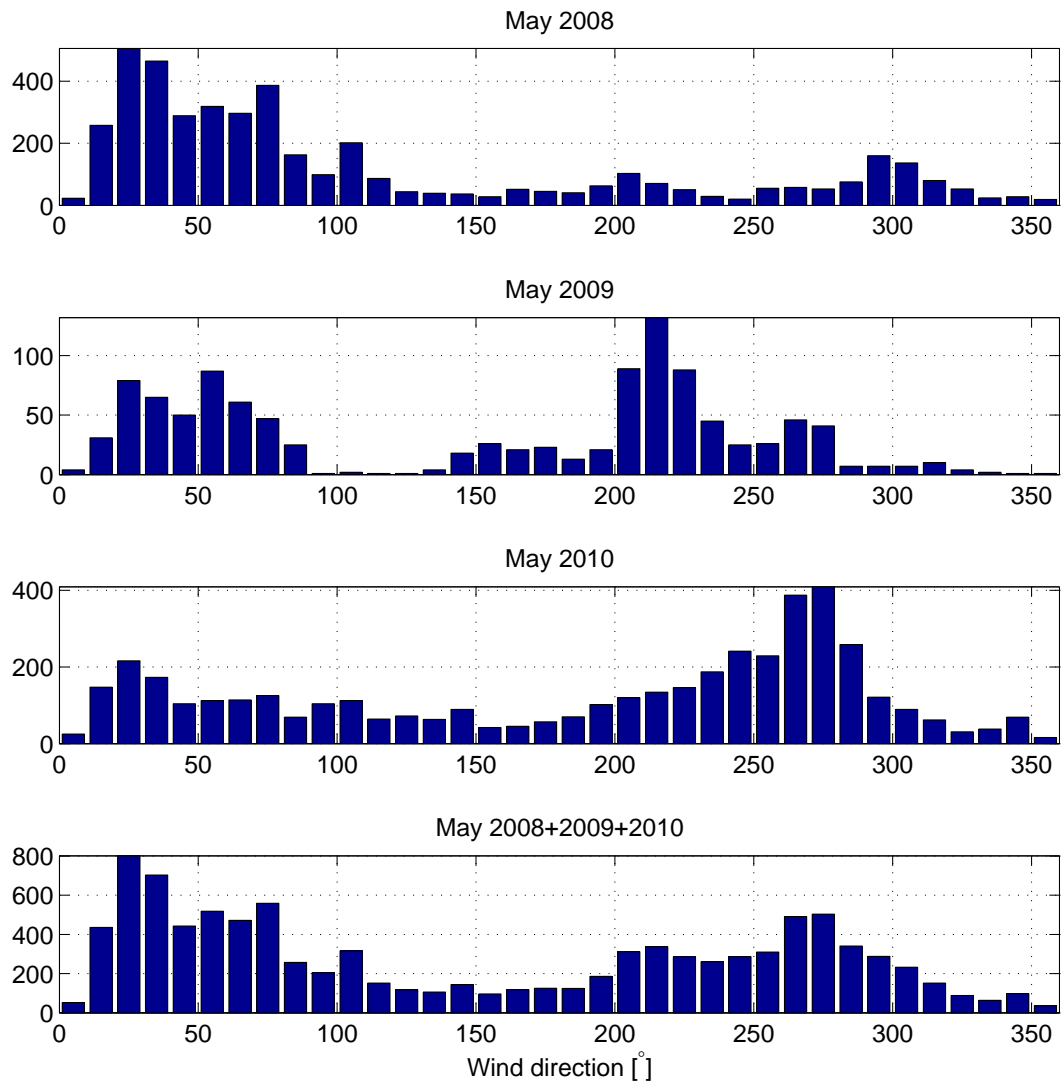


Figure 11: Distribution of 10 minute average wind direction in May