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Summary:
In this deliverable the plan for validation of control strategies developed in Aeolus is described. The first chapter contains the plan for experimental validation that will be conducted on Thanet wind farm. The second chapter describes the tests that will be conducted in simulation.

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

Deliverable 1.6a:
Plan for validation of control strategies - Addendum

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Abstract

In this deliverable the plan for validation of control strategies developed in Aeolus is described. The first chapter contains the plan for experimental validation that will be conducted on Thanet wind farm. The second chapter describes the tests that will be conducted in simulation.

Contents

Experiments on Thanet wind farm **2**
Experiment 1 Validation of wind farm models developed in WPs 2 and 5 4
Objective 4
Turbine selection 4
Signals to be measured 4
Test procedure 5
Experiment 1.1 Single turbine wakes 5
Expected outcomes 5
Experiment 1.2 Multi wake 7
Experiment 2 Validation of static feedforward wind farm model developed in WP 4 8
Objective 8
Turbines and signals 8
Introduction to experiment 8
Experiment 8
Expected outcome 10
Experiment 3 Validation of wind turbine control model developed in WP 3 15
Objective 15
Turbine selection 15
Signals to be measured 15
Test procedure 15
Experiment 3.1 Higher wind speed 16
Experiment 3.2 Lower wind speed 16
Purpose of the test 16
Expected results 17

Validation of control strategies in simulation **20**

Bibliography **24**

Experiments on Thanet wind farm

In this chapter the experiments that will be conducted on Thanet wind farm are described.

Thanet Offshore Wind Farm is situated off the cost of Great Britain and consists of a hundred Vestas V90 3MW turbines.The met mast on site is situated in the middle of the wind farm.

Figure 1: Location of Thanet Offshore Wind Farm

The gathering of wind farm measurements and the dispatch of wind turbine power references is handled by a SCADA server. This system does not allow the implementation of a dynamic wind farm controller due to variable delays in data transfer and possible losses in data transfers. Therefore, the control solutions developed in Aeolus can not be tested in full-scale. Therefore, the smaller-scale experiments are devised to validate the developed models and thus justify the design of model-based controllers.

Other restrictions on the experiments are the following:

- The onsite SCADA server is used to log signals at 1 Hz.
- There is a delay of 0.5 – 1 second before a turbine registers a new power set point.

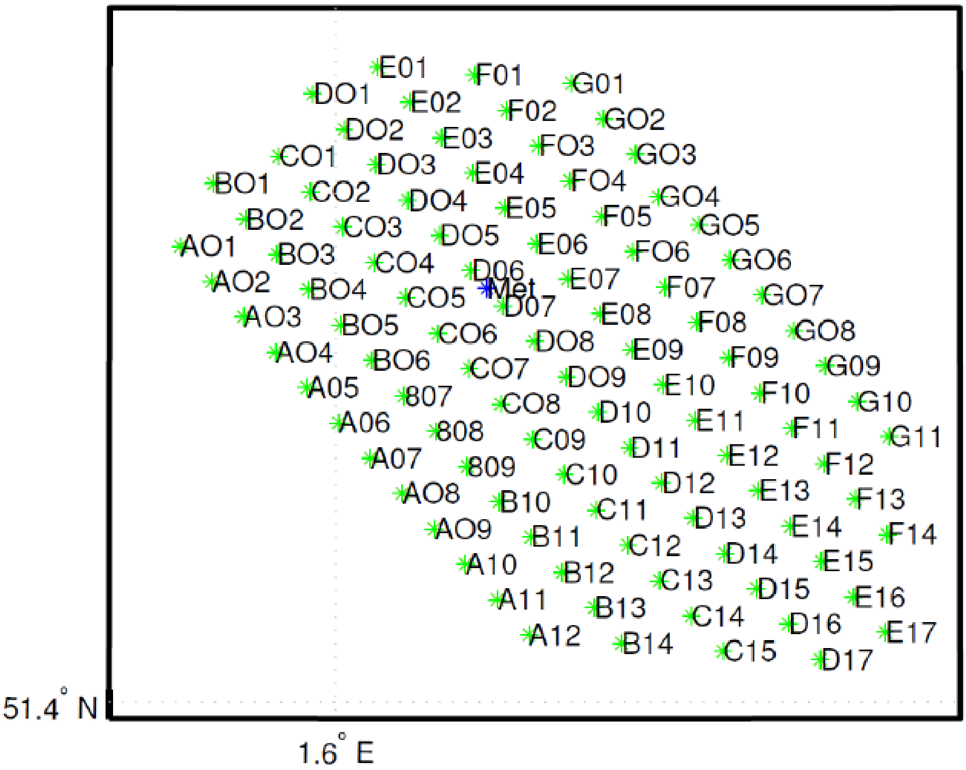

Figure 2: Thanet Offshore Wind Farm layout

- The turbine controllers have a rate limitation of 100 kW/s.
- It is not advised to update the power setpoint more often than every 5 seconds.

In the following the planned experiments are described.

Experiment 1. Validation of wind farm models developed in work packages 2 and 5

Objective

The objective is to do model validation and if necessary parameter estimation. There are a number of models involved where it is reasonable to use the same data.

These models are:

1. Static models relating effective wind speed at a down wind turbine to the wind speed and C_t for upwind turbines assuming the wind direction along a row. Frequencies down to 1/600 Hz. (See D2.5).
2. Dynamic models as the above but covering frequencies down to 1 Hz. (See D2.5).
3. Dynamic models as the above but covering varying directions. (See D2.3).
4. Dynamic models based on finite volume models. (See D2.4).
5. The SimWindFarm simulator. (See D5.4)

Turbine selection

A01-A08 plus B03-B04.

Signals to be measured

For each turbine as selected above the following measurements are taken at 1 Hz and stored, e.g. for A01:

- A01_GeneratorRPM,
- A01_NacelleDirection,
- A01_PitchAngle,
- A01_Power,
- A01_PowerRef,
- A01_RoterRPM,
- A01_TowerAccLong,
- A01_TowerAccTrans,
- A01_WindDir,
- A01_WindSpeed,

- A01_System_turbine_state;

and for the met mast:

- MET_AirTemperature,
- MET_WindDir1,
- MET_WindDir2,
- MET_WindSpeed1,
- MET_WindSpeed2.

Test procedure

The suggested test procedure is to test the response of a step change in power reference to the turbines. Two types of experiments are described.

Experiment 1.1. Single turbine wakes

Turbines A02-A08 and B03-B04 remain operating in standard operation. Select turbine A01. The turbine is running with a power setpoint P_{init} (A01). At a point when the wind speed (at the met mast) is $V \pm V_{\text{tol}}$ and the wind direction is $D \pm D_{\text{tol}}$ a new set point P_{new}(A01) is sent to the wind turbine. The wind turbine A01 is left in this new state for t seconds then return to P_{init} (A01) where it remains for t seconds. The test is repeated n times. Signals are measured from all 10 turbines selected above.

$D(10 \text{ min average}) = 318°,\ D_{\text{tol}} = 5°,\ V_{\text{tol}} = 1$ m/s.

Table 1: Experiment 1.1

Exp. no.	V (10 min average)	P_{new}	t (sec)	n
1c	12	$0.4 \cdot P_{\text{init}}$	80	10
1e	16	$0.4 \cdot P_{\text{init}}$	80	10
1i	12	$0.4 \cdot P_{\text{init}}$	300	5
1k	16	$0.4 \cdot P_{\text{init}}$	300	5

Expected outcomes (test 1d)

A simulation of the test 1d) is presented here with the test specification defined in Table 2.

The simulation is performed using 5MW NREL turbines, for simplicity as they allow full shutdown and startup. The results are, however, general. The test starts at $t = 200$ seconds and the simulation result is depicted in Figure 3 for $n = 5$. The first

Table 2: Experiment 1d

Exp. no.	V (10 min average)	P_{new}	t (sec)	n
1d	12	0	60	10

row shows the generated power by A01. The second row shows the measured wind speed at A02 which is denoted by V_{m}(A02).

To be able to see the effect of the test, another simulation is performed in which there is no change in the power reference of A01. V_{E} denotes the expected wind speed at A02 when the power reference of A01 remains constant with the value of 5MW. The third row shows the difference between (V_{m}(A02)) the measured wind speed at A02 when the power reference is changing as specified above and V_{E}(A02) - the expected measurement at the same turbine when the power reference is constant i.e. V_{m}(A02)-V_{E}(A02).

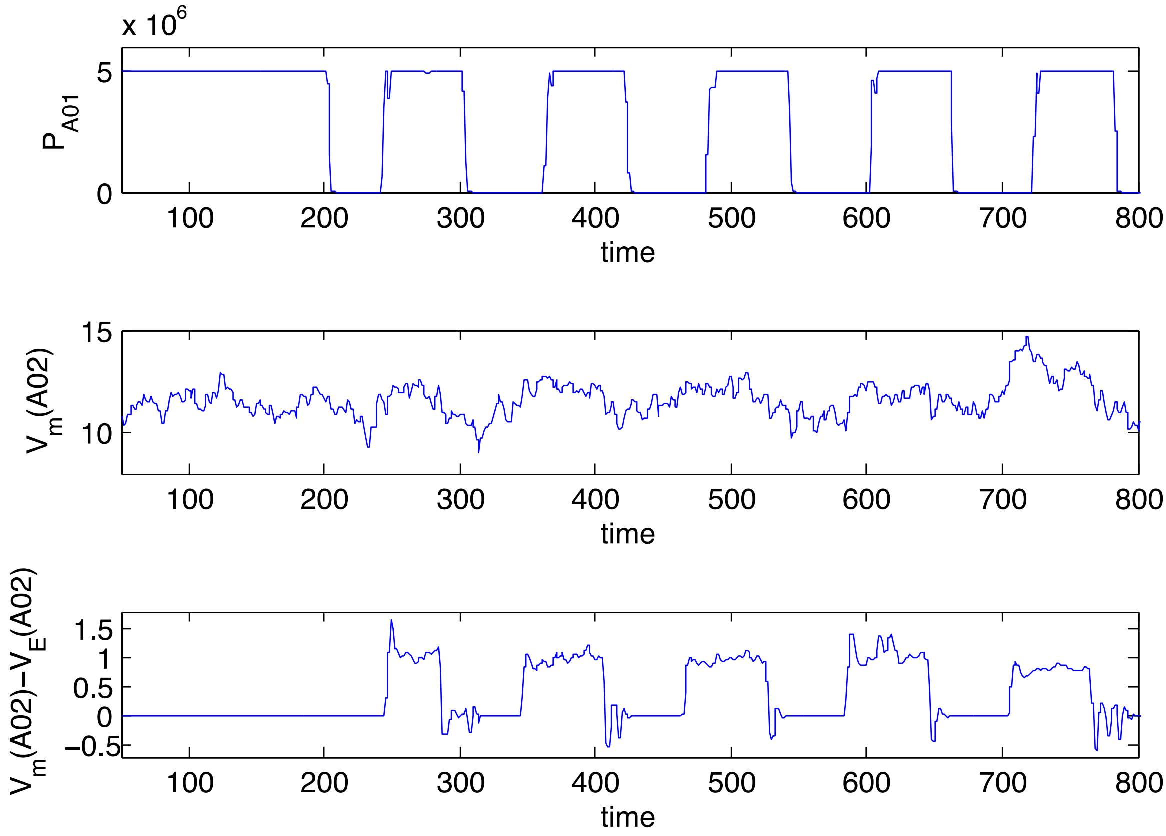

Figure 3:

The results demonstrate the effect of turbine de-rating on the downwind deficit. Note in the bottom subplot in Figure 3, that the deficit is only about 1 m/s, which illustrates the expected wind speed deficit on a downwind turbine. The effects are hence very limited and not immediately visible from data as seen in Figure 3, middle subplot. Also note the approximately 40 sec time delay, which is expected given the spacing and the wind speed. Capturing this effect would allow us to model the interaction between turbines using systems identification methods as outlined in D2.5 and D2.4.

Experiment 1.2. Multi wake

Turbines A03-A08 and B04 remain operating in standard operation. Select turbine A01, A02 and B03. The turbines are running with a power setpoint $P_{\text{init}}(\text{A01})$, $P_{\text{init}}(\text{A02})$ and $P_{\text{init}}(\text{B03})$. At a point when the wind speed (at the met mast) is $V \pm V_{\text{tol}}$ and the wind direction is $D \pm D_{\text{tol}}$ the procedure is initiated and $t = t_0$. For each of the turbines A01, A02 and B03 the following test cycle is carried out: the turbine is de-rated to 750 kW for 4.5 min after which it returns to P_{init} for 4.5 min. The test cycle is repeated $n = 4$ times. The test cycles are initiated at the times 0, 180, 360 sec after t_0 for turbines A01, A02 and B03 respectively.

$$D(10 \text{ min average}) = 318°,\ D_{\text{tol}} = 5°,\ V_{\text{tol}} = 1 \text{ m/s},\ V(10 \text{ min average}) = 12 \text{ m/s}.$$

Experiment 2. Validation of static feedforward wind farm model developed in work package 4

Objective

The objective of these experiments is twofold: try to increase power production, and to evaluate the following model:

$$v_{n+1} = v_n + k'(v - v_n) - kvC_{T_n} \tag{1}$$

The latter is the main objective. In (1), n is the turbine index, $n = 1$ corresponding to the most upwind turbine. v is ambient incoming wind speed, v_n is the 10 min wind speed at turbine n, and C_{T_n} is the thrust coefficient at turbine n. k is a distance parameter used to model the effect of a turbine on its immediate downwind neighbour, and k' is a distance parameter used to model the recovery the wind speed experiences between two adjacent turbines.

Turbines and signals

Data should be at 1 Hz logged from turbines: A1-A10.

Turbines derated: A01 – A08

Signals logged from each turbine: Wind speed, Nacelle direction, Rotor power estimate, Pitch Angle, Rotor RPM, Generator RPM, Active power, Power reference, Wind direction, Relative wind direction, Acceleration in X-direction.

Introduction to experiment

The expected result are based on the following parameters:

$$k = 0.129 \quad k' = 0.424$$

These parameters where chosen based on the AEOLUS ECN model.

Consider the following case: 10 V90 turbines in a row, and incoming wind speed 9 m/s, $k = 0.129$, and $k' = 0.423$. We now try to maximize power subject to (1). Figure 4 shows the result, and Figure 5 shows the *increase* in produced power for each turbine relative to the case when all turbines extract max.

The power total power increase in the farm was 0.6% or 36 kW.

Experiment

Since a major objective of the experiment is to understand how wind speed increases downwind when limiting upwind turbines, we need to make sure the effect is visible. In order

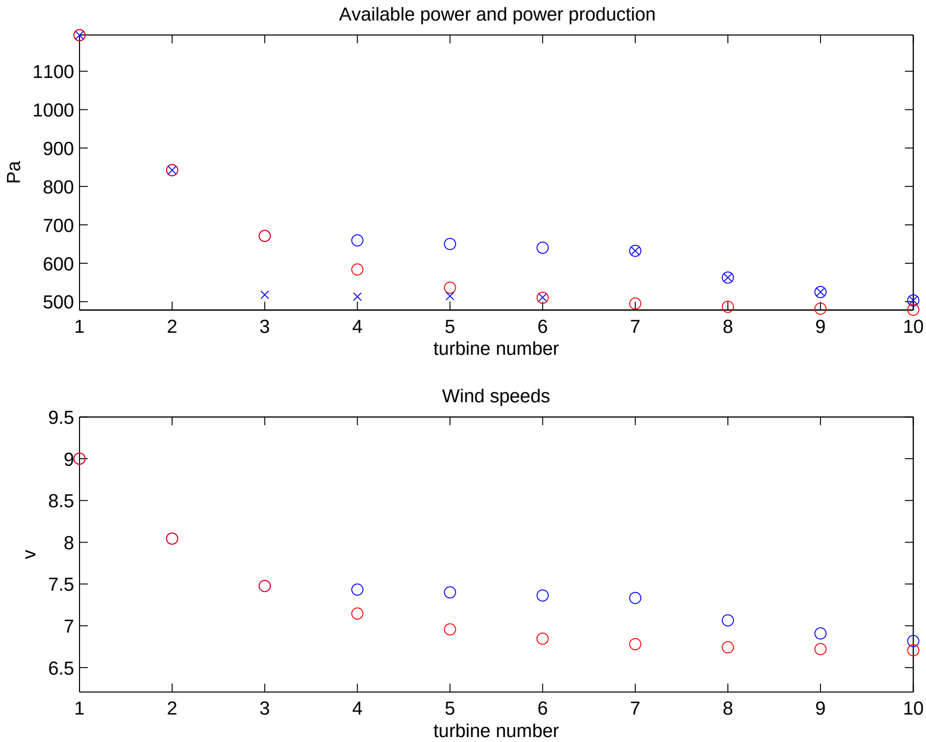

Figure 4: Power distribution and wind speeds at an incoming wind speed of 9 m/s. UPPER PLOT: Blue circles – power available when some turbines limited, Red circles – power available (produced) when all turbines extract max (nominal case), Blue crosses – Power produced when some turbines limited'. LOWER PLOT: Blue circles – wind speeds when some turbines limited, Red circles – wind speeds in nominal case.

not to be to dependent on the inital parameters, we will derate upwind turbines more than suggested by figure 4. For some wind speeds we will use the result in Figure 5 in order to understand how derating turbines further downwind effects the wind field. The experiment should be carried out as follows:

When incoming 10 min wind speed at turbine A01 is $V = [7, 9, 11, 13, 15]$ m/s ± 1 m/s, and the incoming 10 min mean wind direction is $d = 318 \pm 5°$, do the following:

1. Log data from turbines A01-A10 for 10 min. The 10 min power produced by turbine $A0i$ is denoted by $P_{\text{init}}(A0i)$ [kW].
2. Set the power reference to turbine $A0i$ to $P\text{new}(A0i) = C_{0i} P_{\text{init}}(A0i)$. The constants C_{0i} are given in Table 3. Note that turbines $A09$ and $A10$ remain in standard operation.
3. Log data for 15 min.
4. Reset the turbines to normal operation, and log data for 5 min.

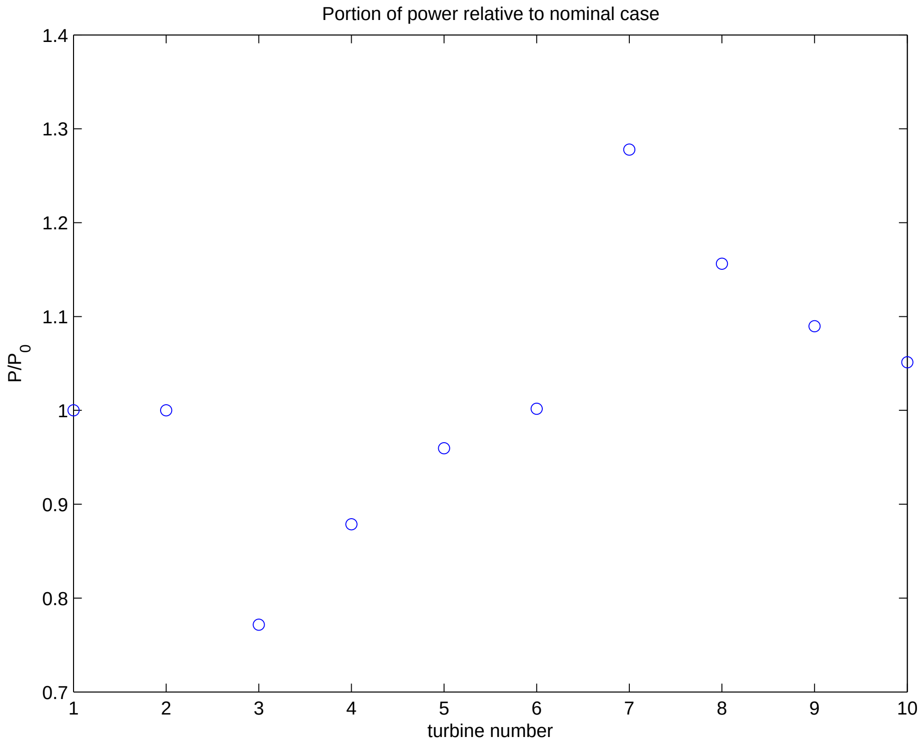

Figure 5: $P_i/P_{0,i}$, where P_i is power produced by turbine i when some turbines are limited, and $P_{0,i}$ is power produced by turbine i when all turbines extract max.

This experiments should be repeated 30 times for each wind speed.

Expected outcome

In the case of $V = (7, 11, 15)$, the power production is decreased in turbines A01-A03, kept at its previous value for turbines A04-A06, and increased for turbines A07-A08. The results are illustred in Figures 6-8.

For cases $V = (9, 13)$ m/s the results are shown in Figure 4, and 9.

The resulting power increase is shown in Table 4.

Table 3: Constants C_{0i} for the different wind speeds. The value “Max” denotes a set point of 3000 kW.

V	$A01$	$A02$	$A03$	$A04$	$A05$	$A06$	$A07$	$A08$
7	0.9	0.9	0.95	1.15	1.15	1.15	1.4	1.4
9	Max	Max	0.8	0.9	1.0	1.1	Max	Max
11	0.9	0.9	0.95	1.1	1.1	1.1	1.3	1.3
13	Max	Max	0.80	0.90	1.0	1.1	Max	Max
15	0.9	0.9	0.95	1.0	1.0	1.0	1.05	1.05

Table 4: Power increase when limiting turbines

V	%	kW
7	-2.1	-64
9	0.6	36
11	-1.71	-227.6
13	-2.18	-490.2
15	-2.6	-761.73

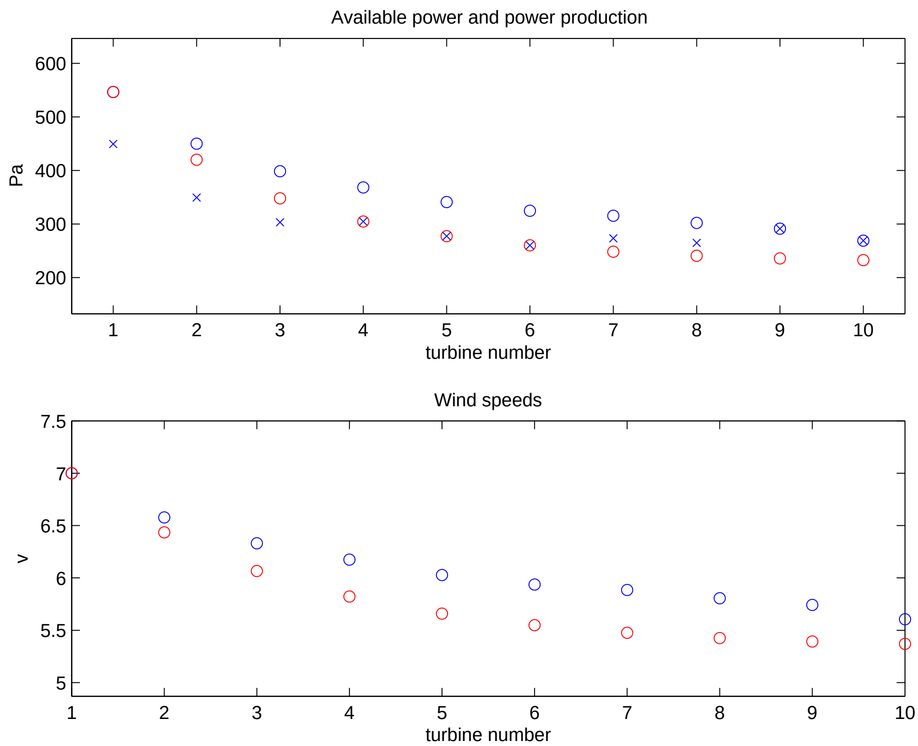

Figure 6: Power distribution and wind speeds with incoming wind speed of 7 m/s. UPPER PLOT: Blue circles – power available when some turbines limited, Red circles – power available (produced) when all turbines extract max (nominal case), Blue crosses – Power produced when some turbines limited. LOWER PLOT: Blue circles – wind speeds when some turbines limited, Red circles – wind speeds in nominal case.

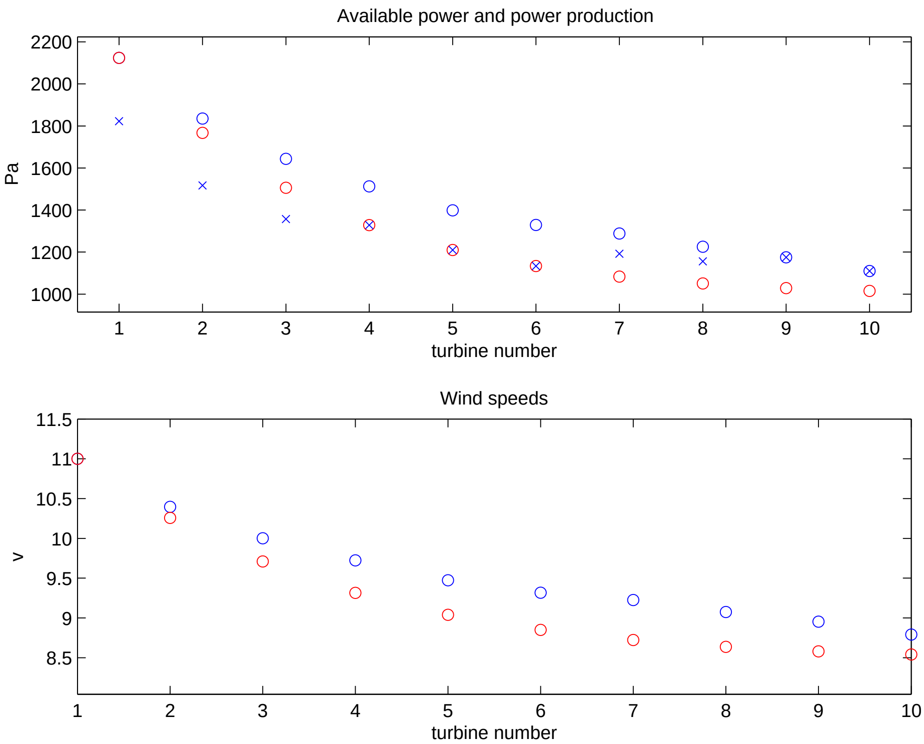

Figure 7: Power distribution and wind speeds with incoming wind speed of 11 m/s. UPPER PLOT: Blue circles – power available when some turbines limited, Red circles – power available (produced) when all turbines extract max (nominal case), Blue crosses – Power produced when some turbines limited. LOWER PLOT: Blue circles – wind speeds when some turbines limited, Red circles – wind speeds in nominal case.

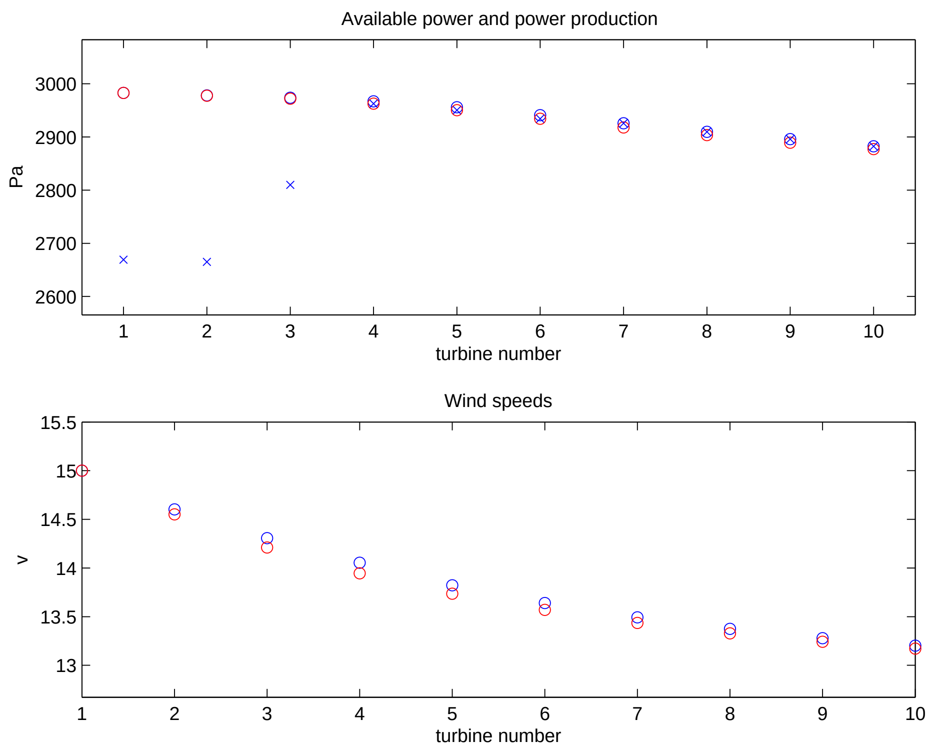

Figure 8: Power distribution and wind speeds with incoming wind speed of 15 m/s. UPPER PLOT: Blue circles – power available when some turbines limited, Red circles – power available (produced) when all turbines extract max (nominal case), Blue crosses – Power produced when some turbines limited. LOWER PLOT: Blue circles – wind speeds when some turbines limited, Red circles – wind speeds in nominal case.

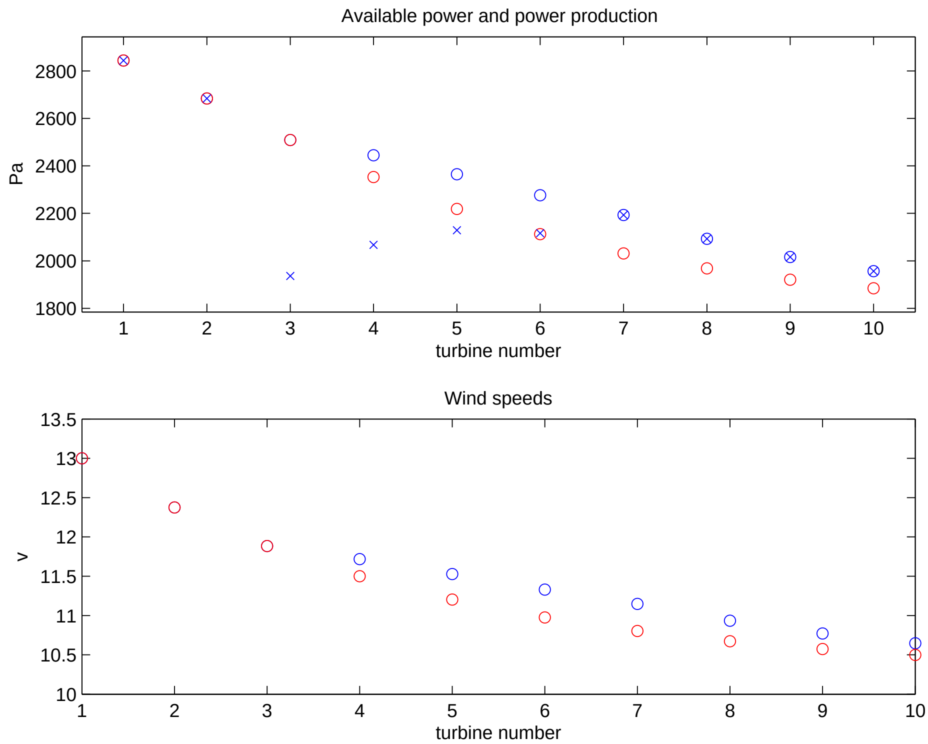

Figure 9: Power distribution and wind speeds with incoming wind speed of 13 m/s. UPPER PLOT: Blue circles – power available when some turbines limited, Red circles – power available (produced) when all turbines extract max (nominal case), Blue crosses – Power produced when some turbines limited. LOWER PLOT: Blue circles – wind speeds when some turbines limited, Red circles – wind speeds in nominal case.

Experiment 3. Validation od wind turbine control model developed in work package 3

Objective

The objective is to validate the simplified V90 wind turbine model (to be) developed by UZAG for controller design purposes as well as the wind speed estimator developed by AAU.

Turbine selection

A01.

Signals to be measured

The following measurements are taken at 1 Hz and stored:

- A01_PowerRef,
- A01_WindSpeed,
- A01_WindDir,
- A01_NacelleDirection,
- A01_PitchAngle,
- A01_GeneratorRPM,
- A01_RotorRPM,
- A01_TowerAccLong.

Test procedure

The suggested test procedure is to test the response of the wind turbine to small step changes in power reference and turbulent wind.

Wind turbines A02-A08 and B03-B04 remain operating in standard operation.

For this test the exact value of the mean wind direction D is not important. However, the wind direction should remain within $D \pm D_{\text{tol}}$ during a particular experiment, $D_{\text{tol}} = 5°$, and wind turbine rotational axis should be aligned with the wind direction. The measurements of the nacelle direction and wind direction will be used to check this condition.

The control design model we are testing is described in Aeolus report [1]. Its inputs are the wind turbine power reference and the effective wind speed. The effective wind speed is not measurable, but it can be estimated based on system measurements. The effective wind speed estimator is developed in WP2 of the Aeolus project. The details on this estimator can be found in [2]. The experimental setup is depicted in Figure 10. The result of this experiment is the comparison of the control model outputs and the wind turbine measurements on each wind turbine.

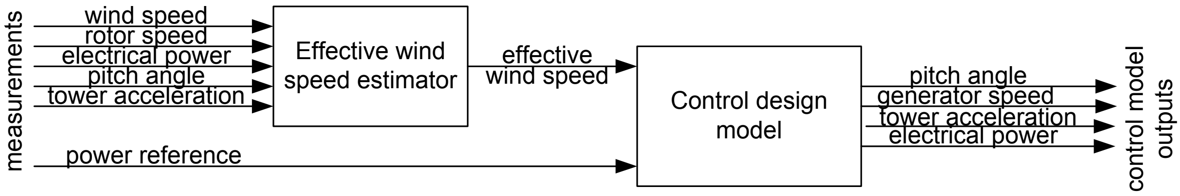

Figure 10: Obtaining the control model outputs

Experiment 3.1. Higher wind speed

The ten minute mean wind speed is 15 m/s. The power reference signal depicted in Figure 11 is applied to the wind turbine. The experiment is repeated $n = 5$ times. The signals from wind turbine A01 are measured and stored.

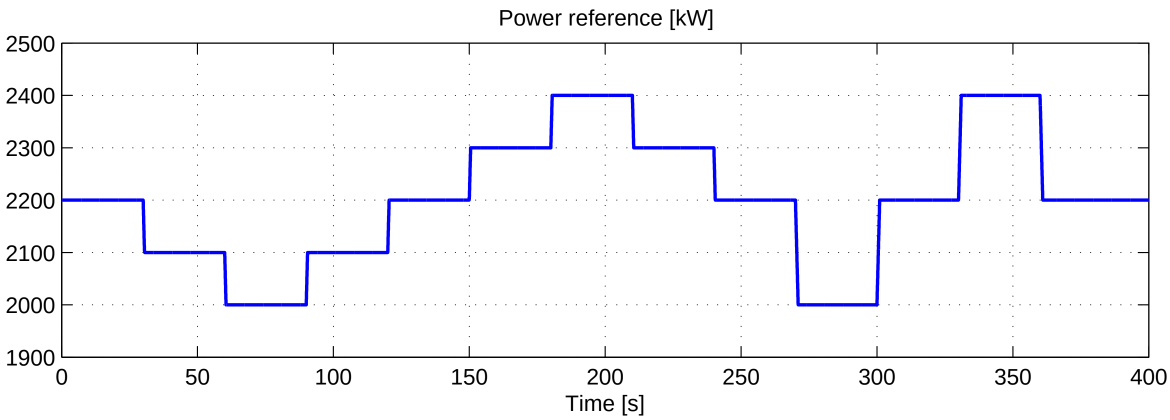

Figure 11: Power reference for experiment 3.1

Experiment 3.2. Lower wind speed

The ten minute mean wind speed is 11 m/s. The power reference signal depicted in Figure 12 is applied to the wind turbine. The experiment is repeated $n = 5$ times. The signals from wind turbine A01 are measured and stored.

Purpose of the test

For control design purpose the wind turbine control design models have been developed. These models are, compared to the system complexity, very simple. Still these models need

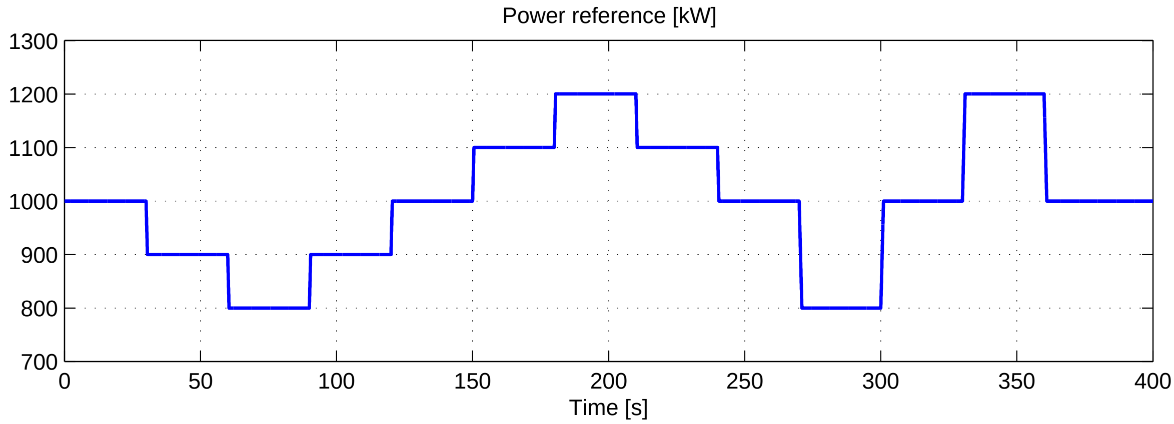

Figure 12: Power reference for experiment 3.2

to capture the important dynamics of the wind turbine system in response to fluctuating wind input and to (small) changes in power reference. These tests are designed to validate and (if required) improve the wind turbine models for control design.

Expected results

In Figures 13 and 14 we give an example of the expected results generated by using the Simulink model of the V90 wind turbine. The measurements are obtained by simulation of the full-scale nonlinear model.

The results with and without the effective wind speed estimator are depicted. In simulations it is possible to extract the effective wind speed out of the model and use it as an input to control design model, which is not possible in the real experiment.

The simulation outputs show that the outputs of the control design model, even though the control design model is very simple and linear, match the full-scale model very well. When the effective wind speed estimator is introduced a certain lag between the full-model outputs and experiment outputs occurs, which we also expect to see in the experimental tests. This simulation experiment, however, is not entirely representative of the experimental setup because the models are strictly deterministic, i.e. there is no measurement noise modeled. In a real experiment stochastic disturbances are expected for which this estimator is specifally designed.

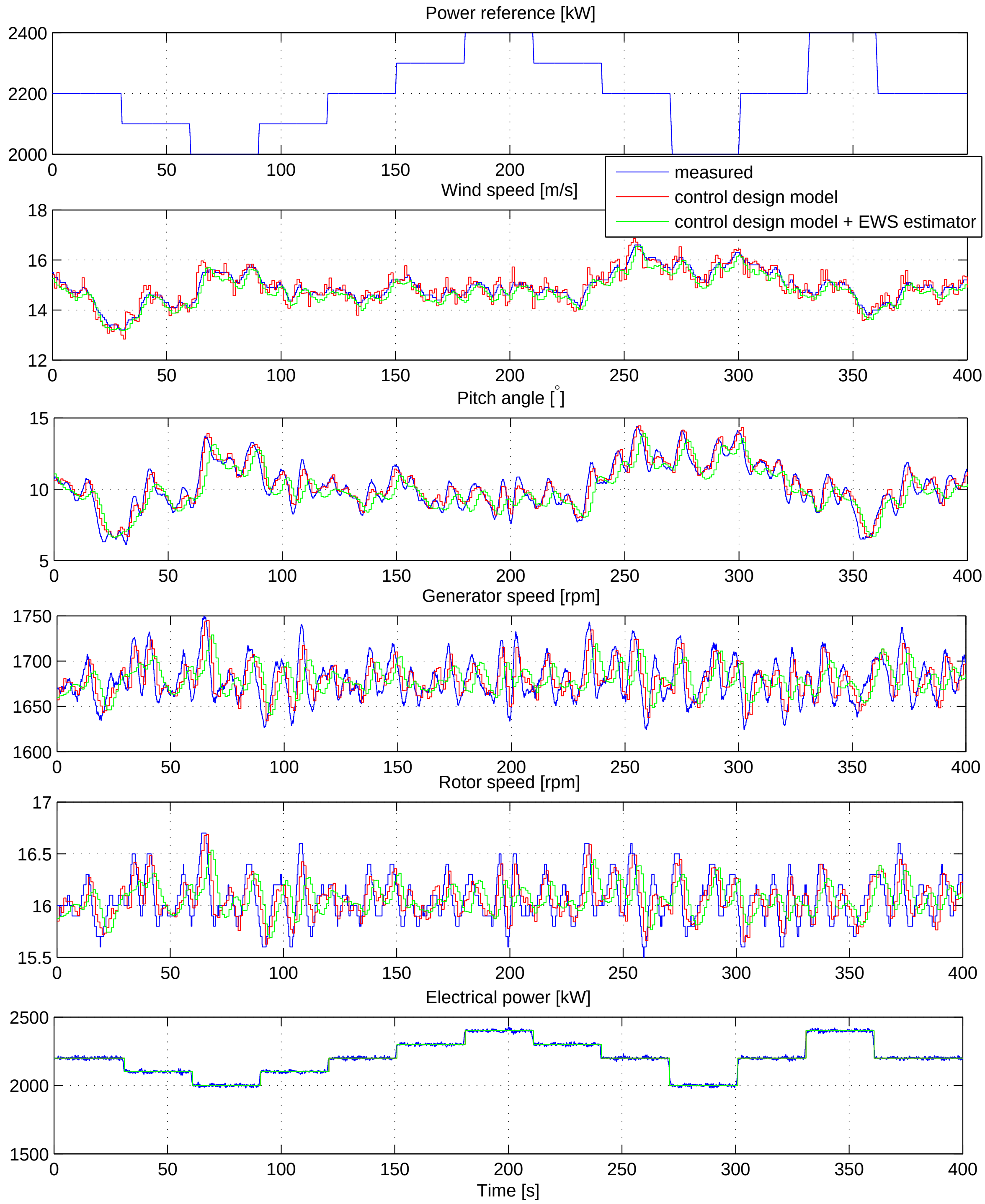

Figure 13: Expected results for experiment 3.1

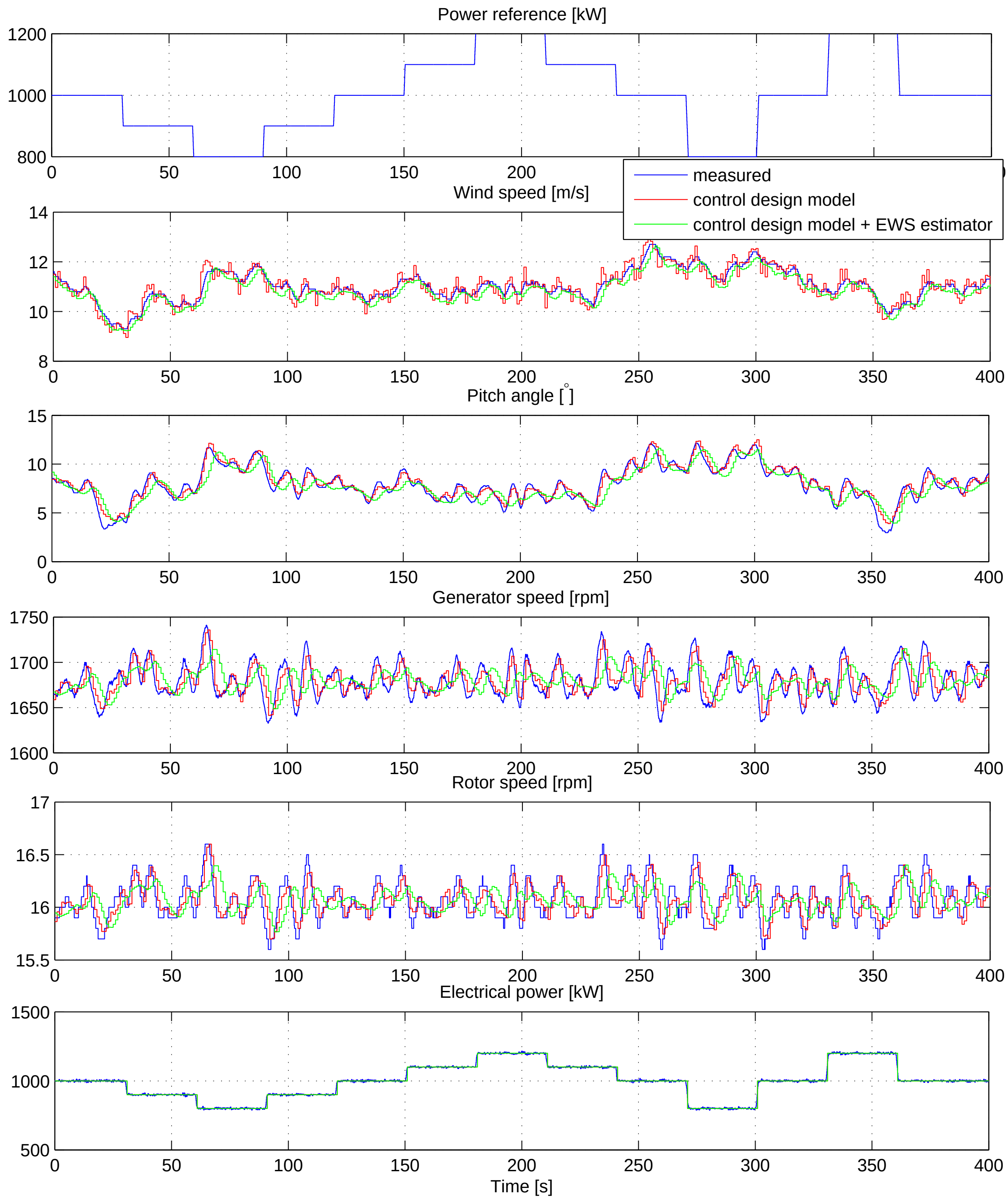

Figure 14: Expected results for experiment 3.2

Validation of control strategies in simulation

Due to the fact that the controller setup at the Thanet wind farm does not allow the implementation of the feedback controller, the developed control strategies will be tested in simulation.

The simulation is based on the wind farm simulator developed in WP5 with the 5MW NREL wind turbine. The layout of the wind farm agreed among the partners consists of 8 wind turbines in a row, with distance of 500 meters between neighboring wind turbines. The wind direction is parallel to the row of the wind turbines (i.e. parallel to the imaginary line drawn to connect the wind turbines). This layout is chosen because it demonstrates the effect of wind farm controller most obviously.

The wind farm controller setups to be tested are:

1. **No wind farm controller** - benchmark,
2. **PI controller (T=10 s)** - benchmark,
3. **Supervisory controller (T=10 s)** - developed in WP3,
4. **PI controller (T=1 s)** - benchmark,
5. **Hierarchical WF controller: PI controller (T=10 s) + reconfigurable controller (T=1s)** - developed in WP3,
6. **Hierarchical WF controller: supervisory controller (T=10 s) + reconfigurable controller (T=1s)** - developed in WP3, and
7. **Decentralized WF controller** - developed in WP4.

Wind farm controllers will be tested for two operating regimes:

1. Mean wind speed of 15 m/s, turbulence intensity 10%, mean wind farm power reference 36 MW; and
2. Mean wind speed of 10 m/s, turbulence intensity 10%, mean wind farm power reference 20 MW.

In the first operating regime there is a large reserve in the available power and the wind farm power reference is relatively low. Therefore, it is very unlikely that the wind farm controller will face the wind turbine power limits. In the second operating regime the wind farm power reference is (still lower but) close to the available wind farm power, so it is expected that the wind farm power reference will not be met without the active control. This operating regime demonstrates the ability of the controller to handle the constraints.

The following simulation scenarios are tested for each of the operating regimes:

1. **Hold power reference** - the wind farm is given a power reference which it needs to track during the entire simulation. When the mean wind speed is 15 m/s the power reference is 36 MW, while when the mean wind speed is 10 m/s the power reference is 20 MW;
2. **Track power reference** - the wind farm power is supposed to track a changing wind farm power reference - step changes are imposed around the mean power reference;
3. **WF losses** - a modeling error is introduced: $P_{\text{WF}} = 0.98 \cdot \sum_{i=1}^{N_{\text{WT}}} P_i$. This test checks whether the controllers are able to compensate for modeling errors. Physically, this can be the model of losses in the wind farm transmission grid.

These scenarios demonstrate the ability of controllers to track a time-varying reference with no steady-state offset even in case of modeling error (which is to be expected in a real wind farm).

All simulations are run for 630 seconds, from which the first 30 seconds are considered the simulation warm-up, while the statistics are computed on the remaining 10 minutes of simulation.

The simulator interface is depicted in Figure 15. The 'Turbines' block consists of N_{WT} blocks that model each individual wind turbine. The template of the wind turbine model is given in Figure 16. In block 'WT' the wind turbine is modeled and the measurements are collected for logging. Every wind turbine block has a corresponding estimator block in which the states of each individual wind turbines can be estimated (at a sampling frequency of the wind turbine measurements).

For design of different controllers the block 'WF_control' and 'Estimator' can be edited freely, as long as the interface to other blocks remains unchanged. Other blocks should not be changed. The aim of this template is to keep the same (realistic) interface for all the controllers and to collect the measurements in exactly the same manner. The wind farm controller inputs the measurements from the wind turbines (the measurements of electrical power, rotor speed, pitch angle, wind speed and wind turbine status - on/off), the estimations of wind turbine states (x_{est}, d_{est}, and P_{availest} which are defined differently, depending on the estimator design) and the wind farm power reference. The wind farm controller outputs the power references for individual wind turbine and an estimation of the available wind farm power.

The simulation outputs are logged and the statistics are computed in order to compare different controllers. The computed statistics include damage equivalent loads of tower and shaft and mean value and standard deviation of the power tracking error.

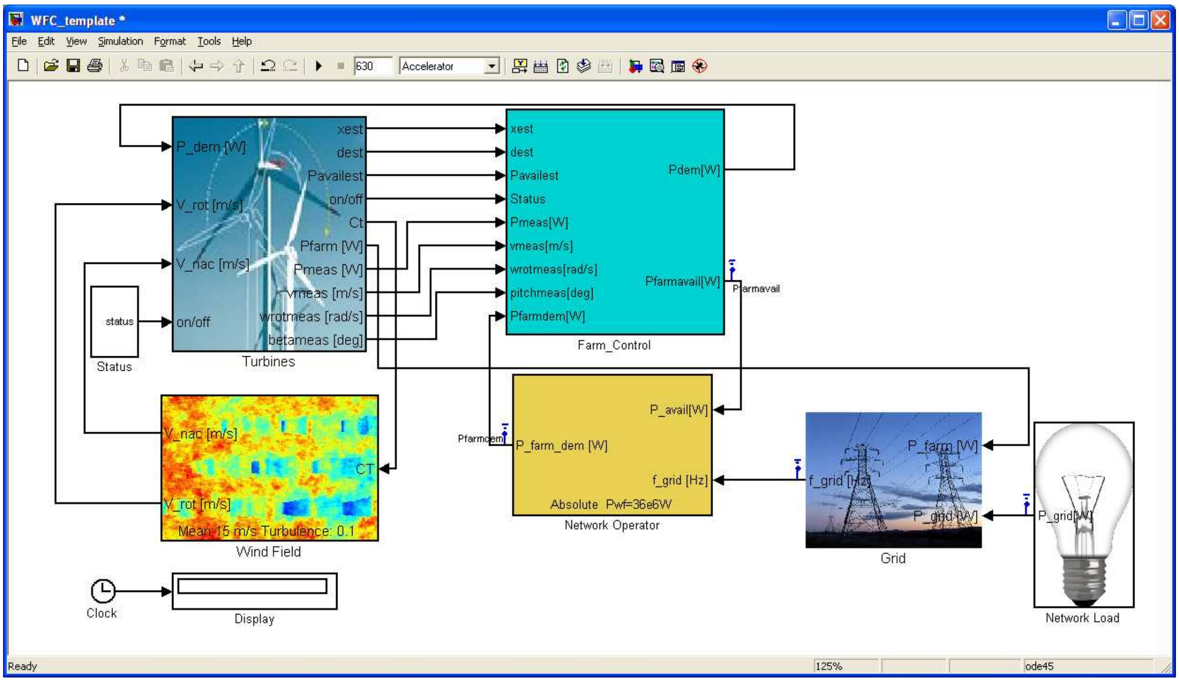

Figure 15: Wind farm controller simulator template

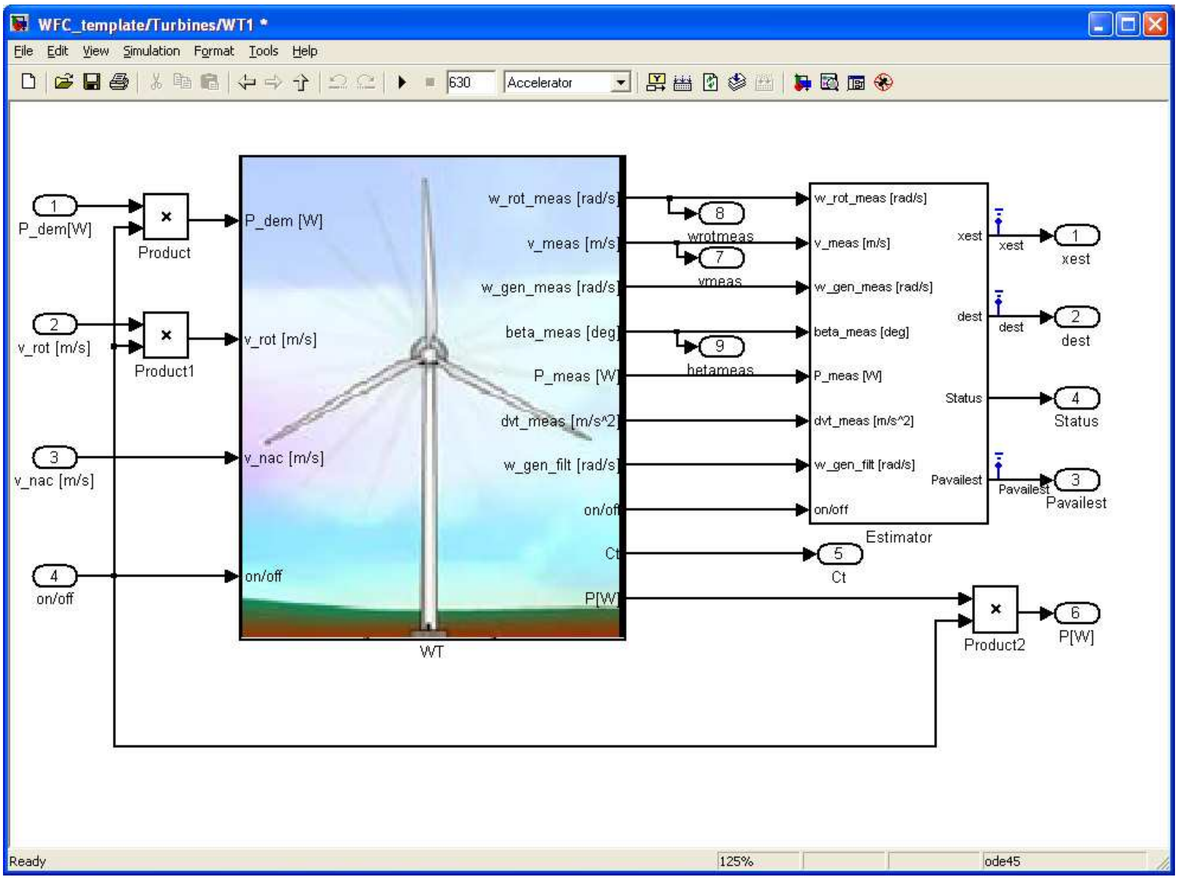

Figure 16: Template for the wind turbine block

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