TotalControl

Advanced integrated supervisory and wind turbine control for optimal operation of large Wind Power Plants

TotalControl Wind Power Plant Control Toolbox D5.11

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Document information

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Contents

ATTACHMENTS

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

4 of 33

Executive Summary

The ambition of the TotalControl project is to develop the next generation of wind power plant (WPP) control tools, improving both WPP control itself and the collaboration between wind turbine and WPP control.

This deliverable collects and briefly introduces the main tools developed, enhanced and used in the TotalControl project. This includes mathematical models, control strategies and algorithms, as well as datasets and physical devices. Some of the tools are open source, while others are not publicly available. This document summarises the main functionalities of the tools and where to find further information.

1 Introduction

TotalControl is a project funded by the European Union under the Horizon 2020 Framework [1]. The project focuses on control systems of wind turbines (WT) and wind power plants (WPP) to improve the overall performance of the WPP. This has been targeted by moving the controller design philosophy from the optimization of individual wind turbines to optimization of the entire WPP. To achieve this, the project investigates the control for maximum power production balanced with turbine loading and electricity price, reduced operational cost and to provide ancillary services to the grid. Eight partners from five countries worked together to achieve the desired results, all of which are listed in Table I.

Table I: Partners of TotalControl

Partner	Abbreviation	Country
Technical University of Denmark	DTU	Denmark
DNV		United Kingdom
Equinor		Norway
Offshore Renewable Energy Catapult	ORE	United Kingdom
Siemens Wind Power	SWP	Denmark
SINTEF Energy Research	SINTEF	Norway
University of Leuven	KUL	Belgium
Vattenfall	VF	Sweden

An important aspect of the power production are the aerodynamic turbine interactions. A turbine extracting energy from the wind causes disturbances in the downstream air, also called the wake. This wake both reduces the power production of any turbine within the wake and may cause additional structural loading and fatigue of the downstream turbines. TotalControl therefore aims at reducing the wind turbine interactions either by yaw steering, meaning rotation of the rotor to steer the wake away from downstream WTs, or by induction control, which is reducing the power extraction of any upstream wind turbine to reduce the intensity of the wake. The goal of these control actions is to increase the overall power production of the wind farm, even if they may reduce the power extraction of individual wind turbines.

The project is divided into six work packages (WP) as shown in Table II. Figure 1 visualises the work flow, where WP2, WP4 and WP3 go from high level control to low level control from top to bottom. In addition, all of these WPs receive information from WP1. WP6 is the overall management of the project and WP5 is the dissemination with the ambition of sharing the knowledge gathered in the project with the world.

Table II: Work packages of the TotalControl project to enhance wind turbine (WT) and wind power plant (WPP) control.

Work package	Title	Description
WP1	Models and tools for WPP control design and testing	Models
WP2	Open-loop quasi-static control schemes	Wind farm control, control timestep 10 - 20 min
WP3	Enhanced WT control schemes	Wind turbine control
WP4	Closed-loop dynamic control schemes	Wind farm control, control timestep < 1 min
WP5	Dissemination, communication and exploitation	Sharing knowledge and tools
WP6	Management and coordination	Project management

PROJECT
TotalControl

REPORT NUMBER
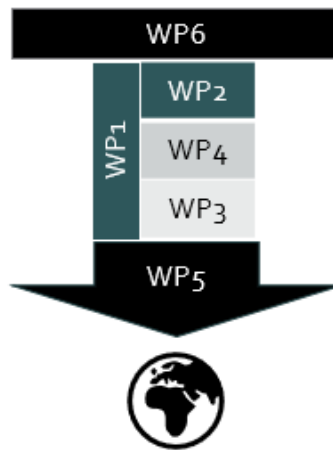D5.11

VERSION
1.0

6 of 33

Figure 1: Visualisation of work packages of the TotalControl project.

This document is a guide to the tools used, enhanced or developed during the TotalControl project. These span from models, control strategies and algorithms to datasets and physical components. Some of the tools are open source and available to the public, while others are commercial. For either, this document will advise how the tools have been utilised in the TotalControl project and where to find further information.

Three main platforms were used for testing and validation of the tools, i.e., the Total Control Reference Wind Power Plant (Section 2.1), the Levenmouth wind turbine (Section 2.2), and the Lillgrund offshore wind farm (Section 2.3). These are briefly introduced in the next section to provide the background for the description of the tools. Table III categorises the TotalControl tools and shows the structure of the remaining document.

Type	Name	Section
Measurement devices	DTU SpinnerLidar	3.1
Tools for WPP simulation and analysis	LongSim	4.1
	Static Gaussian Wake Merging Model	4.2
	Cost model for fatigue degradation and O&M	4.3
Flow databases	Precursor simulations	5.1
	Wind farm simulations	5.2
WT control strategies	Frequency support using Virtual Synchronous Machine	6.1
	Tower load reduction using active damping	6.2
WPP control strategies	Hierarchical supervisory controller	7.1

Table III: Overview of tools used, enhanced or developed in the TotalControl project for wind turbine (WT) and wind power plant (WPP) control.

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

7 of 33

2   Platforms for testing and validation

2.1   TotalControl Reference Wind Power Plant (TC-RWP)

A reference wind farm has been defined in the H2020 TotalControl project. The TotalControl reference wind power plant (TC-RWP) [2] is a virtual test bed for wind farm control. Figure 2 shows the staggered pattern of the TC-RWP with 32 wind turbines. High-resolution simulations with different atmospheric conditions and different orientations have been performed in the TotalControl project using the KU Leuven SP-Wind and the DTU EllipSys3D solver.

Apart from the layout shown in Figure 2, the electrical design of collection grid and export system has also been specified [2], [3].

Before the end of the TotalControl project, the TC-RWP has already been established as benchmark for wind farm flow models and control. It was used, for example, in the H2020 FarmConners project for both the benchmark [4] and the showcases [5].

2.2   Levenmouth turbine

The Levenmouth turbine operated by ORE Catapult was used in TotalControl to test wind turbine control strategies. The turbine from Samsung has a capacity of 7 MW.

2.3   Lillgrund offshore wind farm

The Lillgrund offshore wind farm operated by the project partner Vattenfall was available for data collection. The wind farm is located between Malmö and Copenhagen and consists of 48 wind turbines with a capacity of 2.3 MW each.
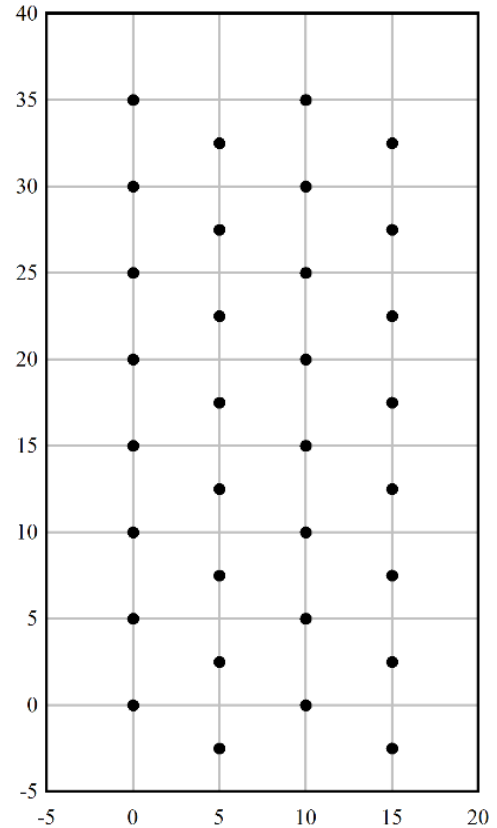

Figure 2: Layout of the TotalControl Reference Wind Power Plant [2]. Dots indicate the turbine locations. Axes are in rotor diameter.

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

8 of 33

3 Measurement devices

3.1 DTU SpinnerLidar for prevision wind and gust field measurements

Title	DTU SpinnerLidar for prevision wind and gust field measurement
Description	High resolution wind and gust field lidar, version 1.2
Developed by	DTU
Tool software	Software version 1.1
Tool file format	.spec, .spin
Related tools	Lidar-assisted control (LAC) and CFD simulations
TotalControl deliverable	D1.1, D3.5, D3.6, D3.9
Link	www.windscanner.eu https://iopscience.iop.org/article/10.1088/1742-6596/854/1/ 012021
Contact	Mikael Sjöholm, misj@dtu.dk Gunner Chr. Larsen, gula@dtu.dk

The DTU SpinnerLidar is a hardware tool that may be used for measurements of the wind inflow field or wake of wind turbines [6]. In the TotalControl project, the DTU SpinnerLidar was used for wind inflow measurements, while the wake measurements were performed using the DTU long-range WindScanner system (LRWS) [7]. Traditionally, the inflow measurements have been performed by meteorology masts at the wind farm combined with anemometers installed on the nacelle for wind speed measurements at the hub height. However, the Light detection and ranging (lidar) measures the wind flow ahead of the rotor which is more representative of the inflow wind flow field [7]. The lidar also provides the input signal in the Lidar assisted control (LAC) in the TotalControl deliverable D3.5 and the measurements are used in CFD models that estimate the rotor plane inflow.

The DTU SpinnerLidar was developed for mounting on the nacelle and in the TotalControl project, it was installed on the 7 MW Levenmouth turbine, facing forward [7]. Because of this configuration, the blades will block the scanning area. However, the internal data processing has been designed to cope with the blade passing.

The laser technology used in the lidar is based on continuous wave principles which enables a high sample rate and makes it suitable for short-range measurements (up to ~150 m) [7]. The scanner head has two optical prisms that rotate at a constant speed and use laser technology that directs light continuously and focus at discrete points in the 3D space. With use of these prisms, the wind field in TotalControl was scanned by steering the laser beam in a pattern as shown in Figure 3. The laser points from the scan are further used to reconstruct the wind vector (u,v,w) which is used in the turbine controller interface.
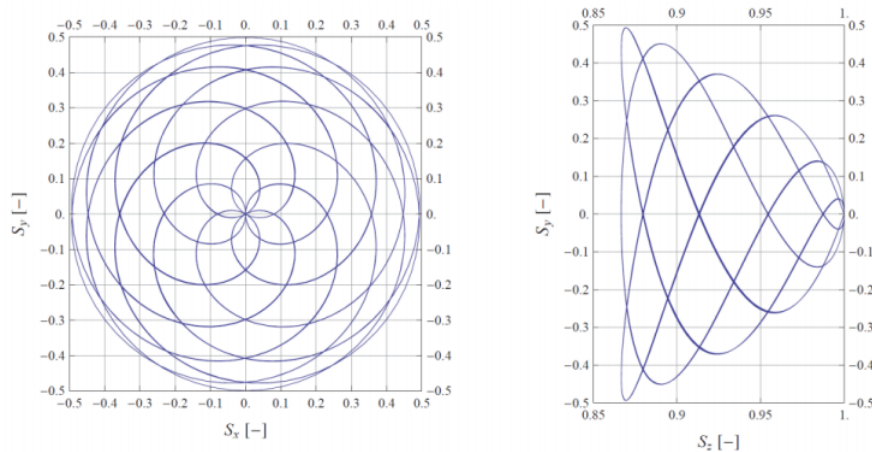

Figure 3: DTU SpinnerLidar scan pattern [7].

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

9 of 33

The DTU SpinnerLidar also has the capability of scanning at constant distance from the scanner at predefined intervals with a half angle at approximately 30°, which means that the measurements are taken at the surface of a sphere at each interval [6]. Please see Figure 4 for visualization of measurements with five scan surfaces. The full measurement of one scan surface takes 2 seconds for around 984 data points, and the refocusing between each scan surface takes about 2 seconds.
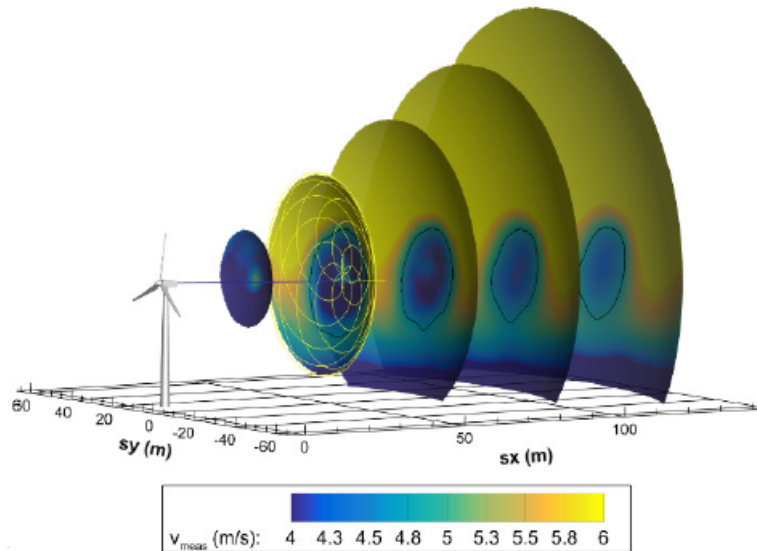

Figure 4: Scan surface of DTU SpinnerLidar [6]

The measurement output of the DTU SpinnerLidar yields two files; a .spin file which includes information about the lidar system including a special record and processed line-of-sight measurements and a .spec file that contains raw Fourier-transformed spectral data [7]. The .spin file output is shown in Table VI.

Table IV: Format of .spin files [7]

Name	Type	Description
Index	uint16	Sample number in scan pattern
Utc	int64	UTC time
Vlos	float32	Line of sight velocity estimate. NaN if no wind speed can be determined
Quality	float32	Qualtiy of the estimate. $q \in [0, 1]$ where 1 is best
Power	float32	Total power in spectrum
Azimuth	float32	The azimuth of the lidar. 0 corresponds to side where the motor is pointing upwards
Sx	float32	The x-component of the unit vector $\hat{s}$
Sy	float32	The y-component of the unit vector $\hat{s}$
Focus	float32	The focus distance in meters
Inclination	float32	Inclination of the lidar
ScalingFactor	float32	$^{\max(\text{spectrum})}/_{65535}$. Multiply spectrum with this value to obtain the original spectrum
temperature	float32	Temperature in the control box

The special record added to the .spin-file is stored with the index number 10000 [7]. This is a calculated vector and the format and content of this record is shown in Table V.

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

10 of 33

Table V: Format of the special record of .spin files, indicated by index 10000 [7]

Name	Type	Description
Index	uint16	10000
u	float32	u-component
v	float32	v-component
w	float32	w-component
Neff	Int32	Number of good point in estimate
NA	Char·32	Bytes added for correct size of record

The .spec file includes the spectrum in the format shown in Table VI.

Table VI: Format of .spec files [7]

Name	Type	Description
FftData	unit16[256]	The normalized spectrum

In addition to these outputs, the DTU SpinnerLidar has a special feature that allows for live streaming of the measured scan pattern in terms of an UDP-packet of the calculated vector. This output is shown in Table VII.

Table VII: Format of UDP-packet [7]

Name	Type	Description
u	float32	u-component of estimated wind vector
v	float32	v-component of estimated wind vector
n	Int32	The number of good measurements of estimated wind vector

Prior to the installation on the turbine, the DTU SpinnerLidar was calibrated by first using an infrared camera to capture the scanning pattern and then by scanning the area around a met mast for comparison [7]. Additionally, the measurements captured after installation on the wind turbine nacelle were compared to measurements of met masts at the site.

For further interest in the utilization of the DTU SpinnerLidar, please visit `www.windscanner.eu`, `https://www.totalcontrolproject.eu/` or contact Mikael Sjöholm or Gunner Chr. Larsen at DTU.

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

11 of 33

4   Tools for WPP simulation and analysis

4.1   LongSim

Title	LongSim
Description	Wind farm optimisation and simulation tool
Developed by	DNV
Tool software	MATLAB (can be compiled to Windows executable)
Tool file format	N/A
Related tools	D4.1-grid model KERMIT
TotalControl deliverable	D1.3-D1.9, D2.2, D2.3, D2.7, D4.1
Link	N/A, not open source
Contact	Ervin Bossanyi, ervin.bossanyi@dnv.com

LongSim is a tool developed by DNV for optimisation and simulation of wind farms and has been used for several of the deliverables in TotalControl as well as for other projects, including CL-Windcon and FarmConners. The main applications are:

- Steady-state optimisation of setpoints for wake steering and/or induction control
- Quasi-static evaluation of wind farm wake steering and/or induction control schemes
- Fast-running dynamic time-domain simulation of wind farms with wind turbine and wind farm controls

The fast-running simulation in LongSim includes wakes that are dynamically integrated in stochastic correlated wind fields which vary with time. This is matched with measured met data, and in the TotalControl project the model was validated with the use of detailed datasets from measurements at Lillgrund wind farm [8].

LongSim includes a choice of wake models and has the capability of simulating wind farm control strategies such as induction control and/or yaw misalignment [9]. The control of turbine torque and collective pitch, based on standard PI(D) controller including pitch gain scheduling, can be simulated, along with supervisory control actions such as cut-in/cut-out and yaw control.

As the name indicates, the program can run simulations for a long period of time, even for several years, despite using a relatively short timestep: for typical applications, a timestep in the range $0.1 – 10$ seconds would be chosen by the user, depending on the level of detail required. This enables the program to capture important turbine dynamics, while also providing the possibility of evaluating the performance of the wind farm control in changing environmental conditions and capturing infrequent control events [9]. To maintain simulation speed, the turbine structural dynamics are not included, but a surrogate model for the turbine loads is provided instead.

The program was originally developed for optimising the supervisory control parameters of a single turbine. However, since the combination of fast simulation time and short time step makes it ideal for wind farm control, the model has been extended to cover the whole wind farm [8]. This has been achieved by adding a wind farm controller and extending the turbine controller to respond to this, adding a dynamic model for wake effects and generating a correlated wind field over the whole farm based on actual meteorological conditions. The combination of low computational cost, short time step and simulation over long time makes LongSim well suited for testing and evaluating different wind farm control algorithms in realistic time-varying conditions. The model specifications can be seen in Table VIII.

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

12 of 33

Table VIII: LongSim model specifications [9] [8].

Parameter	Details
Computational cost	Can run wind farm with around 100 turbines in real time on typical laptop
Turbine aerodynamics	C_P and C_T given as functions of tip speed ratio, pitch angle and yaw misalignment or by power- and thrust curves
Turbine dynamics	Rotor speed, pitch & yaw degrees of freedom
Turbine control	Generator torque, blade pitch and yaw control, and supervisory control
Turbine loads	Look-up database or surrogate model fitted to results of previous aeroelastic simulations in *Bladed*
Time step	Typically ~ 1 second
Input wind data	10-minute averages from met mast, or other similar sources
Simulation length	From hours to years
Wind field	Low frequencies correlated across farm, evolving as it advects
Wake profile	Ainslie model or other Gaussian models are available, e.g. Bastankah
Wake turbulence	Quarton-Ainslie and Crespo-Hernandez models are available
Wake meandering	Driven by low-frequency turbulence in wind field
Wake advection	Driven by low frequency wind field with wake deficit modification
Wake deflection	Jímenez, Bastankah and other models are available
Wind farm control	Induction control, wake steering, coordinated yaw control etc.

To achieve this fast running model, some simplifications are made, for instance in relation to aerodynamics or turbine loads which are not included directly in the simulation [9]. Several of these simplifications are mitigated by first running detailed aeroelastic simulations of a single turbine in *Bladed*, and using the results in the LongSim simulation in terms of look-up tables or functions that are curve fitted to the data. This is the case for the turbine aerodynamics and yaw misalignment effects, and also for the turbine loading.

From the above mentioned parameters and model, the output of the tool is performance and control of each turbine with detailed information as well as the performance of control of the total wind farm [9]. Dynamic plots are available, including a contour plot of wind speeds and wakes across the wind farm which may be stored as video and time history data for many parameters. Included in the detailed outputs are the power production, time-domain and damage-equivalent loads based on the surrogate loads model and supervisory control action both overall and for each turbine.

For more information and details regarding LongSim, please see [8] and [9]. Note that LongSim is an internal program in DNV, however its capabilities are available through commercial consultancy and a commercial release of the code is in preparation. For further information and interest in LongSim, please contact DNV, contact details to Ervin Bossanyi are included above.

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

13 of 33

4.2 Static Gaussian Wake Merging Model and Three Layer Model

Title	**Static Gaussian Wake Merging Model and Three Layer Model**
Description	Wind farm simulations and interaction
Developed by	KU Leuven
Tool software	Python
Tool file format	.py
Related tools	
TotalControl deliverable	D1.8, D2.3
Link	
Contact	..., <u>...</u>

The model for delivery D1.8 consists of a fast boundary layer model called Three Layer Model (TLM) coupled with a Gaussian Wake Model (GWM) [10]. The TLM utilises a linearised background Navier-Stokes model of the atmospheric boundary layer (ABL) and in the TLM the atmosphere is divided into three layers vertically; two atmospheric boundary layers (ABL) and one layer for the free atmosphere above the ABL. The two atmospheric boundary layers consist of a lower region called the wind farm layer, where the turbine forces directly influence the wind, and a higher region that is affected indirectly by the wind farm through turbulent transport of momentum vertically. The GWM is an analytical wake merging model and accounts for the turbine wake interactions. Together, the models may account for wind farm wakes, turbine to turbine interactions, stratification effects and gravity wave effects. This model was validated by comparing results to data from Large Eddy Simulations (LES) and it showed that they are in good agreement [11].

For deliverable D2.3, the Gaussian Wake model have been extended to include the capabilities of yaw steering of individual turbines [11]. This capability is useful for fast evaluation of strategies concerning yaw steering in varying inflow conditions. In this deliverable the TLM was not utilised, as the main task was to determine yaw set points for the wind farm in various atmospheric conditions and several wind directions.

4.3 Cost model for fatigue degradation and O&M

Title	**Cost model for fatigue degradation and O&M**
Description	Quantitative influence of wind farm control on fatigue- and electrical damage and on operation and maintenance cost
Developed by	DNV
Tool software	Microsoft Excel
Tool file format	.xlsm
Related tools	-
TotalControl deliverable	D2.1
Link	-

This tool is developed in order to quantify the impact that wind farm control may have on fatigue degradation of components and equipment as well as operation and maintenance cost [12]. It is a simplified model designed to fit the Excel format, and it consists of an Excel document with the following sheets that indicate where to include the inputs and display the outputs:

1. Control & Wind (Inputs-Outputs)
2. Turbine (Inputs)
3. Failure (Inputs)
4. Wake & Damage
5. Wake Location (Display Only)

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

14 of 33

Note that this model does not include the electrical equipment discussed in the report accompanying deliverable D2.1 due to difficulties in the integration of the different models. However, please refer to [12] for discussions and background theory.

The following is a guide to the model on how to utilise this tool. For simplicity, the guide is split per sheet and will list information regarding the inputs and outputs of each sheet. This enables the possibility to fill in the Excel document one sheet at the time, but also makes it easier to navigate this guide. The model has been developed with the possibility for input of 8 turbines and the spatial coordinates for these are among the inputs. Note that this documentation will give a brief overview of the main functionality of the model. For any intermediate calculations or background theory, please refer to the report for deliverable D2.1 [12].

Sheet: Control & Wind (Inputs-Outputs)

The blue table at the top left side of the sheet marked "Notes" gives information regarding the sheet and Macro and consist of the following information:

All sheets that have "input" in the sheet title require input within the sheet.

All tables or rows that contain the word "input" and are highlighted in orange require input.

The tables with red headings or text must not be moved or removed.

Do not move or remove sheets. This will cause the macros to fail.

Anywhere it states "Instantaneous" in the sheets, the wind input velocities states in the table called "Wind inputs" is utilised.

The parameters of all the tables in this sheet is given in Table IX.

Derating inputs:
On the left hand side, the Derating inputs for each turbine may be included with the percentage of derating per freestream wind speed as given in first column. This table can be extended to any length required and any velocity values may be used as long as they are monotonically increasing [12].

Wind inputs:
This part revolves around the wind inputs. As mentioned above,the information written here is used anywhere it says "instantaneous". Please see Table IX for description of the parameters.

Cumulative power and fatigue normalised to baseline turbine:
Beware that only the row for "u inputs" shall be filled in in this table. All other fields have formulas for calculations and must not be altered. Please see Table IX for details of each parameter.

Table IX: Sheet: Turbine (Inputs) [12] - Table details

Table: Wind inputs

Parameter	Description
I_inf	The ambient turbulence and is given in percentage [%]
u_inf	The free stream wind speed of the wind farm in [m/s]
ρ	Air density [kg/m^3]
Wind direction	Direction of the wind [Deg]
Wake length	Only used for the display sheet [m]
Weibull_alpha	α in the Weibull distribution for metocean data
Weibull_beta	β in the Weibull distribution for metocean data
γ_t	Empirical constant for wake strength

Table: Cost inputs

Parameter	Description
Capital cost	Cost of each turbine when purchasing [£ per turbine]
Lifespan windfarm	Lifespan of the wind farm [y]
Strike price	Price of energy as agreed [£ / MWh]
O&M estimate	Estimated cost for operation and maintenance [£per watt per year]
Downtime estimate	Estimate of downtime over windfarm lifetime [y]

Table: Cumulative power and fatigue normalised to baseline turbine

Parameter	Description
u inputs	Wind input [m/s]
Δu	Wind speed bin width. They sum up to 25 which is the total width of wind speed range
Pr(u=U)	Probability that wind speed u will occur
P	Normalised Power
F_f	Normalised relative flapwise fatigue of the blade
F_g	Normalised relative fatigue of gearbox
F_t	Normalised relative fatigue of the tower and nacelle
F_p	Normalised relative fatigue of the pitch system
At the bottom of each of the five last parameters is a row that gives the mean for each wind speed	

Table: Display choice: 1-8 or Mean

Pick one of the turbines or the mean value to display the power and fatigue of that choice.
Also alters the graph called Cumulative Power and Fatigue of Selected Turbine explained in Table X

To the right of table Cumulative power and fatigue normalised to baseline turbine in the Excel file are two additional cells. The top one gives the mean wind speed of the inputs in the same row and the bottom shows the total probability of the wind speeds listed occurring, meaning that this is the probability that the wind speed is within the range specified in the table.

The sheet also includes a few graphs, which are explained in Table X.

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

16 of 33

Table X: Sheet: Turbine (Inputs) - Graph details.

Graph: Instantaneous Wake Boundaries in Wind Farm	
Graph made from the table given under sheet Wake Location (Display Only) and gives the wake location from each of the turbines, calculated with value from Wind Inputs from Table IX	
x-axis	The right column of y* from sheet Wake Location (Display Only). Specified in Table XVII
y-axis	The x-coordinate, given in sheet Wake Location (Display Only). Specified in Table XVII

Graph: Cumulative Power and Fatigue of Selected Turbine	
Graph showing the cumulative distribution of power and fatigue of the turbine selected under the table called display choice	
x-axis	The global freestream velocity [m/s]: [0, 2, 4, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 18, 20, 22, 24, 25] (hard coded)
y-axis	Value of the cumulative distribution normalised against baseline turbine

Graph: Power Curve for Each Turbine including Wake Losses	
This graph shows the power curve for each of the turbines, including the wake losses	
x-axis	The freestream velocity [m/s]: [0, 2, 4, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 18, 20, 22, 24, 25] (hard coded)
y-axis	Input from P per turbine ID in sheet Wake & Damage under table Wind Speed Range Results

Graph: Total Power and Fatigue of Each Turbine	
The graph gives the total power and fatigue for each of the turbine ID's for P, F_f, F_g, F_t and F_p explained in Table IX	
x-axis	Turbine ID
y-axis	Value, normalised against baseline turbine.

Sheet: Turbine (inputs):

This sheet contains details regarding the wind turbines. It consist of five tables where three require inputs and are marked with orange headings. The turbine curve inputs are generated by *Bladed* or *Windfarm*. The parameters in the different tables are presented in Table XI.

   Note that the table called "Sample layouts - paste to 'Turbine locations'" is not included in the overview because it just holds sample layouts that can be pasted into "Turbine location inputs" and therefore have the exact same descriptions.

Table XI: Sheet: Turbine (Inputs) [12].

Table: Turbine curve inputs - Generated by *Bladed* or *Windfarm*

Parameter	Description
u_∞	Freestream wind speed of wind farm [m/s]
Ω	Rotor revolutions per minute [RPM]
T_st	Static thrust [N]
P_0	Power curve production [kW]
$d\theta/du$	Gradient of pitch speed curve at current speed [deg per m/s]
T_st (averaged)	Not input. The averaged static thrust of previous and next value of T_st [N]

Table: Turbine inputs

Parameter	Description
m_b	The material coefficient for blades
m_t	The material coefficient for towers
I_des	The turbulence at the rated speed the turbine was designed to survive. Depending on type class
B	Number of blades
h	Hub height [m]
R	Blade radius, half the rotor diameter [m]

Table: Turbine constants

Parameter	Description
u_co	Cut-out wind speed of the turbine [m/s]
u_pci	Cut-in wind speed of the pitch system [m/s]
A_s	Area swept by the rotor [m^2]

Table: Turbine location inputs

Parameter	Description
ID	Turbine ID, up to eight
x	x-coordinate in Cartesian coordinate system
y	y-coordinate in Cartesian coordinate system

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

18 of 33

Sheet: Failure (inputs):

This sheet consists of the failure information of wind turbine parts. Note that in this sheet, only the columns listed as input in the right column Table XII should be changed.

Table XII: Sheet: Failure (Inputs) [12].

Table: Inputs

Parameter	Description	Type of information
Column A	Reference to the fatigue given on the first sheet, as shown in Table IX	Information
Failure type	The type of equipment that fails	Information
Consumable	If the input in CapEx / failure is 0 it will return FALSE, else it will return TRUE	Formula
Baseline failure rate	The number of failures per year	Input
CapEx/failure	Cost of each failure	Input
Downtime/failure	The downtime per failure in the unit of year	Input

Table: Failure rate

Description	Type of information
Calculated Failure rate from input parameters for each of the 8 wind turbines	Formula

Table: Lifetime Capex

Description	Type of information
Calculated lifetime Capex from input parameters for each of the 8 wind turbines	Formula

Table: Lifetime Downtime

Description	Type of information
Calculated lifetime downtime from input parameters for each of the 8 wind turbines	Formula

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

19 of 33

Sheet: Wake & Damage:

This sheet contains formulas that are used in the other sheets. The description of each parameter will be included, but only for information as the sheet should not be changed. The calculations are given in Section 7 of report for deliverable D2.1 [12]. Instantaneous Wake calculations are given in Table XIII while Instantaneous Wake calculations are given in Table XIV.

Table XIII: Sheet: Wake & Damage - Instantaneous Wake calculations [12]

Table Instantaneous Wake calculations

Parameter	Description
ID	Turbine ID
x	x-coordinate of turbine in Cartesian coordinates
y	y-coordinate of turbine in Cartesian coordinates
d	Derating of turbine [%]
T_st	Static Thrust [N]
C_t	Thrust Coefficient
k	Parameter for calculating Δu
$R\_9.6$	Radius of the wake 9.6 meters downstream. Used for calculating Δu [m]
x_0	Parameter for calculating Δu and blade radius R
c_1	Parameter for calculating Δu
x_n	Length of the near wake region [m]
n	Parameter for calculating I_wake
r_0	Parameter for calculating I_wake
m	Parameter for calculating I_wake
dr/dx	Wake growth rate
dr/dx_α	Growth rate due to ambient turbulence. Used for calculating I_wake
dr/dx_m	Growth rate due to shear-generated turbulence. Used for calculating I_wake
dr/dx_λ	Growth rate due to mechanical turbulence. Subscript τ used in [12].
λ	Tip speed ratio. τ used in [12]
Ω	Rotor speed [rad/s]
Wake from turbine ID (same input for all turbine ID)	
in wake	TRUE if the wind turbine is in the wake from the turbine ID, FALSE if its not
x	Distance between the turbine that produces wake and the influenced turbine [m]
R_w	Radius of the wake [m]
r	Radial distance from the centre of the wake [m]
Δu	Velocity behind individual turbine
Δenergy	Internal state for calculation of u
I_+	Additional turbulence
u	Wind speed upstream of the turbine [m/s]
I_wake	Total turbulence in wake
P	Power [W]

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

20 of 33

Table XIV: Sheet: Wake & Damage - Instantaneous Damage Calculations [12]

Table: Instantaneous Damage Calculations

Parameter	Description
d	Derating of turbine [%]
T_st	Static Thrust [N]
T_st (average)	The averaged static thrust of previous and next value of T_st [N]
u	wind speed at the turbine [m/s]
I_wake	Total turbulence in wake
P	Power [W]
u_pci	Cut-in wind speed of the pitch system [m/s]
dθ/du	Gradient of pitch speed curve at current speed [deg per m/s]
T_dyn	Normalised dynamic thrust [N]
F_f	Relative flapwise fatigue of the blade
F_g	Relative fatigue of gearbox
F_t	Relative fatigue of tower and nacelle
F_p	Relative fatigue of the pitch system

The table in the Excel model named "Wind Speed Range Results" is calculated using the macro called 'Looping'. Because of this macro, it is very important that any table with red head is neither moved nor removed. The wind speed goes from 0 to 25 m/s and at the end there is a column that averages the results prior.

Table XV: Sheet: Wake & Damage - Wind Speed Range Results [12]

Table: Wind Speed Range Results

Parameter	Description
u	Wind speed upstream of the turbine
F_f	Relative flapwise fatigue of the blade
F_g	Relative fatigue of gearbox
F_t	Relative fatigue of tower and nacelle
F_p	Relative fatigue of the pitch system
Average	Weibull weighted average of the row values, taking in the weibull parameters from Control & Wind (Inputs-Outputs)

This sheet also includes a few graphs for visualisation of the parameters. Please see description in Table XVI.

Table XVI: Sheet: Wake & Damage - Graph details.

Graph: Instantaneous Power of Each Turbine

Graph giving the power of each turbine taken from table Instantaneous Damage Calculations explained in Table XIV.
Derived from Wind input in Control & Wind (Inputs-Outputs) from Table IX.

x-axis	Turbine ID
y-axis	Power [W], P in Table XIV

Graph: Instantaneous Velocity of Each Turbine

Graph showing the cumulative distribution of power and fatigue of the turbine selected under the table called display choice
Derived from Wind input in Control & Wind (Inputs-Outputs) from Table IX.

x-axis	Turbine ID
y-axis	Velocity [m/s], u in Table XIV

Graph: Instantaneous Turbulence of Each Turbine

This graph shows the power curve for each of the turbines, including the wake losses
Derived from Wind input in Control & Wind (Inputs-Outputs) from Table IX.

x-axis	Turbine ID
y-axis	Turbulence intensity, I_wake in Table XIV

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

21 of 33

Sheet: Wake Location (Display Only):

This sheet displays the x- and y-coordinates of the wake at fractions of the total wake length. The wake length is decided and given as input in the sheet called Control & Wind (Inputs-Outputs). The parameters are shown in Table XVII.

Table XVII: Wake Location (Display only)

Parameter	Description
y* - left column	Fraction of wake length
y* - right column	Fraction of wake length multiplied with the length of wake from Wind inputs in Control & Wind sheet
x	Cartesian x-coordinate per wind turbine ID
y	Cartesian y-coordinate per wind turbine ID

5 Flow databases

5.1 Flow Database for reference wind farms - Part 1: Precursor simulations

Title	**Flow Database for reference wind farms - Part 1: Precursor simulations**
Description	Unsteady 3D flow data of unperturbed atmospheric boundary layer
Developed by	KU Leuven & DTU
Tool software	Python3 +hdf5
Tool file format	.hy5, .py
Related tools	Section 5.2
TotalControl deliverable	D1.4a
Link	`https://zenodo.org/communities/totalcontrolflowdatabase/` `?page=1&size=20` (SP-Wind dataset by KU Leuven) `https://data.dtu.dk/articles/dataset/Description_of_` `TotalControl_Reference_Wind_Farm_Simulations/13160606` (EllipSys3D dataset by DTU)

This tool consists of a database of unsteady 3D flow data of an unperturbed atmospheric boundary layer (without turbine influence) from high-fidelity simulations, which may be used for instance to characterise incoming atmospheric flow conditions or as input to an offline aero-elastic model [13]. The data is developed by solving 3D, unsteady and spatially filtered Navier-Stokes momentum- and temperature equations by using two numerical solvers: SP-Wind by KU Leuven and EllipSys3D by DTU.

The atmospheric conditions have been simulated both with pressure-driven boundary layer (PDBL) cases and conventionally-neutral atmospheric boundary layer (CNBL) cases. The dataset files are arranged according to Table XVIII, with the parameters given in the last column.

Table XVIII: Name of datasets from simulation cases for Section 5.1 [13]

dataset	Simulated by	Boundary Layer Theory	Parameter
PDk	KU Leuven	PDBL	$z_0 = 2 \cdot 10^{-4}$ m
PDd	DTU	PDBL	$z_0 = 2 \cdot 10^{-4}$ m
PDkhi	KU Leuven	PDBL	$z_0 = 2 \cdot 10^{-3}$ m
CNK2	KU Leuven	CNBL	$z_0 = 2 \cdot 10^{-4}$ m, $\Delta\theta = 2$ K ($h = 500$ m)
CNK4	KU Leuven	CNBL	$z_0 = 2 \cdot 10 \, 10^{-4}$ m, $\Delta\theta = 4$ K ($h = 250$ m)
CNd	DTU	CNBL	$z_0 = 2 \cdot 10 \, 10^{-4}$ m, $\Delta\theta = 2$ K ($h = 500$ m)

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

22 of 33

The full dataset consist of sets of time averaged flow variables, snapshots of the flow field and the full spatio-temporal solution fields in the fringe region, one set for each atmospheric condition explained above. Due to the size of the full data, a subset is made available in this tool. However, the full dataset may be made available upon request.

The subset from SP-Wind consists of three HDF$_5$ files as listed in Table XIX, and these are supplied for each of the specified boundary level case given in Table XVIII. In addition to the subsets, a Python script named `read_inflow.py` is provided which may be used to import, manipulate, and visualise the data.

<div align="center">Table XIX: SP-Wind dataset details [13]</div>

Filename	Details
`precursor_snapshot.h5`	Snapshot of the full velocity- and temperature field at t=75 min
`precursor_timeavg.h5`	Streamwise velocity spectra at every height, averaged over spanwise direction
	Spanwise velocity spectra at every height, averaged over streamwise direction
	Profile: Velocity components including temperature
	Profile: Reynolds stresses
`precursor_timeseries.h5`	Viritual met mast data of velocity components and temperature at 2 Hz resolution
	Cross section (yz) of velocity components and temperature at 0.2 Hz resolution
	3D box at 0.2 Hz resolution

The repository (DOI: 10.11583/DTU.13160606) contains the publicly available data created using Ellip-Sys3D and Flex5 by Niels Troldborg (ORCID 0000-0003-4508-4837, niet@dtu.dk) and Søren Juhl Andersen (ORCID 0000-0002-5935-751X, sjan@dtu.dk).

It contains both LES precursor simulation data and LES wind farm flow data. The LES wind farm flow data is organized in separate folder for each flow scenario and wind farm orientation. The layout of the TotalControl Reference Wind Farm is shown for all directions in "TotalControlReferenceWindFarmLayout.pdf", where all turbines are numbered.

The folders are named according to type of boundary layer, e.g. conventional neutral boundary layer ("cnbl"), the roughness length of for instance z0 = 2e-3 m denoted as "z02e3m", and finally the rotation of the TotalControl reference wind farm within the flow, i.e. "rot90".

The public database contains the following cases with corresponding DOI: 1. "cnblz02e3m": Precursor dataset using z0 = 2e-3 m without wind farm. DOI: 10.11583/DTU.13353161 2. "cnblz02e3m_rot00": Reference wind farm simulation using with 0 deg rotation. DOI: 10.11583/DTU.13122224 3. "cnblz02e3m_rot90": Reference wind farm simulation using with 90 deg rotation. DOI: 10.11583/DTU.13090113

Files in each folder are given the corresponding naming where "TCal" corresponds to actuator line (AL) simulations performed in TotalControl (TC), while "TCad" corresponds to actuator disc (AD) simulations. The dataset contains the following three datatypes with example names:

1. Horizontal (xy) planes of flow fields (u, v, and w) extracted at hub height in standard NetCDF format. Naming: TCal_horiz.nc

2. Vertical inflow (yz) planes of flow field (u, v, and w) extracted 1R upstream each of the 32 wind turbine (wt) in standard NetCDF format. Naming: TCal_inflow_wt01.nc

3. Time series of each of the 32 wind turbines and their performance and loads in ascii format. The files contain time, u velocity at hub height, power, flapwise bending moment, for the three blades, tower bottom bending moment fore-aft and side-side, thrust force, blade pitch, and rotational speed. Naming: TCal_wt01.dat

The precursor simulations in SP-Wind and EllipSy3D are used as input to develop the wind farm simulations in Section 5.2. The combination of these two are also used as wind flow input to the CFD models. It has been used for the validation of the model in Section 4.2.

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

23 of 33

5.2 Flow Database for reference wind farms - Part 2: Wind farm simulations

Title	Flow Database for reference wind farms - Part 2: Wind farm simulations
Description	Wind farm flow database from precursor simulations including the turbines
Developed by	KU Leuven & DTU
Tool software	Pyton3 +hdf5
Tool file format	.hy5, .py
Related tools	Section 5.1
TotalControl deliverable	D1.4b
Link	`https://zenodo.org/communities/totalcontrolflowdatabase/` `?page=1&size=20` (SP-Wind dataset by KU Leuven) `https://data.dtu.dk/articles/dataset/Description_of_` `TotalControl_Reference_Wind_Farm_Simulations/13160606` (El-lipSys3D dataset by DTU)

This toolbox contribution consists of a flow database for the TotalControl reference wind power plant shown in Figure 2. In contrast to the dataset in Section 5.1, it includes the influences from the turbines [14]. The precursor simulations from Section 5.1 are utilised as inlet conditions to the wind farm in the simulation to develop this database. The name and parameters of the inflow for the simulations are shown in Table XX.

Table XX: Precursor dataset name for simulation cases used in Section 5.2 [14]

dataset	Simulated by	Boundary Layer Theory	Parameter
PDk	KU Leuven	PDBL	$z_0 = 2 \ 10^{-4}$m
PDkhi	KU Leuven	PDBL	$z_0 = 2 \ 10^{-3}$m
CNK2	KU Leuven	CNBL	$z_0 = 2 \ 10^{-4}$m, $\Delta\theta = 2$K (h = 500 m)
CNK4	KU Leuven	CNBL	$z_0 = 2 \ 10^{-4}$m, $\Delta\theta = 4$K (h = 250 m)
CNK8	KU Leuven	CNBL	$z_0 = 2 \ 10^{-4}$m, $\Delta\theta = 8$K (h = 125 m)
CNK4	KU Leuven	CNBL	$z_0 = 2 \ 10^{-4}$m, $\Delta\theta = 4$K (h = 250 m)
CNz24	DTU	CNBL	$z_0 = 2 \ 10^{-4}$m, $\Delta\theta = 2$K (h = 500 m)
CNz23	DTU	CNBL	$z_0 = 2 \ 10^{-3}$m, $\Delta\theta = 2$K (h = 500 m)
CNz25	DTU	CNBL	$z_0 = 2 \ 10^{-5}$m, $\Delta\theta = 2$K (h = 500 m)

PROJECT
TotalControl

REPORT NUMBER
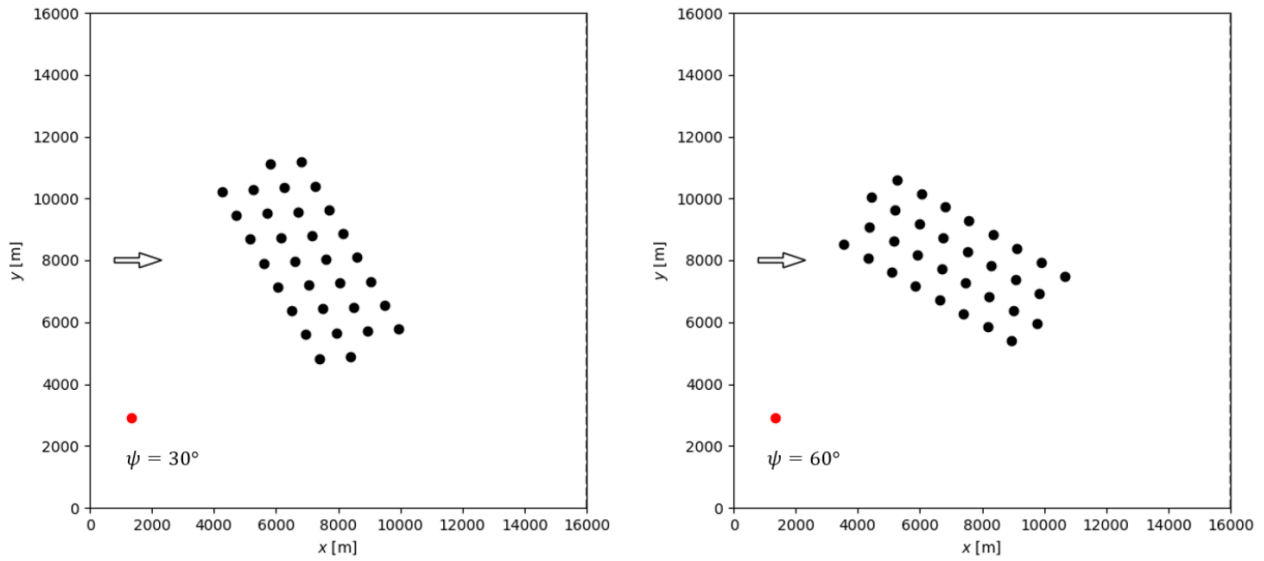D5.11

VERSION
1.0

24 of 33

Figure 5: Angle of wind farm in relation to wind heading [14]

For the wind farm simulations, each of the subsets is given a name that starts with the inflow parameters and a number that specifies the angle of the wind farm in relation to the wind heading. The rotation of the wind farm in relation to the wind is visualised in Figure 5, showing $\psi = 30°$ and $\psi = 60°$. The details and parameters of each simulation are given in Table XXI. Note that all these simulations are at turbine height, $h = 119m$.

Table XXI: Name of inflow dataset for simulation cases used in Section 5.2 [14]

dataset	Simulated by	Wind farm rotation	Parameter
PDkhi 0	KU Leuven	$\psi = 0°$	$V_\infty = 7.8$ m/s
PDk 0	KU Leuven	$\psi = 0°$	$V_\infty = 9.4$ m/s
PDk 30	KU Leuven	$\psi = 30°$	$V_\infty = 9.4$ m/s
PDk 90	KU Leuven	$\psi = 90°$	$V_\infty = 9.4$ m/s
CNk2 30	KU Leuven	$\psi = 30°$	$V_\infty = 11$ m/s
CNk2 60	KU Leuven	$\psi = 60°$	$V_\infty = 11$ m/s
CNk4 30	KU Leuven	$\psi = 30°$	$V_\infty = 11.3$ m/s
CNk4 90	KU Leuven	$\psi = 90°$	$V_\infty = 11.3$ m/s
CNk8 0	KU Leuven	$\psi = 0°$	$V_\infty = 11.4$ m/s
CNk8 90	KU Leuven	$\psi = 90°$	$V_\infty = 11.4$ m/s
CNz23 00	DTU	$\psi = 30°$	$V_\infty = 10.5$ m/s
CNz23 90	DTU	$\psi = 90°$	$V_\infty = 10.5$ m/s
CNz24 00	DTU	$\psi = 0°$	$V_\infty = 11$ m/s
CNz24 30	DTU	$\psi = 30°$	$V_\infty = 11$ m/s
CNz24 45	DTU	$\psi = 45°$	$V_\infty = 11$ m/s
CNz24 60	DTU	$\psi = 60°$	$V_\infty = 11$ m/s
CNz24 90	DTU	$\psi = 90°$	$V_\infty = 11$ m/s
CNz25 00	DTU	$\psi = 0°$	$V_\infty = 11.6$ m/s
CNz25 90	DTU	$\psi = 90°$	$V_\infty = 11.6$ m/s

The subset of the dataset from KU Leuven consists of the files shown in Table XXII. In addition to these, some sets of Python scripts follow to import, manipulate and visiulize data like `plot_3D_plot.py` and `plot_field.py`

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

25 of 33

Table XXII: SP-Wind dataset details [14]

Filename	Details
`precursor_snapshot.h5`	Snapshot of the full velocity- and temperature field at t=75 min
`turb_timeavg.h5`	Turbine performance: Aerodynamic performance data for all turbines at 1 Hz resolution
	Turbine performance: Aeroelastic data for all turbines at 100 Hz resolution
`cross_sections_timeseries.h5`	Cross section (xy) of velocity components including temperature at z=119 m at 0.2 Hz resolution
	Cross section (xz) of velocity components including temperature at top row of turbines at 0.1 Hz resolution
`field_snapshot.h5`	Velocity data in a 3D box around a turbine at 1 Hz resolution for the last 15 min of simulation

The flow databases developed in Section 5.1 and in this section can be used as input to WPP simulations. For more detailed information, please refer to TotalControl D1.4b [14].

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

26 of 33

6 Wind turbine control strategies

6.1 Primary frequency and voltage support

Title	Control algorithms for primary frequency and voltage support
Description	Ancillary services: Frequency support using Virtual Synchronous Machine (VSM)
Developed by	SINTEF Energy Research
Tool software	Simulink
Tool file format	.mdl
Related tools	Task D4.1
TotalControl deliverable	D3.2
Link	
Contact	Salvatore D'Arco, salvatore.darco@sintef.no
	Santiago Sanchez Acevedo, santiago.sanchez@sintef.no

This tool explores the use of virtual synchronous machine (VSM) to control the active power by an internal inertia model in wind turbines to achieve fast frequency support to the grid [15]. The VSM will provide inertia support and have grid forming capabilities [16]. The tool consists of a model and a file with the required parameters and configuration to run together. It was made for TotalControl deliverable D3.2 and further developed and validated in TotalControl deliverable D4.1 [15].

For the model, an ac ac converter consisting of a rectifier, dc link and inverter is utilised as shown in Figure 6. The VSM must be implemented on the grid side converter to provide fast frequency response to the grid [15] [16]. There were two options for the implementation of the VSM; VSM converter controlling the dc bus voltage or the VSM converter controlling the power extraction. Both of these schemes were tested in D3.2. When the VSM converter is controlling the power extraction, the generator side will control the dc bus voltage meaning that the turbine rotor- and generator inertia can contribute to the grid side, which will not be possible if the VSM converter is controlling the dc bus voltage. This is partly the reason for choosing the VSM converter controlling the power extraction during model validation in D4.1 [16].
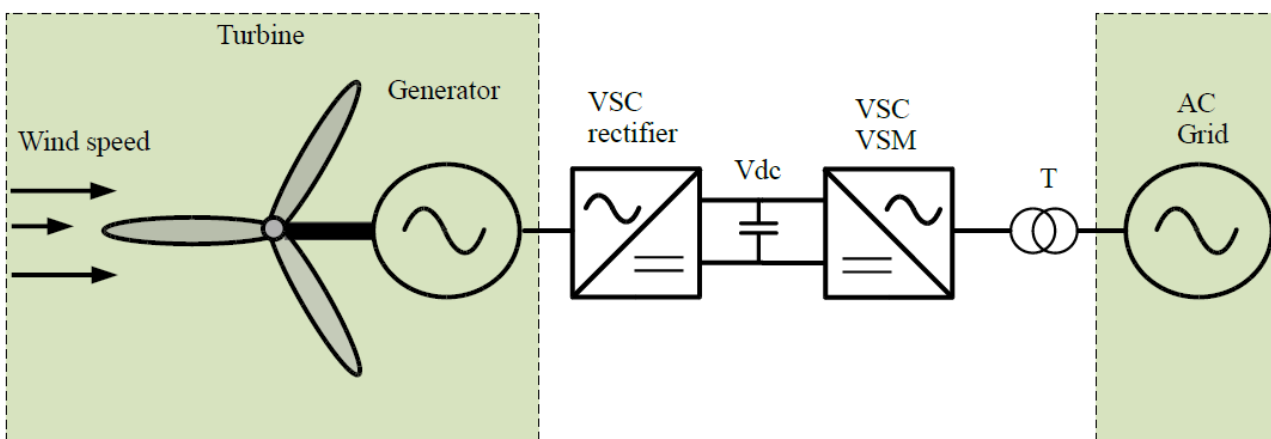

Figure 6: Overview of the wind turbine conversion system [16].

For deliverable D3.2, a numerical simulation was first run to test different schemes with a simplified model of the wind turbine operating at optimal speed for maximum power generation [15]. Afterwards, numerical simulations with a complete wind turbine model were performed. For simplicity, the VSM was operating with a constant damping term and the droop gain removed. The frequency change required to test the fast frequency response by VSM was produced by increasing the active power load by 25 MW after 30 seconds of simulation.

PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

27 of 33

All simulations assumed a 6 m/s wind speed and with 12% rated power production. The simulations were performed with inertia time constant, τ_{vsm}, between the low value of 0.5 s and a high value of 8 s as shown in Table XXIII.

Table XXIII: The inertia time constant used in numerical simulations for D3.2 [15].

Parameter						
Inertia time constant no	1	2	3	4	5	6
τ_{vsm}	0.5 s	2 s	3.5 s	6 s	6.5 s	8 s

In the simulation with the simplified wind turbine model, two typologies control structures of the virtual synchronous machine (VSM) were investigated, namely Voltage Control VSM and Current control VSM [15]. Additionally, for the current control, the armature reactance of the machine was modelled both with a dynamic model and a quasi-stationary model. An overview is shown in Table XXIV.

Table XXIV: Types of VSM algoritms tested [15].

Name	Control Structure	Model type
VCVSM	Voltage Control VSM	-
CCVSM-QSEM	Current Control VSM	Quasi-stationary electrical model
CCVSM-DEM	Current Control VSM	Dynamic electrical model

The results from the first simulation indicated that the CCVSM-QSEM has better stability than CCVSM-DEM, especially for larger constants, as the power ripples were found to be smaller [15]. It also gave indication that the dependence of the VSM was smaller for the VCVSM model than for CCVSM since the power oscillations was a bit bigger for VCVSM model. Overall, CCVSM-QSEM performed the best, although with small margines.

In the numerical simulations with a complete wind turbine model only the CCVSM-QSEM was tested [15]. The results gave an indication of risks and limits of using VSM, especially regarding control interactions. It also became apparent that the tuning is important for avoiding instabilities.

For deliverable D4.1, the validation was performed by the use of power hardware in the loop (PHIL) consisting of two converter units and real-time simulation models for grid, wind turbine and control algorithms for the VSM converter, the latter with a fixed time step of 100 µs [16]. Although the model was originally developed with three different strategies for implementation of the VSM, CCVSM-QSEM was used during the validation [16] since it performed better in the numerical simulations for deliverable D3.2 [15]. Additionally, the VSM converter were set to control the power extraction because it was difficult to achieve significant inertia support from the VSM when it controlled the dc voltage.

The setup used in the validation is shown in Figure 7 [16]. The dc connection of the two voltage source converters (VSC) are shown in blue, while on the ac side they are connected to a grid emulator unit via two transformers. The transformers are included for galvanic isolation and do not alter the voltage level. The green line indicates a fibre optic link to the real-time simulator.

PROJECT
TotalControl

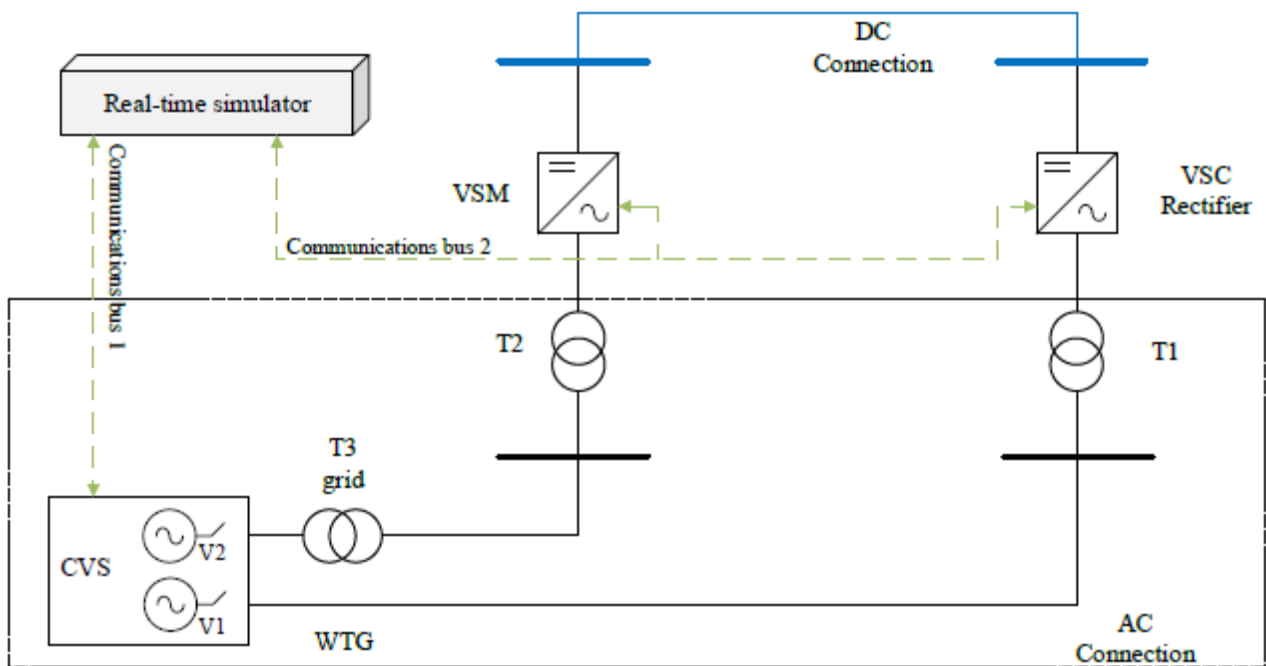REPORT NUMBER
D5.11

VERSION
1.0

28 of 33

Figure 7: Laboratory single line diagram of the connections in the validation experiment [16].

During validation of the model in D4.1, several tests were run. Firstly, the system response characterisation of power production changes in the wind turbine was tested and showed that the power from the VSM and rectifier converter closely follow the power change with a negligible speed variation [16]. The second test was included to test the inertia support to the grid frequency variations and was performed by inducing two different frequency steps to the system, both quite large. It revealed that the inertia support did not contribute significantly, with only a few percentage of the kinetic energy transferred to the grid. Next, a test was performed both with and without a feedforward term in the VSM model, which had been included for better link between power reference change and the power injected to the grid. With the feedforward term, the response was faster, more damped and there were less transient oscillations. Subsequent tests evaluated the value of a backtracking coefficient which was added to reduce the wind-up in the integrator for the speed PI-controller to avoid possible overshoot of speed and resulting power oscillations. The results showed that the backtracking term do prevent these issues. Lastly, the response to the power load variations in the grid was tested, both with and without inertia support and showed that the VSM can reduce the rate of change of frequency and improve the minimum value of frequency during transients.

Further information may be found in the TotalControl reports for deliverable D3.2, [15], and D4.1, [16]. The model may be reproduced from the information shared in the report for deliverable D4.1 which also includes a more detail explanation of the setup of the validation test and system parameters. Report for deliverable D3.2 includes the parameters used for each of the components within the model. Note that the above mentioned models were not developed with the intent of sharing and they are dependent on SINTEF internal library of converters. Due to this, the model will not be made available as open source model to the offshore wind community.
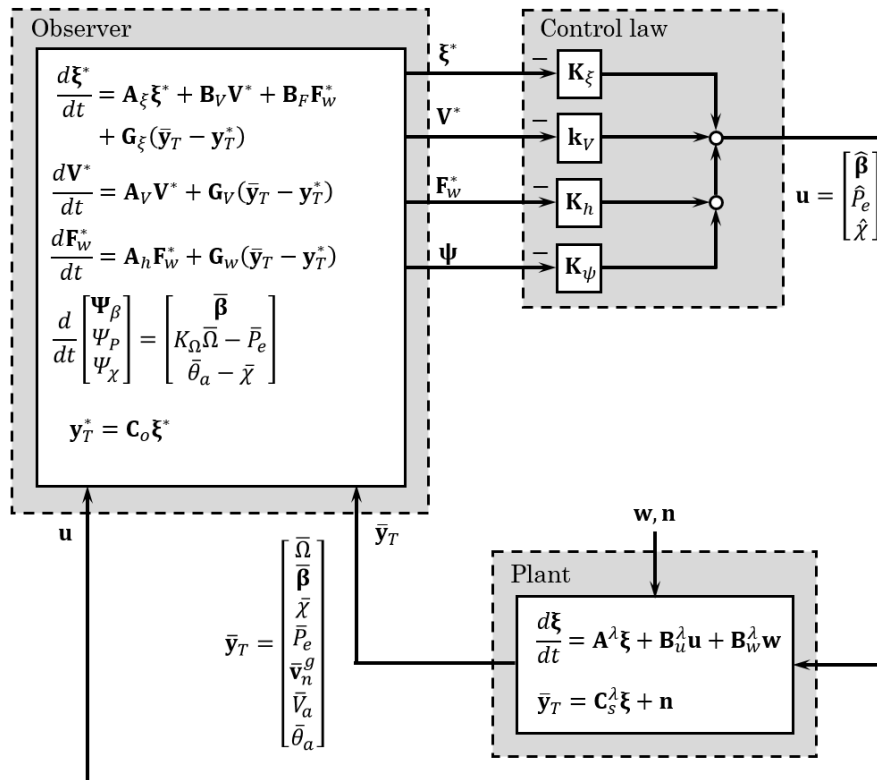
PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

29 of 33

Figure 8: Block diagram of the wind turbine controller for tower load reduction [18].

6.2   Tower load reduction using active damping

Title	Tower Load Reduction Using Active Damping
Description	Wind turbine control
Developed by	SINTEF Energy Research
Tool software	MATLAB/Octave
Tool file format	.m
Related tools	D4.2
TotalControl deliverable	D3.3
Link	`https://github.com/SINTEF-Energy-Wind/STAS-WPP`

This tool consists a framework for linear-quadratic (LQR) control synthesis developed with STAS [17]. The tool was applied to case studies involving directional control of fatigue in monopile foundations, and active damping of wave-driven tower resonance when the turbine is idling.

The control framework is shown in **??**. The controller itself consists of an observer, which estimates the states of the plant (wind turbine); and a control law, which applies some gain to each of the states, the output being the blade pitch, electric power, and yaw angle commands sent to the wind turbine. In turn, the turbine provides sensor measurements to the observer: rotor speed, blade pitch, yaw angle, electric power, nacelle velocity (or acceleration), anemometer wind speed, and anemometer wind angle. These are the sensors that are typically available for use in the control of a modern offshore wind turbine. The observer in **??** is based on a high-order (around 300 state variables) model of the wind turbine. The controller can then be reduced in order after finding the optimal gains: the approach is "top-down". This differs from the usual "bottom-up" approach to LQR control, based on a low-order wind turbine model with perhaps 10 state variables. The top-down approach has more freedom and may find control actions that are not visible with the simpler model.
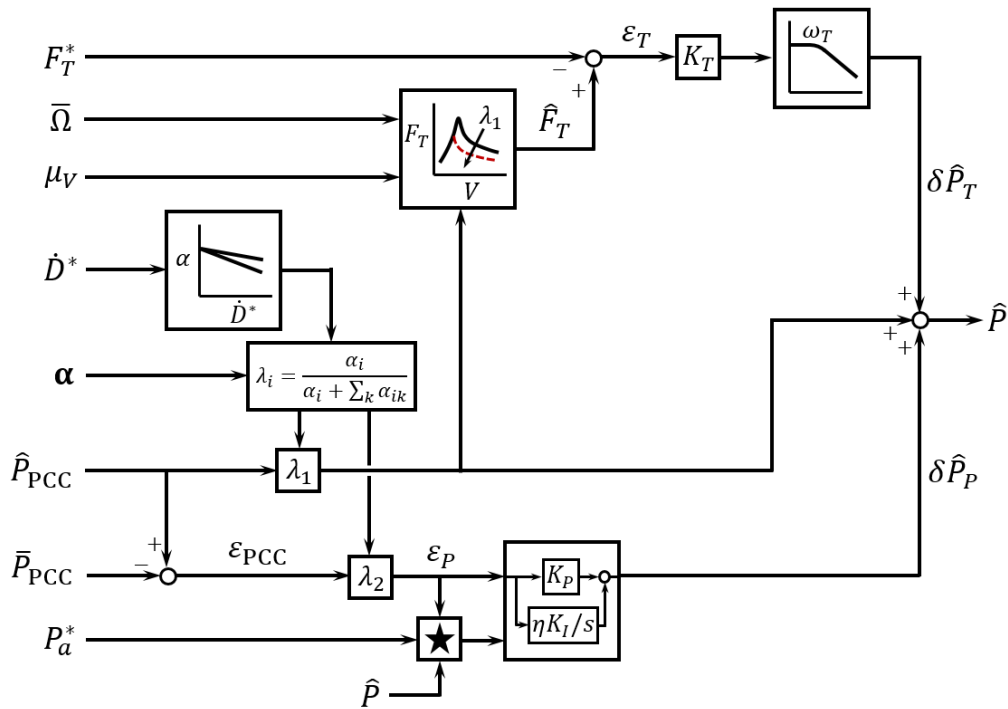
PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

30 of 33

Figure 9: Architecture of the hierarchical wind power plant supervisory controller [19].

7 Wind power plant control strategies

7.1 Hierarchical Wind Power Plant Supervisory Controller

Title	Hierarchical Wind Power Plant Supervisory Controller
Description	WPP control strategy trading the provision of ancillary service with structural load reduction and actuator wear
Developed by	SINTEF Energy Research
Tool software	MATLAB/Octave
Tool file format	.m
Related tools	TC-RWP, D3.3
TotalControl deliverable	D4.2
Link	`https://github.com/SINTEF-Energy-Wind/STAS-WPP`

The developed hierarchical WPP controller is a baseline plant controller that uses only typically available SCADA data. The two control objectives of power tracking and thrust compensation are targeted by an architecture of proportional-integral (PI) control shown in Figure 9. A proportional-integral (PI) controller provides power command tracking, and a proportional controller with low-pass filter provides thrust compensation. Although the two control objectives may conflict, the structure of the controller ensures that power command tracking will prevail and dominate the response. By that, it is ensured that the plant can meet grid code requirements. A large number of wind turbines allows an effective thrust compensation.

The performance of the controller is illustrated in Figure 10 for the TC-RWP, where damage rates were randomly assigned to the wind turbines. Compared to the reference WPP operation in grey with equally dispatched power set-points, the standard deviation in low-frequency thrust fluctuations is significantly reduced for most turbines while it is increased for a few. In particular, the thrust for those with high damage rates (here above 0.3) is reduced at the cost of those with low damage rates, demonstrating the capability of compensating the thrust
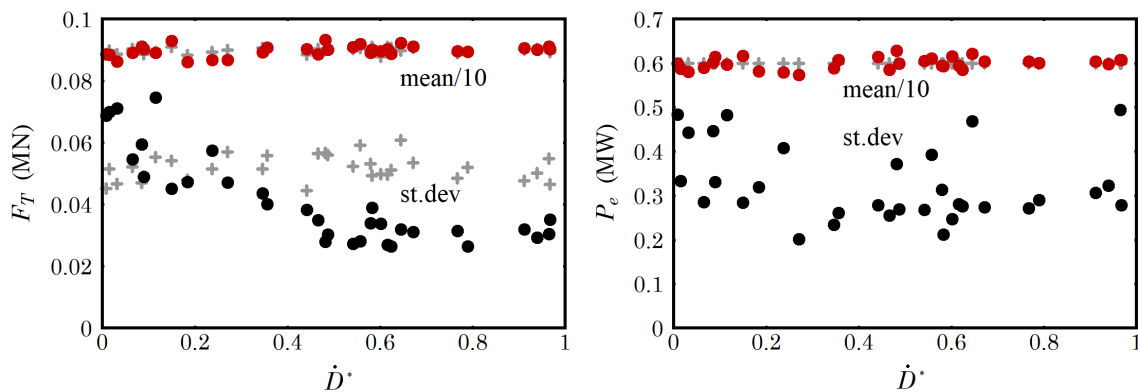
PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

31 of 33

Figure 10: Mean (red) and standard deviation (black) of thrust (F_T) and power (P_e) fluctuations with the hierarchical wind power plant controller, as a function of normalised damage rate ($\dot{D}^*$). Each point represents one turbine in the TotalControl Reference Wind Power Plant. Nominal results for the case with a constant, uniform power command sent to all the turbines are shown in the background as grey crosses [19].

equally over the plant.

8   Summary

The tools developed and enhanced in TotalControl cover different aspects of wind farm control. This includes hardware for field measurements that provide input to the control system, high-fidelity simulation models and flow datasets, ancillary services, aspects of O&M, algorithms for WT control, as well as static and dynamic WPP control.

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PROJECT
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32 of 33

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PROJECT
TotalControl

REPORT NUMBER
D5.11

VERSION
1.0

33 of 33

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