TotalControl

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

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EXECUTIVE SUMMARY

This report lists the main tools, algorithms and methodolgies developed by the partners within the project and the exploitation strategy of these.

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 interaction between wind turbine and WPP control.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. The TotalControl Wind Power Plant Control Toolbox (D5.11) summarises the main tools developed by partners within the project.

In the below part of the report a short introduction is made and hereafter the main tools, algorithms and methodologies are listed. The report concludes with an overview of the different platforms on which the tools are being disseminated both actively and passily.

TOOLS DEVELOPED WITHIN THE PROJECT

1.1 Introduction to the project

TotalControl is a project funded by the European Union under the Horizon 2020 Framework. The project focuses on control systems of individual wind turbines (WTs) and WPPs to improve the overall performance of the WPP. This has been targeted by moving the controller design philosophy from the optimization of individual WTs 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.

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.

To acheive this the following tools, algorithms and methodologies listed in Figure 1, have been developed by the partners within the partnership.

Figure 1: Tools, algorithms and databases resulting from TotalControl.

Name	Type
TotalControl Reference Wind Power Plant	Platform for testing and validation
Levenmouth turbine	Platform for testing and validation
Lillgrund offshore wind farm measurememts	Platform for testing and validation
DTU spinner lidar for prevision wind and gust field measurement	Measurement device
LongSim	Tools for WPP simulation and analysis
Fuga	Tools for WPP simulation and analysis

Static Gaussian wake merging model and three layer model	Tools for WPP simulation and analysis
Cost model for fatigue degradation and O&M	Tools for WPP simulation and analysis
Flow database for reference wind farms – part 1: Precursor simulations	Flow databases
Flow database for reference wind farms – part 2: Wind farm simulations	Flow databases
Optimal open-loop WPP control schedules	WPP control strategies
Primary frequency and voltage support	Wind turbine control strategies
Tower load reduction using active damping	Wind turbine control strategies
Hierarchical Wind power plant supervisory controller	Wind power plant control strategies

The tools, algorithms and methodologies listed above represent the main contribution in terms of tools to be exploited further.

Description and exploitation of the tools, methods and algorithms

2.1 Explotation strategy for tools, algorithms and methods and its future use

Cost of energy (COE) is the most important single factor in deployment of renewables in the energy system. Reduction of COE is, among other things, directly related to operational control of Wind Power Plants (WPP) as a whole and the individual wind turbines (WT) within them. In the Total Control project the COE reduction has been pursued by developing and validating advanced integrated WPP/WT control schemes, where all essential interactions between the WPP WT's are accounted for.

The strategy is to use the tools and results of the project to improve wind farm performance and thereby reduce the cost of energy.

TotalControl Reference Wind Power Plant

Description: The TotalControl Reference Wind Power Plant (TC RWP) is an idealized, regular layout with a dense spacing of 32 turbines in a staggered pattern. The number of turbines results from a compromise between limiting the computational cost of high-resolution flow simulations and having an array that is large enough to be relevant as an offshore wind power plant. It is intended for studies involving high-fidelity flow analyses, and suited for investigating how plant control can make possible denser layouts, with better utilization of concession areas. TC RWP is designed with symmetry in order to facilitate high-resolution numerical flow simulations. For scientific work intended for open publication, the IEA/DTU 10 MW Reference Wind Turbine (RWT) was used. Besides wind turbine layout, the TC RWT also includes design of the wind power plant grid consistent with the EERA DTOC inter-array design procedure. It consists of two strings of 7 turbines, and 3 strings of 6 turbines. Branching reduces the overall length of the thickest (500 mm2) cable. The inter-array grid voltage is 66 kV, which is foreseen as the standard for the next generation of offshore wind power plants, with turbines approaching a 10 MW rating. The electrical substation contains two 66/220 kV transformers rated at 180 MVA each. The AC system frequency is 50 Hz.

Contacts: Søren J. Andersen, sjan@dtu.dk; Johan Meyers, johan.meyers@kuleuven.be

Details: Andersen, S.J., Madariaga, A., Merz, K., Meyers, J., Munters, W. and Rodriguez: Reference Wind Power Plant - TotalControl deliverable D1.3, 2018.

Levenmouth turbine

Description: The field tests on the 7MW Levenmouth demonstration turbine have produced very valuable datasets, with concurrent turbine SCADA and LiDAR wake scan information, which is intended to be further analysed in order to validate e.g. models for wake centreline deflection and velocity deficit for turbines operating in yaw.

Contacts: Paul McKeever, paul.mckeever@ore.catapult.org.uk; Elliot Simons, ellsim@dtu.dk

Lillgrund offshore wind farm measurements

Description: the TotalControl project has resulted in a unique set full-scale of wind farm measurements including lidar-based flow field recordings and associated wind turbine SCADA data. The Lillgrund offshore measurement campaign was carried out between September 2019 - February 2020. Three long-range DTU WindScanners (i.e. pulsed scanning Doppler wind LiDARs) were installed on Lillgrund wind turbine transition pieces and used to measure the flow field both upstream and within the farm. The resulting processed data formats are easy to work with and traceable- due to the inclusion of the raw data and program codes used to generate the final data products.

Contacts: Elliot Simons, ellsim@dtu.dk; Gunner Chr. Larsen, gula@dtu.dk

Details: Simons, E.: Lillgrund measurement campaign dataset - TotalControl deliverable D 1.1, 2021.

DTU spinner lidar for prevision wind and gust field measurement

Description: The field measurements are particularly useful for further development, and particularly for validation, of KUL's, DTU's and DNV's wake modelling capabilities. The LiDAR scan data from Lillgrund wind farm is expected to be very useful for validation of several aspects of the wake models, which is used for wind farm control design and simulation testing.

Contacts: Mikael Sjöholm, misj@dtu.dk; Gunner Chr. Larsen, gula@dtu.dk

Details: High resolution wind turbine wake measurements with a scanning lidar - IOPscience.

LongSim

Description: As well as already using the LongSim code for commercial projects on wind farm control, DNV is considering the best way to make the code itself available externally, thus taking commercial application of wind farm control to a new level.

Contacts: Ervin Bossanyi, ervin.bossanyi@dnv.com

Link: N/A - not open source

Fuga

Description: Fuga is a linearized CFD RANS model, which, popular speaking, is one million times faster than a conventional non-linear CFD RANS solver, and therefore eminently suited for wind farm control optimization, where a very large number of wind farm flow field computation inevitable needs to be simulated. Wind turbines are modelled as actuator discs. Non-homogeneous force distribution over the rotor disc can be specified, and the solver can also handle yawed wind turbines; thus in addition to turbine de-rating supporting wake deflection type of wind farm control.

Contacts: Gunner Chr. larsen, gula@dtu.dk

Details: Ott, S., van der Laan, P. and Larsen, G.C.: Upgrade of Fuga - TotalControl deliverable D 1.7, 2019.

Static Gaussian wake merging model and Three Layer Model

Description: The Three Layer Model (TLM) is a fast boundary layer model, which is coupled with a Gaussian windfarm force model to enable faster study of wind farm response in different atmospheric conditions. The TLM code utilizes a Gaussian Wake Merging (GWM) approach to represent the wind farm forces in the domain, and it is coupled to a linearized background Navier–Stokes model of the ABL that allows for a representation of boundary-layer development over the wind farm, stratification effects, and gravity waves. Comparison of the wind farm power output of the TLM and CFD LES results, as based on the TotalControl Reference Wind Power Plant, show very good agreement, with total wind farm power output and the trends of the power reduction across the windfarm rows matching well between the two codes.

Contacts: Johan Meyers, johan.meyers@kuleuven.be

Details: Sood, I., Meyers, J., and Lanzilao, L.: Coupling of Gaussian wake merging to background ABL model - TotalControl deliverable D 1.8, 2020.

Cost model for fatigue degradation and O&M

Description: A number of basic models that can be used to quantify the relation between loads, degradation and O&M costs are presented and discussed along with cost models for fatigue degradation and O&M of mechanical and electrical components. Further, selected basic and component models are used together in a wind farm cost model which enables estimation of the influence of turbine control on the LCOE and profit of a wind farm. The main focus is on the corrective maintenance cost models, but also the other models are discussed. Regarding degradation of electrical components, models are presented for converters and transformers. Based on developed/selected mechanical and electrical component sub-models, a cost model for an entire wind farm is developed. Facilitating estimates of the influence of turbine control on the energy production, the loads on different components, the O&M costs, and finally the LCOE and profit of a wind farm. The model is implemented as a MS Excel based tool including wake turbulence and wake deficits. It quantifies the impact on fatigue damage and power capture and subsequently translates these effects into increase/decrease of failure rates of components and the costs.

Contacts: Salvatore D'Arco, salvatore.darco@sintef.no

Details: D'Arco, S., Evans, M., Foros, J., Natarajan, A. and Welte, T.: Cost model for fatigue degradation and O&M - TotalControl deliverable D 2.1, 2018.

Link: MS Excel based tool

Flow database for reference wind farms – part 1: Precursor simulations

Description: The turbulent inflow conditions for wind-farm inflow are simulated using state-of- the-art CFD LES solvers (SPWind, Ellipsys) and stores as publicly available precursor data in the TotalControl Flow database (Munters et al., 2019). The precursor data contains unsteady three-dimensional flow data of an unperturbed atmospheric boundary layer (i.e. without the influence of turbines). The database comprises of two Pressure Driven Boundary Layers (PDBL) and three Conventionally Neutral Boundary Layers (CNBL), spanning different surface roughness lengths and boundary layer heights.

Contacts: Johan Meyers, johan.meyers@kuleuven.be; Søren J. Andersen, sjan@dtu.dk

Links: Munters, W., Sood, I., and Meyers, J.: Precursor dataset PDk, https://doi.org/10.5281/zenodo.2650100, 2019; Munters, W., Sood, I., and Meyers, J.: Precursor dataset PDkhi, https://doi.org/10.5281/zenodo.2650102, 2019; Munters, W., Sood, I., and Meyers, J.: Precursor dataset CNk2, https://doi.org/10.5281/zenodo.2650096, 2019; Munters, W., Sood, I., and Meyers, J.: Precursor dataset CNk4, https://doi.org/10.5281/zenodo.2650098, 2019.

Flow database for reference wind farms – part 2: Wind farm simulations

Description: The aeroelastic LES solvers SP-Wind (KUL) and Ellipsys (DTU) has been used to simulate the operation of the Lillgrund wind farm during the full-scale measurement campaign (cf. Lillgrund offshore wind farm measurements). First, the atmospheric conditions at the Lillgrund site are recreated in the numerical domain by analyzing incoming flow field LiDAR measurements. Second, instead of initializing the flow field from scratch, this work proposes a framework for reusing a previously generated precursor flow database for matching the conditions during the measurement campaign, substantially reducing the associated computational costs and time for LES wind farm validation studies.

Contacts: Søren J. Andersen, sjan@dtu.dk; Ishaan Sood, ishaan.sood@kuleuven.be; Johan Meyers, johan.meyers@kuleuven.be

Details: Andersen, S.J., Bernard, V., Beudet, V., Da Costa, L., Deglaire, P., Meyers, J. Sood, I. and Troldborg, N.: Validation of high-fidelity models against Lillgrund wind-field and load data - TotalControl delivarable D 1.2, 2021. Sood, I., Simon, E., Vitsas, A., Blockmans, B,. Larsen, G.C. and Meyers, J.: Comparison of Large Eddy Simulations against measurements from the Lillgrund offshore wind farm. https://doi.org/10.5194/wes-2021-153.

Optimal open-loop WPP control schedules

Description: Together with Vattenfall and Siemens, DTU and DNV is pursuing further gains in productivity of the full-scale offshore wind farm Lillgrunden. This is done using optimal open-loop wind farm control schedules 'designed' using the numerical tools Longsim (DNV) and Fuga (DTU). More specifically, the one-row demonstration/validation case designed and implemented and analyzed in the context of TotalControl - for a specific inflow sector - will be further consolidated by being extended to the entire wind farm consisting of 48 wind turbines and all wind directions. Thus, an optimal wind farm control schedule, conditioned on ambient wind speed and wind direction, will be developed and implemented as basis for a measuring campaign extending over several months.

Contacts: Gunner Chr. Larsen, gula@dtu.dk

Details: Bossanyi, E., Larsen, G.C., Ruisi, R. and Pedersen, M.M.: Validation of optimized control schemes - TotalControl deliverable D 2.7, 2022.

Primary frequency and voltage support

Description: Special features are added to wind plant controllers so that they can actively contribute to the stable operation of the electricity grid system and make it possible for larger penetrations of wind power to be integrated. Overtview of relevant grid codes are given, and subsequently it is described how wind farms may contribute to both grid frequency and voltage stability. Regarding grid frequency support, it is demonstrated how control algorithms implemented at the wind turbine level can be used for frequency support. A wind farm simulator and a grid simulation code are coupled together, thus permitting time-domain simulations of an entire grid system to be performed.

Contacts: Ervin Bossanyi, ervin.bossanyi@dnvgl.com; salvatore D'Arco, salvatore.darco@sintef.no

Details: Bossanyi, E., D'Arco, S., Lu, L., Madariaga, A., de Boer, W. and Achoot, W.: Control algorithms for primary frequency and voltage support - TotalControl deliverable D 4.1, 2020.

Tower load reduction using active damping

Description: Tradeoffs between production (revenue), structural loading, and actuator wear is studied in the context of control of an offshore wind turbine. A framework for linear-quadratic (LQR) control synthesis is developed and applied to case studies involving directional control of fatigue in monopile foundations as well as active damping of wave-driven tower resonance when the turbine is idling. 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.

Contacts: Konstanze Kölle, konstanze.kolle@sintef.no

Link: https://github.com/SINTEF-Energy-Wind/STAS-WPP

Hierarchical Wind power plant supervisory controller

Description: The aim is maximise the revenue rather than maximising the power production. The reduction of structural loading and actuator wear and the provision of ancillary services will therefore be important in this context. Thus, there is a need for plant control strategies that trade these control objectives and respect the industrial practice, where the different levels in the hierarchy may be provided by different equipment vendors. A setup for a baseline plant controller is developed that uses only typically available data from the turbines' SCADA system. The plant controller is coupled to an observer that provides state estimates at the wind farm turbines. The control achitecture is based on a proportional-integral (PI) controller, which provides power command tracking suplemented with a proportional controller with low-pass filter that provides thrust compensation. The two objectives may conflict, but the structure of the controller ensures that power command tracking will prevail and dominate the response; the plant is therefore sure to meet grid code requirements for active power control. At the same time, the fact that the plant consists of many wind turbines allows the thrust compensation to be effective.

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Link: https://github.com/SINTEF-Energy-Wind/STAS-WPP

Developing and testing of tools, methods and algorithms beyond TotalControl

One such initiative is a joint industry project (JIP) lead by DNV. As a starting point, DNV has issued a position paper detailing the necessary steps towards making wind farm control (WFC) bankable. This report showed that more evaluations of wind farm control implementations in operating wind farms were needed. Thus, the objective of this JIP is to bring together the industry to carry out a number of evaluations of WFC on operating wind farms.

The evaluations will follow a well-defined protocol, including the so-called "toggle tests" analog to those performed in TotalControl, in order to make the results repeatable and firm. The evaluations will use several industry-leading simulation tools (among these LongSim) in order to compare and contrast these.

Lillgrund full scale activities beyond TotalControl

Together with Vattenfall and Siemens, DTU and DNV is pursuing further gains in productivity of the full-scale offshore wind farm Lillgrunden. This is done using optimal open-loop wind farm control schedules 'designed' using the numerical tools Longsim (DNV) and Fuga (DTU). More specifically, the one-row demonstration/validation case designed and implemented and analyzed in the context of TotalControl - for a specific inflow sector - will be further consolidated by being extended to the entire wind farm consisting of 48 wind turbines and all wind directions. Thus, an optimal wind farm control schedule, conditioned on ambient wind speed and wind direction, will be developed and implemented as basis for a measuring campaign extending over several months.

Upcoming Horizon Europe projects

Born out of the core of the TotalControl project team, a consortium is put together to formulate a project - InControl - for the upcomming EU HORIZON-CL5-2022-D3-03-04 call on Integrated wind farm control. This call adresses topics, which lies in natural continuation of the activities dealt with in the TotalControl project, and the consortium is therefore well positioned to harvest the synergies emerging from tightly coupling the results from the TotalControl project with the (proposed) activities in InControl.

2.2 Access to the tools

The tools listed above are all compiled in deliverable D5.11 – TotalControl Wind Power Plant Control Toolbox. In this deliverable you will find extensive descriptions of each of the tools including references for further information.

The toolbox is available at project website www.Totalcontrolproject.eu as well as on the EU commission platfrom.

2.3 Presentations at conferences and workshops

Although COVID-19 did set an effective hault on much of the conference activities during the project period, many of the project results have disseminated through abstracts, conference papers and posters. The goal of this have to been to promote project results and encourage a wider use use of the tools also outside the project consortium

2.3 Journal articles and project videos

The partners within the project have produced a number of journal articles. All journal articles are published as open access. Furthermore four project videos explaining and promoting the project has been made. Journal articles and project videos are available through the project deliverables D5.6 – D5.9 as well as on the EU commission platfrom.