CL-Windcon

Closed Loop Wind Farm Control

DELIVERABLE REPORT

Review on Standards and Guidelines

Deliverable No.	D4.7	Work Package No.	4	Task/s No.	4.6
Work Package Title		Feasibility			
Linked Task/s Title		Task 4.6: Feasibility vs. Standards			
Status		**Draft Final**	(Draft/Draft Final/Final)		
Dissemination level		**Public**	(PU-Public, PP, RE-Restricted, CO-Confidential) (https://www.iprhelpdesk.eu/kb/522-which-are-different-levels-confidentiality)		
Due date deliverable		2017-09-30	Submission date	2019-09-29	
Deliverable version		CL-Windcon_D4.7_DraftFinal_Review Standards Guidelines			

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727477

DOCUMENT CONTRIBUTORS

Deliverable responsible		DNV GL	
Contributors	**Organization**	**Reviewers**	**Organization**
Kai Freudenreich	DNV GL	Giancarlo Potenza	EGP
Wilts Friedrich	DEWI	Stefan Kern	GE
Tobias Gehlhaar	DNV GL		
Nikolai Hille	DNV GL		
Tom Neumann	DEWI		
Phubade Pasakawee	DEWI-OCC		
Tobias Pfeiffer	DEWI-OCC		
Fritz Santjer	DEWI		
Reinhard Schleeßelmann	DNV GL		

DOCUMENT HISTORY

Version	Date	Comment
0.0		Initial draft of document
DraftFinal	2019-09-27	Draft final after internal review

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TERMINOLOGY

Term	Definition	Source	Remark
control system	system implementing the turbine control functions, including sensors, logic elements, actuators, communication networks, and power supplies	IEC 61400-1: 2019 [1], 3.9	"protection system" as used in Grand Agreement is *not* defined in IEC 61400-1 [1].
control functions	functions of the control system that, based on information about the condition of the wind turbine	IEC 61400-1: 2019 [1], 3.8	

	and/or its environment, adjust the turbine in order to maintain it within its operating limits		
protection functions	functions of the control system which ensure that a wind turbine remains within the design limits	IEC 61400-1: 2019 [1], 3.40	
wind power plant	power station comprising one or more wind turbines, auxiliary equipment and plant control	IEC 61400-27-1:2015	Sometime using wind farm (WF) or wind park (WP)
Existing plant control	state of the art wind power plant control with well-defined functionalities, slopes accuracies etc., usually already using closed loop wind farm control strategies.	see section 6.1	built as described in IEC 61400-27-2 [02]
CL-Windcon Plant Control	plant control including new CL-Windcon Plant Control features, synonym to “supercontroller” or “CL-Windcon farm control” etc. in other deliverable reports of CL-Windcon		
yaw demand	angle between wind direction and the turbine orientation used for wake steering. Yaw demand might intentionally be commanded away from 0 ° by CL-Windcon Plant Control. See also Figure 2.		
yaw error	angle between horizontal axis of wind turbine’s rotor and yaw demand. WT control has the task to minimise the yaw error. See also Figure 2.		

LIST OF ABBREVIATIONS

Abbreviation	Description
BEM	blade element method
CFD	computational fluid dynamics
DA	design assessment
DLC	design load case
DWM	dynamic wake meandering
ECD	extreme coherent gust with direction change
EOG	extreme operating gust
ETM	extreme turbulence model
EWM	extreme wind model
EWS	extreme wind shear
EZA-Regler	Erzeugungsanlagenregler (german)
FLS	fatigue load analysis
FMEA	failure mode and effect analysis
FMECA	failure mode, effects, and criticality analysis
FRT	fault ride-through
GCC	grid code compliance
LFSM-O	limited frequency sensitive mode – overfrequency
LFSM-U	limited frequency sensitive mode – underfrequency
NTM	normal turbulence model
NWP	normal wind profile model
PC	project certificate
PCC	point of common coupling
PPA	power purchase agreement
RNO	relevant network operator, formerly known as utility
RPN	risk priority number
-s	suffix for design load cases, indicating site specifc conditions
SCADA	supervisory control and data acquisition
SRP	safety-related part
SRP/CS	safety-related part of a control system
SSDA	side specific design assessment
TC	type certificate
TI	turbulence intensity

ULS	ultimate load analysis
UVRT	undervoltage ride-through
WF	wind farm
WP	wind park, wind power plant
WT	wind turbine

1 SUMMARY

This deliverable deals with the review of the plant control methods proposed by CL-Windcon in relation to the certification standards available for wind energy today. This affects the individual turbine as well as the wind farm as a whole power plant.

After an introduction to standards and certification in the light of plant control, a review of the deliverables from CL-Windcon working packages 1 to 4 is performed. The impact of the new control methods proposed therein is analysed regarding design requirements for the control system of the wind turbine, for the design load cases and for the grid code compliance of the wind power plant.

The risks of the individual methods for CL-Windcon Plant Control are identified followed by a qualitative analysis of their failure modes, effects and criticality.

Finally, recommendations are given how existing standards should be amended regarding control system, design load cases and grid code compliance to prepare for a certification applying CL-Windcon Plant Control. Methods to deal with the challenges in the load simulation and the validation of the load calculation process are proposed. Furthermore, recommendations for test, commissioning and inspection are also given. To deal with the remaining uncertainties in the design process, a modification to the In Service module during Project Certification is proposed.

2 INTRODUCTION

Pressure on the economics of wind power plants is increasing. One way of improving the performance is the implementation of new control strategies to individual turbines and increasingly also to the whole wind farm considering it as a single power plant. Within CL-Windcon work packages WP1 to 4 these new control strategies for the wind power plant have been developed and demonstrated in simulation and onsite measurements.

Certification is an important independent quality assurance for large scale projects like a wind power plant. Basically, the economics of such projects is not the primary focus for certification. Structural integrity of the individual wind turbine as well as the dynamic interaction of all wind turbines within a wind farm and its connection to the electrical grid, play the most important roles. The new outstanding features of the CL-Windcon control strategies are that mechanical loads can be mitigated from one turbine to another as well as the energy output can be maximized. The benefits are a maximised total energy output of the whole wind power plant and an optimised distribution of the mechanical loads. By that the optimisation of each single turbine is given up to the benefit of an optimised wind power plant.

Certification of such novel control strategies is a challenge, as the assessment of the new design can only relate to existing standards. When these standards were written, the present state-of-the-art has been considered. In the best case the original purpose of the standards can be interpreted and applied for the new designs to aim for an adequate assessment. For more complex designs like the control strategies proposed with the CL-Windcon Plant Control this is difficult. The intention of the present CL-Windcon work package WP4.6 is to investigate up to which extend the proposed control strategies require an amendment of existing design requirements to respond to additional risks of the new design. The new requirements shall be in good balance to the expected additional risks of the proposed technology with the intention to support the step from research level within CL-Windcon to the launch of commercial projects.

To this end an alignment of the established procedures of Type and Project Certification with the new control strategies is required. Amendments are expected for the control system which will reflect the more complex control algorithms, additional sensors and optimisation algorithms.

This will in turn imply increased efforts within the calculation of design loads because the new control strategies will lead to operation of the turbines in conditions which are not assumed in conventional control, e.g. the permanent operation at increased yaw misalignments. At the same time the application of new wind farm simulation tools is a challenge as long as they are not sufficiently validated.

Individual national requirements on grid code compliance need to be considered before the erection of a new wind power plant. The integration of additional power to a grid which nowadays is often operated close to its limits for capacity is difficult. It needs to be identified to which extend the new CL-Windcon control strategies may influence these national requirements, how compliance can be ensured, or to which extend the CL-Windcon strategies may even support the integration of such wind power plant into the electrical grid.

It is intended to use the results of the present report within future standards for certification.

2.1 Technologies reviewed

The main objective of CL-Windcon is to bring a closed loop control paradigm to the wind farm level to optimise the interaction between single wind turbines and increase the overall power output of the whole wind farm. Therefore CL-Windcon develops advanced control algorithms, which are described in detail in deliverables D2.1 and D2.2 of the CL-Windcon project. The aim of this section is to provide a short summary of the used control strategies to get a better understanding about what could be an impact to current standardization procedures.

Currently there are three types of control strategies in the main focus of CL-Windcon:

2.1.1 Axial Induction control

Under axial induction control some of the turbines within a farm will lower their energy capture by e.g. increasing their blade pitch angle. The induction factor for a wind turbine is defined as the relative change in wind speed in the rotor plane due to the turbine's extraction of energy from the wind flow. Reducing the axial induction at an upstream wind turbine has the potential to increase the wind velocity and to reduce the turbulence downstream. This possibly increases the available energy on the downstream turbines while at the same time reducing mechanical loads, with an increased overall production from the wind farm.

2.1.2 Wake redirection control/ wake steering

Under wake redirection control, some of the turbines within a wind farm will redirect their wakes, by active yawing or harmonic pitching. This reduces the wake effects (lower wind speed, higher turbulence) with the goal of increasing the power output on other turbines further downstream. Within CL-Windcon wake redirection by active yawing has been emphasised.

2.1.3 Dynamic induction control

With dynamic induction control, faster wake recoveries can be achieved by applying a low frequency sinusoidal excitation with an amplitude below 5 degrees on the collective pitch angles of upstream wind turbines. Further details on this methodology can be found in section 6 of deliverable D2.3 within the CL-Windcon project. This methodology is referenced also as “dynamic induction control” and “wake mitigation technique” inside the different deliverables of CL-Windcon.

2.1.4 CL-Windcon Plant controller

As proposed in the Grant Agreement of CL-Windcon and illustrated in Figure 1 individual wind turbine controllers should allow for set point changes demanded and determined by a wind farm super controller to enable closed loop wind farm control. Such set points could for example be given to blade pitch and generator torque for implementation of wind turbine derating and fast wake recovery strategies. To implement wake steering control methods individual yaw-misalignment set point should be given to upstream turbines.

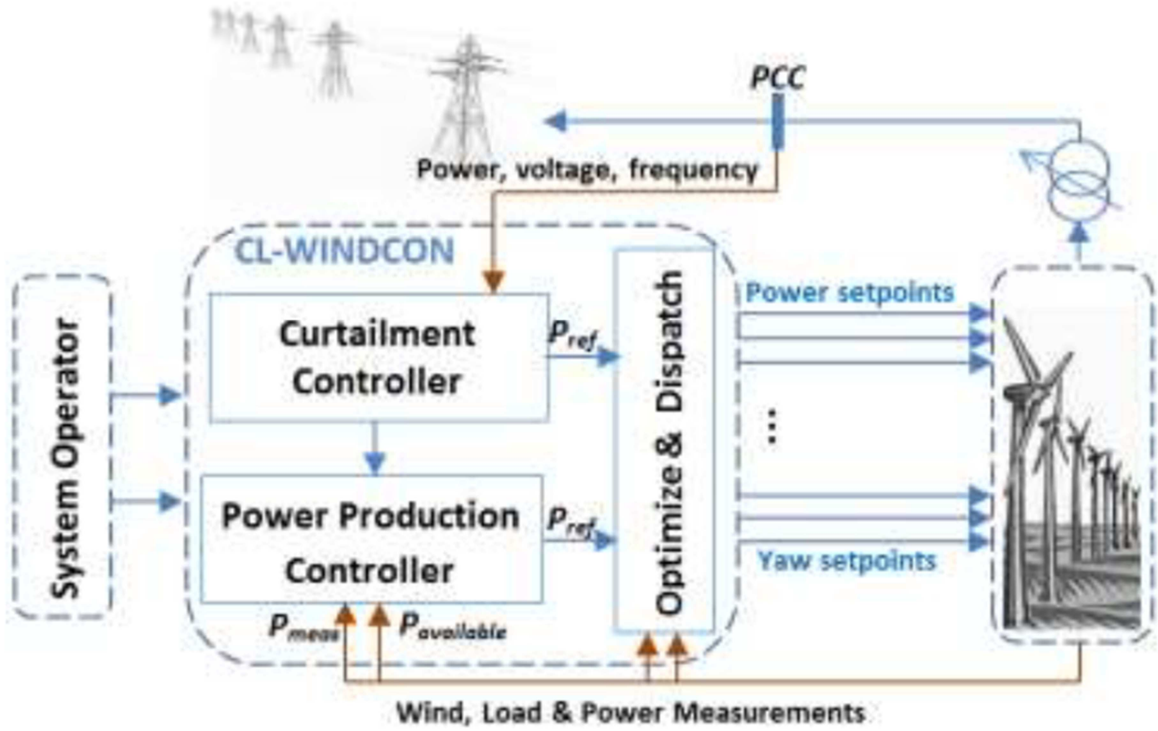


Figure 1: Proposed control schematic of CL-Windcon approach from Grant Agreement

As discussed during the next sections of this deliverable such a super controller as well as the modified turbine controllers should be in accordance with current safety standards and regulations as well as the demanded grid constraints, which sometimes have to override power optimisation algorithms.

The envisaged closed-loop control approach uses real-time algorithms that combine measurement data (e.g. power, loads, fault information) and dynamic models to accurately predict the variability of the flow within the wind farm. This detailed knowledge of the evolution of the flow field and the corresponding uncertainty as a function of the control settings will constitute a complex high-dimensional control problem where physical constraints on the control degrees of freedom will play an important role (e.g. speed, power limits, siting regulations…). The estimated and predicted flow field will serve as an input to a real-time optimization process which has to find an optimal balance between the farm loading and the overall power output.

3 INTRODUCTION TO STANDARDS AND CERTIFICATION

3.1 Standards in wind turbine design

Wind turbines are designed along a set of technical design standards. These can be divided in two groups of standards:

a) Standards for the design of components (e.g. bolts), systems (e.g. hydraulic system) or material properties (e.g. steel grade)
Most of these standards are not special for the wind turbine industry. They are used in different technical applications.

b) Standards for the design of the wind turbines (e.g. IEC 61400-22 [23])
These standards are made for the wind turbine industry only.

In the following we describe the main standards of group b).

3.1.1 IEC set of standards

The *International Electrotechnical Commission* (IEC) in Geneva, Switzerland publishes several standards for wind turbine design. These bear numbers starting with *IEC 61400-* and cover the areas:

- design
(e.g. IEC 61400-1 *Wind energy generation systems Part 1: Design requirements* [1]),
- testing
(e.g. IEC 61400-13:2015, *Wind turbines - Part 13: Measurement of mechanical loads [24]*) and
- certification
(e.g. IEC 61400-22 *Wind turbines – Part 22: Conformity testing and certification* [23]).

The IEC set of standards is widely used in wind turbine business for design, benchmarking, contracting and certification.

3.1.2 IECRE system

The IEC has set up *IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications* (IECRE). IECRE publishes 'Operational Documents' describing the services and certification schemes used in their system.

One example is IECRE OD-501:2018 *Operational Document, Type and Component Certification Scheme* [29].

The IECRE documents are widely used in wind turbine business for certification.

3.1.3 DNV GL publications

DNV GL provides risk management and quality assurance services as well as certification services for systems and products worldwide.

DNV GL publications define their

- services (*Service Specification*, SE),
- technical requirements (*Standards*, ST) and
- technical recommendation (*Recommended Practices*, RP).

A selection of the DNV GL publications for wind turbines is given at https://www.dnvgl.com/energy/renewables-certification/energy-rules-and-standards.html.

The DNV GL publications are widely used in wind turbine business, mainly for contracting and certification.

3.1.4 UL publications

UL is a global independent safety science company with more than a century of expertise innovating safety solutions.

UL has published standards in a wide range also in the field of wind turbine certification. All standards can be found at:

https://ulstandards.ul.com/access-standards/

3.1.5 Other standards

Other organisations publish very few standards for the wind turbine business.

Examples are:

- EN 50308:2004, corrected 2005 *Wind turbines – Protective measures – Requirements for design, operation and maintenance [26]*
- FGW TG 8:2019 *Certification of the electrical characteristics of power generating units and systems in low-, medium-, high- and extra-high voltage grids* [7]

3.1.6 Standards related to CL-Windcon work

3.1.6.1 Loads on wind turbines

Wind farm control measures will influence loads on wind turbines. Those can be reduction of loads (e.g. if a wind turbine is down-rated) or a load increase (e.g. if a wind turbine is operated outside the normal alignment with the wind direction).

Loads on wind turbines and the wind farm influence on the loads as well as related simulation activities are described in the following standards. Therefore, they are related to the CL-Windcon work.

- IEC 61400-1 *Wind energy generation systems Part 1: Design requirements* [1]
- DNVGL-ST-0437 *Standard, Loads and site conditions for wind turbines* [15]

3.1.6.2 Control of wind turbines

The control system of a wind turbine controls the operation through control loops for the pitch angle, generator torque as well as alignment with the wind direction. This control is made inside the control system of the wind turbine itself. In standard applications some parameter settings (maximum electrical active power, on/off signal, etc.) are transmitted from the wind farm controller. The actual control loop however runs inside the wind turbine. Wind farm control measures will function in control loops in the wind farm controller. Thus, more parameters need to be transmitted for the wind turbines to work along (e.g. demand of yaw angle 'out of wind direction').

Control systems of wind turbines are described in the following standards. Therefore, they are related to the CL-Windcon work.

- IEC 61400-1 *Wind energy generation systems Part 1: Design requirements* [1]
- DNVGL-ST-0438 *Standard, Control and protection systems for wind turbines [22]*

3.1.6.3 Grid code compliance

Wind farm control measures might influence the conditions of the electrical current delivered to the grid as well as wind farm's behaviour in case of grid disturbance. Both are defined in grid operators' grid codes to ensure a requested level of grid code compliance (GCC).

Compliance with these grid codes and how to prove the compliance at wind turbine and wind farm level are described in e.g. the following standards. Therefore, they are related to the CL-Windcon work.

- FGW TG 8:2019 *Certification of the electrical characteristics of power generating units and systems in low-, medium-, high- and extra-high voltage grids* [7]
- DNVGL-ST-0125 *Standard, Grid code compliance* [6]

3.1.6.4 Certification Scheme

Certification work at wind turbines is done along standardised working procedures. The structure and definition of deliverables from the certification body are defined in "Certification Schemes". These schemes between other things define the terms "Type Certificate", "Project Certificate", "Conformity Statement", etc. CL-Windcon work adds control loops to the wind farm controller. These might not be covered by the certification schemes.

Certification schemes for the certification of wind turbines and wind farms are described in the following standards. Therefore, they are related to the CL-Windcon work.

- IEC 61400-22 *Wind turbines – Part 22: Conformity testing and certification* [23]
- IECRE OD-501:2018 *Operational Document, Type and Component Certification Scheme* [29]
- IECRE OD-502:2018 *Operational Document, Project Certification Scheme* [31]
- FGW TG8:2019 *Certification of the electrical characteristics of power generating units and systems in low-, medium-, high- and extra-high voltage grids* [7]
- DNVGL-SE-0441:2016 *Service Specification, Type and component certification of wind turbines* [32]
- DNVGL-SE-0190:2015 *Service Specification, Project certification of wind power plants* [27]
- DNVGL-SE-0124 *Service Specification, Certification of grid code compliance* [5]

3.2 Certification

3.2.1 Type Certificate (TC) - wind turbine level

Typically, a type of wind turbine bears the following two Type Certificates:

- "Type Certificate" according to e.g. IECRE OD-501 or DNVGL-SE-0441,
  which attests conformity of the mechanical, structural and electrical design with the related standards,
  and

- “Type Certificate” according to e.g. FGW TG8 or DNVGL-SE-0124,
  which attests conformity with grid code compliance requirements.

3.2.2 Project Certificate (PC) – wind farm level

Wind farms may bear the following two Project Certificates:

- “Project Certificate” according to e.g. IECRE OD-502 or DNVGL-SE-0190,
  which attests conformity of the mechanical, structural and electrical design with the related standards,
  and
- e.g. “System Certificate” according to FGW TG8 or “Project Certificate” according to DNVGL-SE-0124,
  which attests conformity with grid code compliance requirements.

3.2.3 Certification modules

The certification work is structured in “certification modules”. These modules are defined in the applied certification scheme. Finalisation of a certification module is documented by a “Statement of Conformity” or “Conformity Statement”.

The following modules are related to CL-Windcon work.

3.2.3.1 Type testing

As part of the Type Certification the certification module for testing the prototype of a wind turbine is defined.

- IECRE OD-501:2018-05 *Operational Document, Type and Component Certification Scheme* [29]
  “Type testing”
- DNVGL-SE-0441:2016 *Service Specification, Type and component certification of wind turbines*
  “Test certification module”

In this Deliverable Report the term ***Type Testing*** is used.

3.2.3.2 Site Specific Design Assessment (SSDA)

The certification schemes define a certification module for site specific design of wind turbines. However, different names are used for this module:

- IECRE OD-502:2018-10 *Operational Document, Project Certification Scheme* [31]
  "Site-specific wind turbine/RNA design evaluation"
- DNVGL-SE-0441:2016 *Service Specification, Type and component certification of wind turbines*
  "Design certification module - site level"
- DNVGL-SE-0190:2015 *Service Specification, Project certification of wind power plants*
  Certification phase "Design"

Because of these different names, in this Deliverable Report the historic term ***Site Specific Design Assessment (SSDA)*** is used.

3.2.3.3 In-Service

After a Project Certificate is issued, it can be maintained by regular activities of the Certification Body. The related certification module has the following names:

- IIECRE OD-502:2018-10 *Operational Document, Project Certification Scheme* [31]
  "Operation and maintenance surveillance"
- DNVGL-SE-0190:2015 *Service Specification, Project certification of wind power plants*
  Certification phase "In-service"

In this Delivery Report the term ***In Service*** is used.

4 RISK ANALYSIS OF AVAILABLE DELIVERABLES FROM WP2 AND WP4

4.1 Identification of risks regarding safety and function for solutions acc. to WP2 and WP4

The CL-Windcon novel wind farm control features are analysed with respect to guidelines stating wind turbine (WT) design requirements. To do so, the related risks to the WTs, the wind farm (WF), the quality of power delivery and the operation are analysed. Section 4.2 gives a formal risk analysis. In this subclause risks and related mechanisms are discussed. The list of control features is taken from Deliverable D1.1 "Definition of reference wind farms and simulation scenarios" [18].

4.1.1 Axial induction control

Induction control is performed by down-rating selected WTs (group 1) to allow other turbines in the wind farm (group 2) to increase their energy yield.

1.1: There is a principle risk for group 1 turbines, as down-rating may cause prolonged operation time in non-optimal operation conditions. The related risks are in e.g. the following technical areas: operation near to vibration excitement frequencies, less damping than in power optimised mode, operation in non-optimal control loop settings, or others. This group of risks is not new however, as WTs' control systems always include possibilities for down-rating. Down-rating must be done now and again for reasons as noise impact, technical limitations in WT's systems (e.g. component's temperatures) or demand from the grid operator.

1.2: We do not see any risk on the group 2 WTs, as WTs are made and optimised for maximum energy yielding. Group 2 WTs run in their natural operation environment.

Table 1: Risks for axial induction control

	WT affected	risk
1.1	down-rated WTs	non- optimal operation conditions
1.2	downwind WTs	none

4.1.2 Yaw control

Yaw control is performed by yawing selected WTs (group 1) out of the wind by up to 30 ° away from optimal alignment to the wind direction. This is done to optimise the direction of the wake behind the turbines (wake steering). Wake steering allows other WTs (group 2) located downwind of group 1 to increase their energy yield, because the wake is steered away from them.

2.1: Group 1 WTs: Existing design rules assume that WTs are aligned to the wind direction throughout their entire operational life. Tolerances of this alignment are defined along normal technical control processes. Standard fatigue strength calculations (including fatigue and ultimate load calculations) do not cover wake steering activities. Therefore, there is a risk for group 1 turbines, as the operation outside the optimised alignment to the wind direction causes extra loads, mainly increase of fatigue loads. However increased ultimate loads cannot be ruled out. The resulting extra fatigue damage and/or extra ultimate load may not be covered by the strength of WTs' components.

2.2: Another risk is given in the fact, that simulation software is validated from full scale field measurements and scaled wind tunnel measurements in standard operational conditions. The non-aligned operation during wake steering activities is outside the validation envelope of simulation software. That means the accuracy of the load simulation is not known in this operation condition, which increases the uncertainty on design loads. Specifically, large yaw misalignments lead to three-dimensional effects due to inflow along the blade. It is known that the Blade-Element-Method (BEM) does not cover these three-dimensional effects. Simulation codes applying the BEM might deliver uncertain load simulation results.

2.3: In standard WT design the yaw movements are controlled by the WT controller with the aim to align the wind turbine with the wind direction. This is a closed loop feedback control. It normally does not have any interfaces for receiving external commands. CL-Windcon Plant Control access to the WT yaw control, introduced here in the CL-Windcon project, is a novelty. The related changes in WT's control software need to be done carefully. It must be ensured, that the WT never moves out of the allowable yaw angle range. The risk here is to overlook any important matter, when revising WT's control software.

2.4: Most WTs are designed to stay online (generator connected to the grid) for some time in defined grid disturbances (fault conditions of the electrical grid). In such situations, they need to contribute to grid stability by delivering defined amounts of active power and reactive power. Grid conditions (like e.g. voltage) may change very fast at grid disturbances. Therefore, the WTs need to do quite fast control actions to stay online. These actions are tuned for ordinary alignment to the wind. Risk is, that the turbines might switch offline if grid disturbance happens at times of large misalignments.

2.5: We do not see any risk on the group 2 turbines, as WTs are made and optimised for maximum energy yielding. Group 2 WTs run in their natural operation environment. They may run in partial wake conditions, as their rotor plane might be exposed to a wake in some sectors only. This however, is always the case in WPs. However, partial wake conditions due to CL-Windcon Plant Control have to be considered within the design load cases appropriately, see section 7.3.

Table 2: Risks for yaw control

	WT affected	risk
2.1	non-aligned WTs	increased fatigue damage and risk of increased ultimate loads due to prolonged non-aligned operation
2.2		prolonged operation outside simulation software's validation envelope
2.3		increased fatigue damage due to failure when revising WT's software
2.4		premature switch off during grid disturbance
2.5	downwind WTs	none

4.1.3 Wake mitigation technique

Wake mitigation can be done through periodically modulating the collective pitch angle by some degrees and thereby modulating rotor thrust. The period time (in the range of 0.5 to 1 minute) and the amplitude of variation (up to ±5 ° pitch angle) needs to be optimised for given rotor diameters and wind speeds. This is performed by selected WTs (group 1) to reduce the wake behind them and thus allows other turbines (group 2) located downwind of group 1 to increase their energy yield.

3.1: There is a principle risk for group 1 WTs. The periodically pitching activity represents extra loading on the pitch system, as it considerably increases system's operational time and effort. The resulting extra fatigue damage to pitch systems' components might not be covered by their fatigue strength.

3.2: In standard WT design the pitch movements are controlled by the WT controller with the aim to optimise energy yield in the envelope of allowable loads. This is – depending on WT's operational state – a pitch angel adjustment (below rated wind) or a closed loop feedback control (above rated wind). The pitch controller normally does not have any interfaces for receiving external commands. CL-Windcon Plant Control access to the WT pitch control, introduced here in the CL-Windcon project, is a novelty. The related changes in WT's control software need to be done carefully. It must be ensured, that the WT never moves out of the allowable pitch angle range. This range is defined by stall and overload avoidance measures. The risk here is to overlook any important matter, when revising WT's control software.

3.3: WT dynamic behaviour is important to be controlled thoroughly, because wind turbine components will experience large deflections when brought into oscillations, e.g. tower head movements or rotor blade to tower clearance issues. Dynamic behaviour is between other measures controlled by the control loops for pitch angle and generator torque. These control loops are used to perform wake mitigation actions. Therefore, in principle the dynamic behaviour of WTs' components could be influenced negatively.

3.4: We do not see any risk on the group 2 WTs, as WTs are made and optimised for maximum energy yielding. Group 2 WTs run in their natural operation environment.

Table 3: Risks for wake mitigation technique

	WT affected	**risk**
3.1	cyclic pitching WTs	increased fatigue damage on pitch system
3.2		mechanical overload due to failure when revising WT's software
3.3		increased oscillations of components
3.4	downwind WTs	none

4.1.4 Combination of axial induction control and yaw control

We do not see any additional risk by combining the features axial induction control and yaw control. The risks are comparable to the application of each feature separately. Thus the sum of the risks described in sections 4.1.1 *Axial induction control* and 4.1.2 *Yaw control* is applicable.

4.1.5 Wind farm controller

To apply the novel control features, the required functions and control loops need to be included in the WP wind farm controller ("CL-Windcon Plant Control"). However, the new features can potentially conflict with the existing wind farm control functions ("Existing Plant Control"). Details are given in section 6.3 *Conflicts of CL-Windcon to standards and possible gaps* below.

5.1: Wind farm reaction upon grid disturbances must always be performed to fulfil the contract between WP operator and grid operator. Grid disturbance can happen at any time. The risk here is no or no proper reaction upon a grid disturbance as the CL-Windcon Plant Control may impair the Existing Plant Control.

5.2: The novel control features my influence loading on certain wind turbines negatively (e.g. operating non-aligned to wind direction). This extra loading shall be paid off by increased energy yield. This increase however is very difficult to be measured. There is the risk of adding extra fatigue damage to some turbines without balancing it through related rise in earnings.

Table 4: Risks at the wind farm controller

	WT affected	**risk**
5.1	all	no or no proper reaction upon grid disturbance
5.2		extra fatigue damage without benefit

4.1.6 Wind farm communication

As pointed out in section 4 of Deliverable D4.2 "Hardware and infrastructure conditions for energy capture and fatigue improvements" [19] the communication between WP controller and WT controller is an essential part of closed loop wind farm control. This of course also is valid for the communication between WP controller and any sensors outside the WTs.

6.1: The communication may deliver wrong signals either because of failure in the communication or by failure in the interface settings. Therefore, the WT control system must be able to recognise wrong signals to not operate outside the allowable load envelope. It shall in that case fall back into self-control mode. The risk would be WT operation in an unintended condition.

6.2: Also, the WT control system must be able to recognise a non-availability of the communication. It shall in that case fall back into self-control mode. The risk would be a malfunction of transient into self-control mode.

Table 5: Risks at the wind farm communication

	WT affected	risk
6.1	all	WT malfunction because of communication error
6.2		WT malfunction because of communication loss

4.1.7 Priorities in wind turbines' control system

The safe and reliable operation of the individual WT shall not be compromised by the new CL-Windcon Plant Control features. The WT control system shall make sure that the WT always is kept inside the allowable operation parameters. In case of conflict, this has priority over any signals from the CL-Windcon Plant Controller.

7.1: One risk for the WT is malfunctioning because of problems with the priority of WT control over CL-Windcon Plant Control.

7.2: Another risk is malfunction of WT's reaction upon grid disturbance, which in fact can be caused by prioritisation problems.

Table 6: Risks about priorities in wind turbines' control system

	WT affected	risk
7.1	all	WT malfunction because of priority problems regarding CL-Windcon Plant Control

WT affected	risk
7.2	WT non-proper reaction upon grid disturbance because of priority problems regarding CL-Windcon Plant Control

4.2 Qualitative risk analysis, FMECA

FMECA (Failure Mode, Effects and Criticality Analysis) method as per IEC 60812 [20] was chosen to perform the risk analysis.

The purpose of and FMECA is to establish how items or processes might fail to perform their function. An FMECA provides a systematic method for identifying modes of failure together with their effects on the item or process, both locally and globally. It also includes identifying the causes of failure modes. Failure modes are prioritized to support decisions about treatment.

A high level FMECA was performed on main component/system level, rather than a detailed one on component/subcomponent level. The high level was chosen to not make too many assumptions on the design of WTs and the WP. In future wind farm applications, it is recommended to perform a component level detailed FMECA (see also section 5.5.3 below).

In order to generate an FMECA the numbers for the criticality analysis need to be defined. This definition work is shown in subsections 4.2.2, the FMECA is given in Appendix A and the conclusion is drawn in section 4.2.3.

4.2.1 Failure modes and effects

The risks identified in section 4.1 were analysed and further commented using the FMECA method.

As suggested in IEC 60812 [20] the following columns are used:

Asset — term used in the context of WP projects to describe the object in focus.
Here the term refers either to wind turbines "WT", wind park "WP" or "WP communication".

Operation condition — state of the WT or WP in the moment of the possible failure mode to

	happen.
Component	piece of equipment associated to the failure mode
Failure mode	manner in which an item fails
Potential cause of failure	reference to the list of risks given in in section 4.1
Potential effect of failure	impact of the failure on the WT or WP
Detection method	the way, how the failure would be detected before damage occurs

The related aspects were worked out and are presented in Appendix A. Conclusion is drawn in section 4.2.3 below.

4.2.2 Criticality analysis

The criticality analysis was performed following annex B of IEC 60812 [20].

Criticality analysis provide a means of prioritizing failure modes by combining the parameters likelihood of failure (*Probability of occurrence*), the consequences of failure (*Severity*), and the *Detectability* of the failure.

For this prioritisation the method *Risk priority number* as per IEC 60812 section B.4.2 was chosen. This method consists of the steps

- definition of ratings for the parameters mentioned above,
- estimation of the values – the ratings – for each parameter at each failure mode and
- calculation of the RPN (Risk Priority Number) as product of the ratings. The RPN serves as prioritisation of the failure modes relative to each other.

The definitions of the ratings are given below (sections 4.2.2.1, 4.2.2.2 and 4.2.2.3).

A conclusion is drawn in section 4.2.3 below.

4.2.2.1 Occurrence

Probability of occurrence classes				
Class	**Name**	**Description**	**Annual probability of occurrence (p)**	**Reference**
1	Very Low	Event unlikely to occur	p < 1.0E-04	Comparable to structural failure
2	Low	Event rarely expected to occur	1.0E-04 < p < 0.02	50 years event
3	Medium	One or several events expected to occur during lifetime	0.02 < p < 0.1	10 years event
4	High	One or several events expected to occur during each year	0.1 < p < 1	Yearly event
5	Very high	Events expected to occur frequently each year (monthly)	1 < p	Monthly event

4.2.2.2 Severity

Severity classes				
Class	**Name**	**Personnel Safety**	**Operation**	**Asset**
1	Very Low	Negligible injury or health effects	Negligible effect on production, stand-still up to 8 hours	Negligible
2	Low	Minor injuries or health effects	Small loss of production, repair inside scheduled maintenance, stand-still 8 hours to 1 day	Spare part or SCADA monitored, repairable within maintenance interval
3	Medium	Moderate injuries and/ or health effects	Loss of production, repair outside scheduled maintenance, stand-still of single turbine 1 to 7 days	Significant but repairable outside scheduled maintenance
4	High	Significant injuries	Significant loss of production, larger repair activity, stand-still of single turbine up to one month	Major repair (requires external crane) needed and exchange of major components
5	Very high	A fatality	Temporary total loss of production, large repair activity, stand-still of several turbines for months	Loss of turbine or other major system

4.2.2.3 Detection

Detectability classes		
Class	**Name**	**Description**
1	Virtually always possible	Avoidance of consequences is almost always possible, for instance by means of an independent technical system
2	Frequently possible	Avoidance of consequences is frequently possible due to favourable conditions
3	Normally possible	Avoidance of consequences is normally possible
4	Sometimes possible	Avoidance of consequences is only sometimes possible due to unfavourable conditions
5	Virtually not possible	Avoidance of consequences is virtually not possible

4.2.3 Conclusions from the FMECA

The risks identified in section 4.1 were listed in the FMECA and are displayed in Appendix A.

As can be seen from the RPN (risk priority number) the failure mode to be analysed with priority is "fault-ride-through parameters tuned for different operation condition (2.4)" in line 5. The reason for this mainly is, that this failure mode is virtually not possible to detect before the grid disturbance might happen in given operation condition. In a WP design, this has to be considered.

The next highest RPN are lines 2, 3, 8 and 10.

Lines 2 and 3 are related to the WT operating non-aligned to wind direction. In any WP design, this must be considered thoroughly.

Line 8 is on possible negative influence of CL-Windcon control feature 'wake mitigation' on the control loops of the WT. This can be counteracted by extended WT simulations.

Line 10 is on the overall effect of CL-Windcon Plant Control features. To gain confidence on the effect of the CL-Windcon Plant Control activities measurements and statistics need to be drawn up during operation of the WP.

The FMECA analysis doesn't show relevant risks to WTs and WP in applying CL-Windcon Plant Control features, which cannot be controlled.

Also, the FMECA analyses does not result in any suggestions to revise rules and/or standards in the area of Control and Protection (see also section 5.4 below). In the areas Grid Code Compliance and Design Load Cases however, revision of standards is recommended (see sections 6.5 and 7.3 respectively).

5 CONTROL SYSTEM

5.1 Relevant standards for wind turbine control systems

Requirements for control systems of wind turbines are stated in the current standards IEC 61400-1 ed. 4.0 2019-02 [1], IEC 61400-22 [23] (expired), IECRE OD-501 [29], IECRE OD-501-05 [30] (contains also section 4 *Required documentation*, which is a list of required design documentation), ISO 13849-1 [21] and DNVGL-ST-0438 [22]. Generally, WT's are governed by control functions and protected by protection functions.

In general, two operational modes can be distinguished:

- Normal operation: Here several parameters (like electrical power, vibrations, alignment to wind, …) will be used as an input for the control function algorithms. Those parameters have to be simulated in the structural design phase of each WT
- Safe mode operation: When the specific parameters defined in the design load cases have reached their trigger limit, the wind turbine has to be switched to safe mode simultaneously in order to prevent the damage on the structure.

Protection functions shall protect the wind turbine and bring it to a safe condition at the last stage. This is implemented by secondary limits for a set of parameters, which never shall exceed levels defined in the design phase of the WT's. If one of these parameters is ever exceeded, the wind turbine will stop immediately. This protection function must override all commands given by the control system in any case. This includes also all commands by the CL-Windcon specific plant control.

CL-Windcon cases are mentioned in the section 5.3.

Failure mode and effect analysis (FMEA) or an equivalent method shall be used during certification to determine possible failure modes and to evaluate the effect of CL-Windcon Plant Control algorithms on the wind turbine and wind farm. Several errors or faults may lead the WT into the failure modes. The following failure modes shall be considered:

- Common-cause failures: this means failures of different items, resulting from a single event, where these failures are not consequences of each other.
- Fault exclusions is a compromise between technical safety requirements and the theoretical possibility of occurrence of a fault. Fault exclusion is applied, if a fault has no negative impact on wind turbine's or wind farm's safety.

- Systematic failure: this means failure related in a deterministic way to a certain cause, which can only be eliminated by a modification of the design or of the manufacturing process, operational procedures, documentation or other relevant factors.

Within this deliverable the (FMECA) method has been used, results are described in section 4.

5.2 Review of CL-Windcon WP 1 – 4 with regard to standards

The following CL-Windcon deliverables have been reviewed:

- D1.1 Definition of reference wind farms and simulation scenarios
- D1.2 Description of the reference and the control-oriented wind farm models
- D2.1 Minimal loading wind turbine de-rating strategy and active yaw controllers
- D2.2 Methodology for active load control
- D2.3 Control methodology for induction based control and for wake redirection control
- D2.4 Minimal loading power curtailment control techniques
- D3.2 Definition of field-testing conditions
- D3.3 Demonstration of wind turbine controllers and supporting technologies by simulations
- D3.4 Testing in the wind tunnel of wind turbine controllers
- D4.2 Hardware and infrastructure conditions for energy capture and fatigue improvements

Based on results from these deliverables, the results have been reviewed and references to standards and requirements for certification have been found. These are described in the following sections.

The standards under consideration are listed above in section 5.1, 1st para.

5.3 Conflicts of CL-Windcon to standards and possibly gaps

Current standards do not cover the power plant control algorithms developed in this project. However, the following methods may influence current control system designs and shall be considered as extra requirements for WT/CL-Windcon Plant Control modes. Some control functions may have to be disabled or some parameters have to be modified, when implementing new CL-Windcon Plant Control strategies.

5.3.1 Axial induction control

De-rating the WT by pitch control method in order to give more energy yield to downstream WT's may influence control function parameters like the rotor speed, power regulation etc. of the de-rated

WT. However, the standard design procedure, following IEC 61400-1 [1] requires only to prove the none-de-rated conditions of WTs, as they are considered to cause the higher loads. Therefore, the protection functions do not get influenced by axial induction control. The CL-Windcon method 'Axial induction control' do not conflict with current standards.

5.3.2 Wake redirection

Wake steering methods implemented by misaligning upstream WT with some degree in order to steer the wake away from downstream WT to give them more energy yield will need modified control functions, which will allow higher yaw misalignment angle setting in the control parameters. The following protection functions of the wind turbine are influenced by this method and could cause the wind turbine initiating the safety stop:

- Excessive vibration; the WT will not face the direction of the wind and may cause unusual vibration to the structure.
- Yaw error; due to the wake redirection the CL-Windcon Plant Control may override the WT alignment to the wind parameter and the maximum permissible yaw error is reached.
- Watchdog; CL-Windcon Plant Control overrides the WT control, this may cause error in communication between WT controller and WT protection functions.

The following criteria were considered as consequences and used in the FMECA method in section 4 due to the implementation of the wake redirection from the CL-Windcon Plant Control:

- Independent and common cause failure; a failure due to the wake redirection which may lead to another failure shall be considered.
- Systematic failure (defined in section 5.1 above). This can be prevented by considering the FMEA (failure mode and effect analysis) and the measures described in ISO 13849-1 [21].

The pitch speed is regulated by the WT controller, therefore the pitch speed setting by the WT controller in normal operation will be used.

The yaw error angle will be minimised by WT control, as usual. However, CL-Windcon Plant Control will submit the 'yaw demand' value, corresponding to the "out of wind alignment" requirements. Thus, the yaw misalignment may defer considerably from the yaw error. Most times yaw misalignment will be larger than yaw error (figure 2) WT controller needs to be adapted to accept and process the 'yaw demand' value.

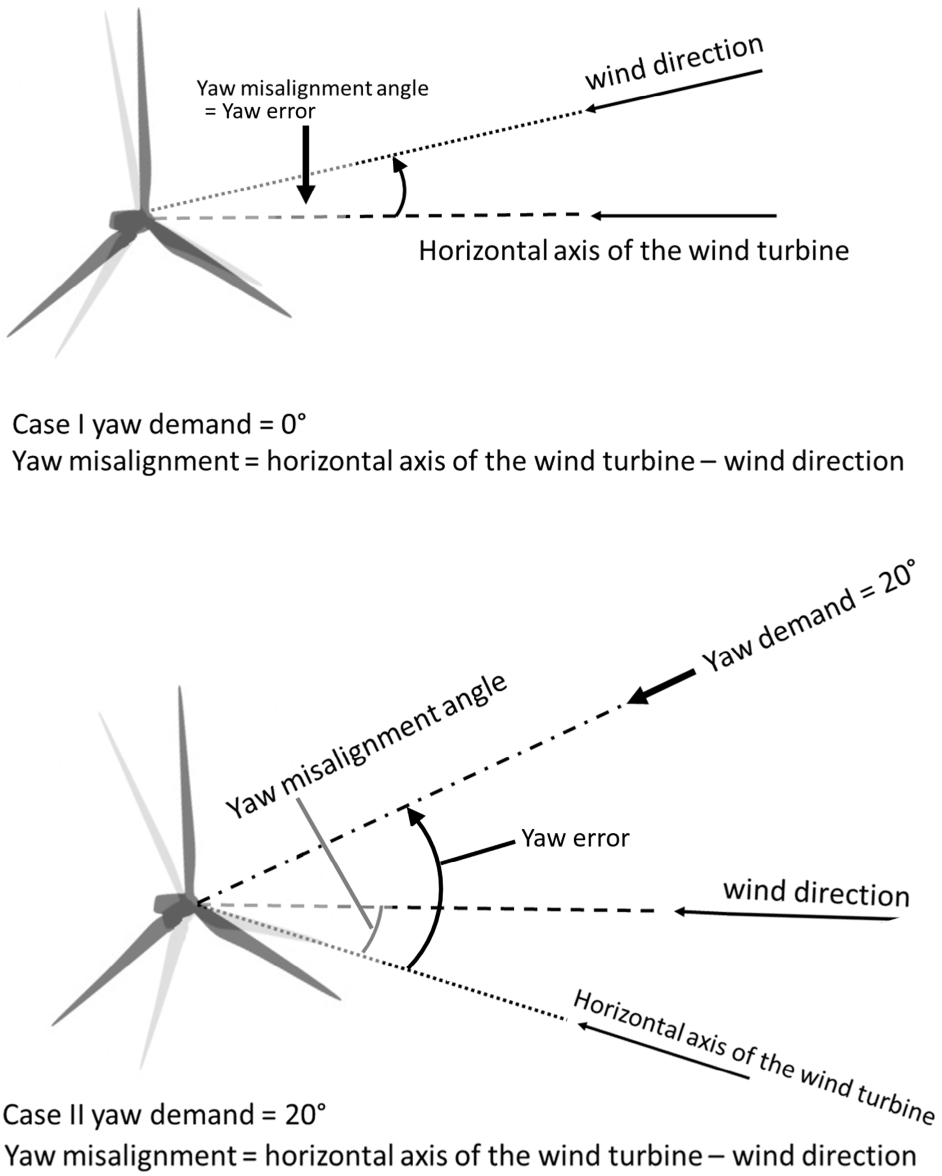


Figure 2 Co-ordination between existing WT control (minimising Yaw Error) and CL-Windcon Plant Control (optimising Yaw Demand)

5.3.3 Wake mitigation technique (fast wake recovery)

Wake mitigation techniques implemented by changing the pitch angle periodically may lead the pitch angle to reach the maximum permissible angle in the control system or causes abnormal vibration on the structure. This has to be assessed by simulating this special load cases like described in section 7.

We would expect the WT control to follow the standard collective pitch control activities. CL-Windcon Plant Control will submit values for the “Wake mitigation pitch offset”, which would be maximum amplitude and cycle time. WT controller needs to be adapted to perform the additional changing pitch angle movements according to the values from CL-Windcon Plant Control.

5.4 Needed amendments of control system standards due to CL-Windcon

From the outcome of the WP 2 and 4, the CL-Windcon advanced control method does influence the pitch and yaw control functions in normal operation mode. Nevertheless, the algorithm of these control functions and protection functions are kept as in the certified WT before the implementation of CL-Windcon Plant Control as much as possible.

The control system of the wind turbine contains the protection functions to protect the wind turbine against faults that may occur during the operation and prevent the structure of the wind turbine from overloading. These protection functions will be overriding any control command or function. As e.g. the wind turbine wake redirection is to be given a command (yaw demand ≠ 0) by CL-Windcon Plant Control to WT control. Even in this case the yaw misalignment protection function must never be disabled. It may be necessary to adapt the protection function to the needs of CL-Windcon control functions. This of course must be done carefully under consideration of the possibly increased load envelope.

The active derating strategies for active power control and for wake control are part of the pitch regulation control which is already available in the WT control system. However, the pitch speed defined in the control system shall be observed. As the pitch system is the primary brake of the WT, the active derating strategies shall be overridden by the stop function of the WT.

As a result, these control methods do not influence the design of the control system nor protection functions, therefore there is no need to update the relevant standards for the WT design requirements in type or project certificate when introducing aforementioned CL-Windcon control method. Suggested changes for the areas Test, Commissioning and Inspection are described in section 5.6, 5.7 and 5.8 respectively.

5.5 “Practical recommendations to CL-Windcon approaches”

For putting CL-Windcon Plant Control features into practical applications, the following recommendations can be given in the area of control system:

5.5.1 Parameters of the protection functions

It can be assumed, that the parameters governing protection functions are stored in WT control system in a manner, that unintended manipulation or changes are impossible (section 8.5 of IEC 61400-1 [1]).

Nevertheless, the following practical recommendation can be given: Double check that commands from any WP control can override neither any protection functions nor its parameter settings in WT control.

5.5.2 Tuning of protections functions

Protection functions and/or their parameters must possibly be tuned/adopted to CL-Windcon specific functions. This in particular might be the case for the allowable yaw misalignment in applications of wake re-direction.

The recommendation is to do the tuning or adaptation of protection functions carefully and under full consideration of related turbine loading.

5.5.3 Control system failure analysis

CL-Windcon Plant Control features can fail.

It is recommended to add related possible failures to the wind turbine failure analysis as per section 8.4 of IEC 61400 1 [1]. See also section 4 above.

5.5.4 Wind turbine behaviour and load simulation

In load simulation of wind turbines, the WT behaviour shall be considered including the CL-Windcon specific CL-Windcon Plant Control actions (see list of load cases suggested in section 7.3 below).

5.5.5 Wind vane calibration

Wind direction sensors on the roof of WT’s nacelle need calibration during the prototype testing of a type of wind turbine. This calibration often is done for yaw misalignment angels of up to ± 20 ° or so. In applications of wake re-direction, the yaw-misalignment angle in operation may be much larger. Typically yaw misalignment of ± 30 ° plus yaw error can be possible (angle definitions in Figure 2 above).

Therefore, the practical recommendation is given to do the calibration of the wind direction sensors up to angles of approximately 40 ° yaw misalignment.

5.6 Test

In addition to the state-of-the-art WT safety and function test plan for the certification module Type Testing according to the IECRE OD-501 [29], the following extra test program shall be supplemented:

- Yaw demand setting, yaw error (definitions in Figure 2 above) and related response times. The parameters shall be taken from the design load case definitions according to IEC61400-1 [1] and section 7.3 below. The minimum and maximum points for triggering the yaw activity must be reached and demonstrated that the below functions are functioning;
  - Yaw system follow the 'Yaw demand' setting
  - Stop initiated by control system upon excessive yaw misalignment, if such stop is defined in WT's control and protection concept
  - Emergency stop initiated by secondary layer protection function upon excessive yaw misalignment, if such stop is defined in WT's control and protection concept.
- Test of all functions transmitted from CL-Windcon Plant Control to WT control. It shall be shown, that the commands from WP to WT control and the related functions in WT control are not able to override WT's protection functions or their parameter settings.
- Test of the wake mitigation function. The test must be performed in the normal operation mode from the lowest up to the highest possible amplitudes and cycle times. It shall show functioning as required.
- In service mode or local control mode, it shall be shown that the commands transmitted from CL-Windcon Plant Control are unable to overcome the local control mode.

5.7 Commissioning

WT and WP are to be commissioned as per state-of-the-art commissioning procedures. In addition, if CL-Windcon Plant Control features shall be used, the commissioning shall be extended to test the related communication lines and functions:

The following communications between the WT controller and CL-Windcon Plant Control shall be considered:

- All related commands from CL-Windcon Plant Control to WT control to be tested
- The test of Yaw Demand and pitch settings for wake mitigation shall be done for both the signals from CL-Windcon Plant Control to WT control and the related function in the WT
- In service mode, the commands from CL-Windcon Plant Control must not override the local WT control.
- Regarding grid code compliance, the priority implementation of the co-ordination between New and Existing Plant Control (see section 6.4 Practical recommendations) should be checked for plausibility as well as signal from system operator.

5.8 Inspection

As part of the certification modules both the Type Testing and the In Service, inspections of the certification body at wind turbines are to be performed.

Inside Type Testing certification module, the inspection is referred to as “Type inspection”. The purpose of the Type inspection is to verify that the WT displays the behaviour and design as predicted in the design certification module. The certification body verifies the satisfactory demonstration of the control system which includes control and protection functions either during the Type inspection or through witnessing of the Safety and Function tests. Therefore CL-Windcon Plant Control features might influence the Type inspection.

At inspections as part of certification module In Service, the test program mentioned in the section 5.7 shall be performed, at least partly. This inspection shall be executed at WT and WP level during the project certification. The successful criteria mentioned in the commissioning (see section 5.7) shall be fulfilled.

6 GRID CODE COMPLIANCE

6.1 Relevant standards for Grid Code Compliance

Grid Codes are asking to fulfil requirements site specifically. The relevant network operator (RNO, formerly known as utility) in charge is depending on the location of the grid connection point. This system operator in question is giving his requirements within grid codes or PPA contracts (power purchase agreements). Within the EU all this needs to be in line with EU regulation 2016/631 (Network Code RfG - requirements for generators) [11]. This regulation is applicable law in all EU member states since it has been published in 2016.

It should be noticed that besides the new “CL-Windcon Plant Control” suggested in this project, some countries (e.g. Germany) have already grid codes requesting a state of the art wind power plant control with well-defined functionalities, slopes accuracies etc. These controllers are named "Existing Plant Control" within this deliverable and are usually already using closed loop wind farm control strategies. These systems are built as described in IEC 61400-27-2 [2], tested per future IEC-61400-21-2 [8] or currently per FGW TR3 [3], certification is done per FGW TR8 (therein called “EZA-Regler”) [7] in Germany and DNVGL-SE-0124 [5] in other parts of the world. Main functions of these Existing Plant Controllers as far as applicable here are:

- receive set points for the whole wind power plant from the RNO regarding
  - output throttling (reducing active power to a specified value in specified time)
  - reactive power, power factor or voltage control set points
- calculation of how to distribute the required demands of the RNO within the plant
  - allocating the overall plant active power reduction requirement to single wind turbines
  - allocating the reactive power set points to the individual wind turbines

6.2 Review of CL-Windcon WP 1 – 4 with regard to standards

The deliverables from work packages 1 - 4 were reviewed. For this section no relevant references to standards or requirements for certification were found.

6.3 Conflicts of CL-Windcon to standards and possible gaps

In order to show the overlapping scopes of the CL-Windcon Plant Control, suggested here, with the Existing Plant Control, the following table can be used. Some functionalities are usually implemented on wind turbine level marked with an x in the column “Wind turbine”, others on wind power plant level, marked an x in the column “Wind power plant”, or x in both columns if the function needs both. Possible conflicts occur where a specific scope is addressed in both the Existing and the CL-Windcon Plant Control.

Table 7: Potential conflicts per functionality in Existing Plant Control versus CL-Windcon Plant Control

Functionality, conditions	Reference	Wind turbine	Wind power plant	Existing Plant Control	CL-Windcon Plant Control	Potential conflict
General	[9] 8.4.1	X	x	x		
Active power control by set point, re-connection control, accuracy in set point	[9] 8.4.2, [7] 2.13.4	X	x	x	x	x
Active power ramp rate limitation and accuracy	[9] 8.4.3, [7] A.1.2.5.1.2	X	x	x	x	x
Frequency control (Limited frequency sensitive mode – underfrequency (LFSM-U)) reducing active power during over frequency	[9] 8.4.4	X		x	x	x
Synthetic inertia changing active power during frequency deviation	[9] 8.4.5	X		x	x	x
Reactive power control as fixed power factor (PF), as PF depending on P, by setting reactive	[9] 8.4.6	X	x	x		x

Functionality, conditions	Reference	Wind turbine	Wind power plant	Existing Plant Control	CL-Windcon Plant Control	Potential conflict
power Q or voltage depending Q, i.e. Q(U)	[7] 2.13.4					
Measuring voltage and current at the plant connection point	[7] 2.13.4		x	x		
Dead time, dynamic, Voltage dead band	[7] 2.13.4, A.1.2.4.2.2	X	x	x		x
Accuracies and slopes	[7] A.1.2.4.2.2, A.2.2.5.1.2	X	x	x		x

From a grid code compliance perspective, regarding the proposed CL-Windcon Plant Control [10], the following points are relevant:

A. Active electric power at the interconnection point of the power plant and at the wind turbine terminals is changed by the CL-Windcon Plant Control

B. Yaw angle and pitch angle in normal operation could be changed continuously or periodically (oscillating) by the CL-Windcon Plant Control

This is critical regarding fault operation of the wind turbines for the very limited durations while faults exist in the electric power grid outside the wind power plant (including times where the grid capacity is not able to transport more electric current, i.e. overloading of lines).

The following fault operations are having potential conflicts between grid code requirements and the CL-Windcon approach. Please find below a table with the fault operations, the relevant requirements and the reasons why this is conflicting with the proposed CL-Windcon plant control:

Table 8: Potential conflicts per fault type between Existing Plant Control and CL-Windcon Plant Control

Fault situation	Typical durations	Requirement	Conflicts
Grid fault	Seconds up to minutes per fault	Specific characteristics	• Unclear if characteristics per [8] can be kept • Unclear if tests for undervoltage ride-through (UVRT) would also have passed with misaligned Yaw • Unclear if UVRT-tests could also be passed having misaligned pitch during wake mitigation operation etc.
Frequency is above 50 Hz	Seconds up to 90 Minutes per case	Reduce active power with specific characteristic	• CL-Windcon Plant Control and Existing Plant Control might have opposite control targets regarding active power
Line congestion (overloading)	Could be longer, e.g. days	Reduce active power output to set points provided via remote control by the RNO	• Dynamics and accuracy are well-defined and tested per turbine as well as certified by turbine type and by plant (project). With the CL-Windcon Plant Control the behaviour of the power plant and of the wind turbines can be different and must be tested and certified additionally.

Other conflicts:

- Within wind power plant simulations regarding electrical load flow and electrical protection verification, specific characteristics are to be proven to be fulfilled in type and project design. Changing control strategies within wind power plants by adding control features on plant level and on turbine level need to take this into account during certification of grid code compliance on both, plant level and turbine level.

- Grid Code requirements from the functionality table 2 above could be opposite regarding the CL-Windcon targets.
    - Strategies for re-connection after faults, e.g. blocking signal for re-connection
    - Ramp rate control regarding a6.4ctive power if required, e.g. active power reduction by RNO

6.4 Practical recommendations

After analysis of the descriptions of the CL-Windcon Plant Control in WP 2 regarding grid code compliance the following recommendations for the design can be given:

- Active Power Control (APC) shall be prohibited while system frequency is outside the values in which no LFSM-O (limited frequency sensitive mode – overfrequency) is required by the grid code.
- While the RNO (system operator in charge for the connection point) due to congestion or other reasons is asking for de-rating the output power, additional APC shall be prohibited (RNO shall overrule the de-rating signals of the CL-Windcon Plant Control)
- New wind farms having the CL-Windcon Plant Control implemented, need to show FRT-compliance also for those fault-ride-through tests with maximum misaligned yaw angle which could happen (additional type testing)
- The co-ordination of an Existing Plant Control module and an additional CL-Windcon Plant Control module needs to be assessed and priorities have to be implemented according to grid code requirements. Two possibilities for an implementation into the control system are seen:
    1. An Existing Plant Control and a CL-Windcon Plant control will be implemented in a parallel approach. The CL-Windcon Plant Control will be deactivated during fault conditions in the grid. The Fault conditions could be detected either by the Existing Plant Control or by an additional feature of the CL-Windcon Plant Control. Such fault conditions include requests from the system operator to reduce the active power output by x % compared to the available power due to congestions in the grid etc., see Figure 3 below.

2. An integrated approach may include the Existing Plant control within the CL-Windcon Plant Control, see Figure 4 below. In this case, reduction signals from the electric power system operator in charge for the grid connection point would be provided directly to the CL-Windcon Plant Control and the Existing Plant Control. Signals controlling the power factor, voltage control and other values related to reactive power will only be handled by the Existing Plant Control, as they are not relevant for mechanical loads nor for wind wakes etc.

The design of implementing the CL-Windcon Plant Control can be done differently. Correspondingly the co-operation-assessment needs to be performed depending on this structure.

- The CL-Windcon Plant Control as proposed within this project is also including some new control strategies to be implemented in the control of each wind turbine. Changing control strategies usually changes at least the dynamic behaviour of the corresponding systems or functionalities. This is influencing the tested and certified grid code compliance regarding the following functionalities, which need to be re-assessed and re-certified or maybe even re-tested. Respective issues and reasons are listed in the following:
    1. Electric active power control dynamic behaviour might change with the new control. Step-response tests might be needed to be repeated
    2. Frequency response (changing electric active power due to electric system frequency measured at the unit)
    3. Reactive power controllability can have a changed dynamic behaviour in those cases where active power needs to be reduced in order to reach the reactive power required
    4. Requirements for limited ramp-up of electric active power output after a period with zero voltage (turbine switch-off) might be different with CL-Windcon Plant Control implemented in the turbine
    5. State of the art fault ride-through testing does not include such huge misalignments of the yaw angle. Performing UVRT tests with such huge misalignments should be tested. Concerns are existing regarding the loads during a voltage dip, when operating the turbine under misalignments of the yaw angle and also concerning the speed and the torque if the turbine is able to run through a voltage dip even with misaligned yaw, showing the same electric characteristics as required.

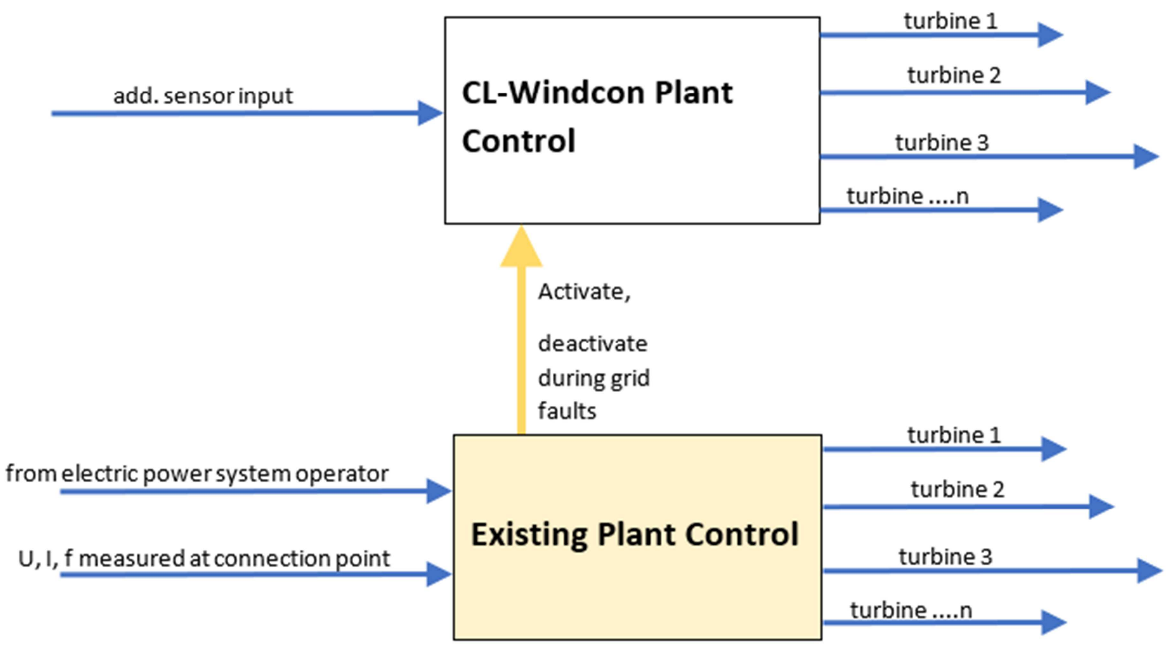


Figure 3: Parallel approach for co-ordination between Existing Plant Control and CL-Windcon Plant Control

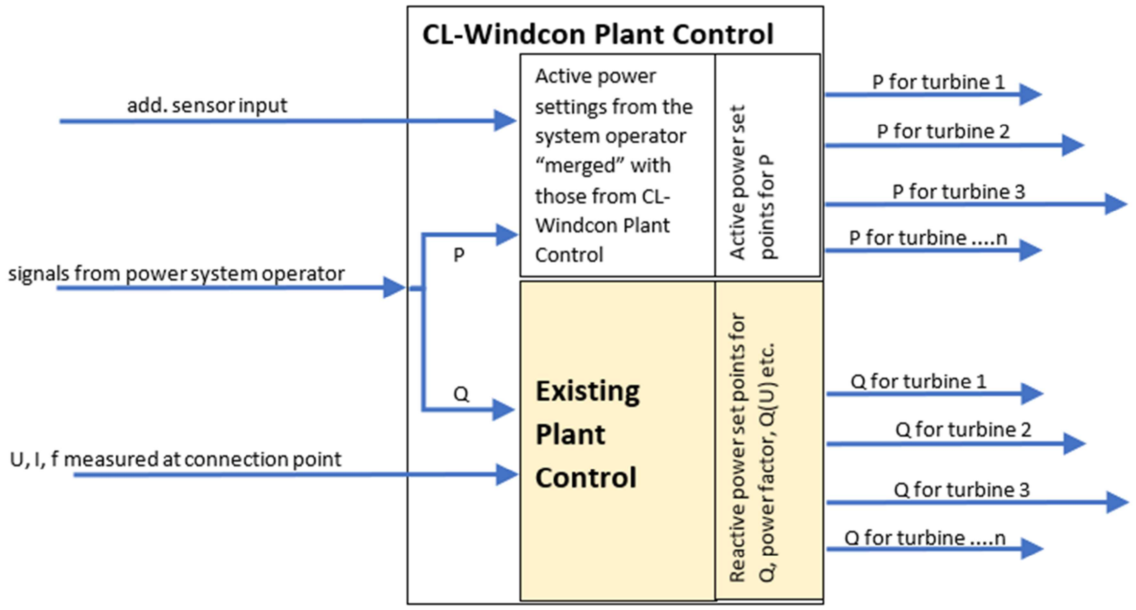


Figure 4: Integrated approach for co-ordination between Existing and CL-Windcon Plant Control (further output signals to turbines besides active power P and reactive power Q like yaw angle setpoints were omitted here for better oversight)

In both cases the functionalities as listed in Table 7 are implemented on turbine level (Figure 5). Each individual wind turbine is usually tested and certified to deliver proper start-up ramp rates regarding active power, step response etc. Therefore, changes in the active power control behaviour due to the proposed new methods within this project will lead to the necessity to test, assess and certify them again if they are changing the conditions from the grid code regarding active power control behaviour.

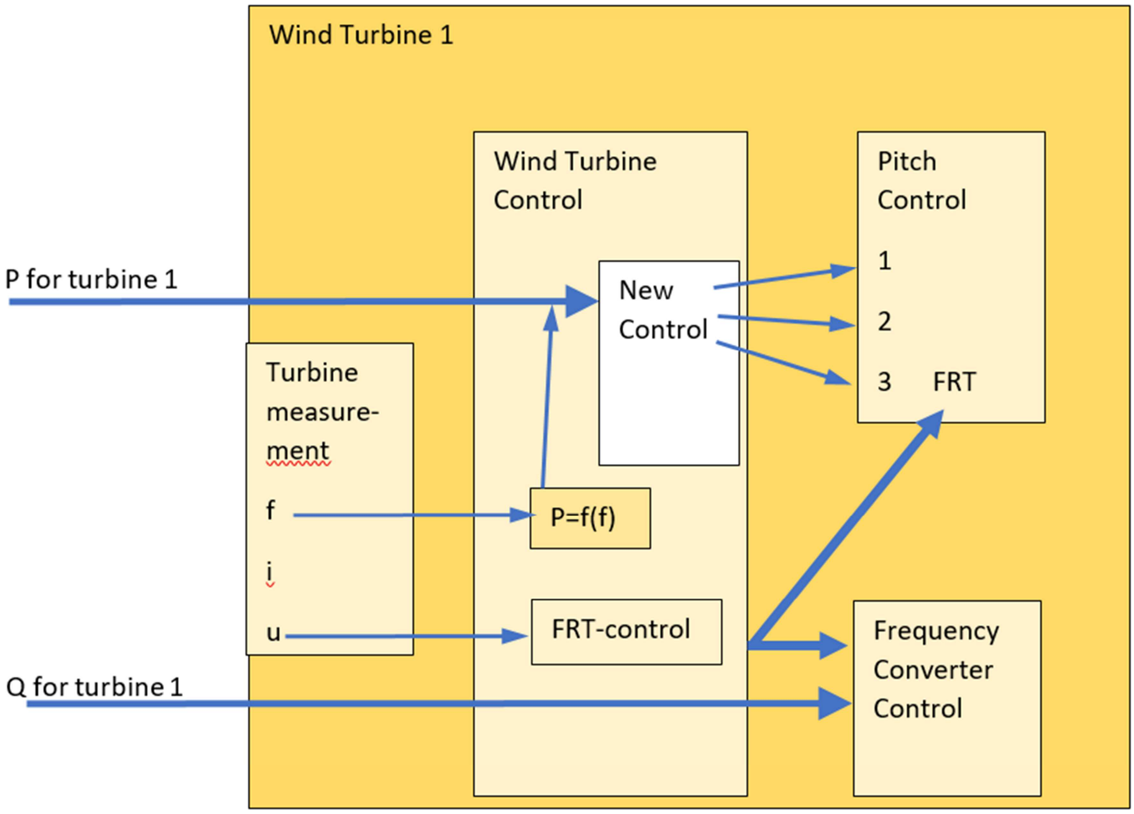


Figure 5: Additional co-ordination of Existing and new CL-Windcon Plant Control on wind turbine level

FRT is only controlled on turbine level, not by any plant control. The reason is the dynamic requirement regarding these issues in time ranges of a few ms only (related to electrical current sine waves with a period of 20 ms). Figure 3 and Figure 4 are only representing less dynamic control issues as e.g. reducing active power by input from the system operator or from CL-Windcon Plant Control.

Depending on design solution of the turbine manufacturer FRT control is also having impact on pitch control and hence is one of the most dynamic load changing events a wind turbine could be exposed to.

6.5 Recommended amendments of standards for GCC

Based on the previous findings recommendations for amendments to standards are proposed which are related to the design and implementation of CL-Windcon Plant Control. The recommendations are divided into recommendations intended for design standards respectively standards applicable for testing as listed in the following sections 6.5.1 and 6.5.2.

6.5.1 Test standards

In addition to the state of the art test plan for GCC the following tests should be amended for a certification of a wind power plant with CL-Windcon Plant Control:

A1. Additionally to the FRT testing procedures being state of the art per DNVGL-ST-0125 [6], IEC 61400-21-1 [9] or FGW TG3 [3], the yaw misalignment should be tested during the FRT tests, too. The success criteria for these additional testing is coming from the corresponding grid code valid at the connection point as it is usually done within grid code compliance project certification. Corresponding simulations could be discussed alternatively if simulation models are available which are validated against test results per FGW TG4 [4] or IEC 61400-27-1 [25] respectively IEC 61400-27-2 [2].

A2. Requirements for assessment of UVRT test results in the standards need to include the misaligned yaw angle per the proposed CL-Windcon plant control, see Table 10: Recommended changes in existing design standards or drafts .

A3. Testing regarding the co-operation of the different functionalities of the CL-Windcon Plant Control and the Existing Plant Control needs to be implemented in the testing and certification standards (new functionalities versus state of the art GCC functionalities), see Table 10.

As grid codes usually already require wind farm control functionalities the validations for new (i.e. CL-Windcon) and Existing Plant Control should go hand in hand. This means, all the state-of-the-art validation against test results as described in [2] and [7] shall apply to the Existing and the CL-Windcon Plant Control simulation models. The changes in the control strategy and in the wind turbine control also need to be implemented in the electric simulation models of the wind turbine units per [2], [4] and [7].

A4. The correct implementation of priorities between the different controls should be tested for the wind turbine unit and also on plant level. This test has to be developed. For details see section 6.5.

A5. Controllability of active power per FGW TG3 [3] or IEC 61400-21-1 [9] shall be tested including the proper co-operation between the CL-Windcon Plant Control and the Existing Plant Control as well as regarding the co-ordination between those in the wind turbine itself (see Figure 5 in section 6.4). This includes ramp-rate-limitation, set point control, step response behaviour and frequency response (LFSM-U) as well as optionally synthetic inertia. These measurements usually also ask for dead times, slopes and other dynamic details which could be changed by changing control strategies as proposed within this project.

A6. Re-connection after faults (e.g. after switch-off due to electric protection tripping) can be tested per FGW TG3 [3] or IEC 61400-21-1 [9].

A7. For the project certification according to the IECRE OD-501 [29], the wind farm communication shall be tested after the implementation of the wind farm control strategies listed in section 5. However, DNVGL-SE-0190 [27] in section 4.2.5, only mentions testing requirement for the communication, but does not specify the test itself.
IEC 61400-25-5 [28] in section 3.8 at least defines SAT (site acceptance test). However, it only states that SAT is based on customer requirements (section 5.1). No specific test procedure is given. As a consequence, appropriate testing procedures need to be developed.

The following Table 9 gives an overview in which test standards changes should be implemented as listed in columns noted with Ax. Standards are listed in lines along with references to the respective documents in the Bibliography.

Table 9: Recommended changes in existing testing standards or drafts

	A1. FRT test including misaligned yaw	A2. Assessment of FRT testing with misaligned yaw	A3. Testing for co-operation Existing and CL-Windcon Plant Control	A4. Testing of priorities between controllers	A5. Testing of controllability of active power	A6. Testing of re-connection after faults	A7. Testing of wind farm communication
[1] IEC 61400-1 (safety)				x			
[2] IEC 61400-27-2 (simulation model validation)					x	x	
[3] FGW TG3 (testing)	x	x	x		x		
[4] FGW TG4 (simulation model valid.)		x			x	x	
[25] IEC 61400-27-1 - generic models						x	
[5] DNVGL-SE-0124 (certification)	x	x	x	x	x	x	
[6] DNVGL-ST-0125 (assessm. test)	x	x	x	x	x	x	
[7] FGW TG8 (GCC certification)	x	x	x	x	x	x	
[8] IEC 61400-21-2 (plant meas.)			x		x		
[9] IEC FDIS 61400-21-1 (testing)	x	x	x		x		

	A1. FRT test including misaligned yaw	A2. Assessment of FRT testing with misaligned yaw	A3. Testing for co-operation Existing and CL-Windcon Plant Control	A4. Testing of priorities between controllers	A5. Testing of controllability of active power	A6. Testing of re-connection after faults	A7. Testing of wind farm communication
[13] VDE-AR-N 41xx (grid code)	x	x	x	x	x	x	
[14] EN50549-x (assessm. test)	x	x	x	x	x	x	
[27] DNVGL-SE-0190 [28] IEC 61400-25-5							x

6.5.2 Design standards

The following recommendations for improving the design standards are given to facilitate the certification of a CL-Windcon plant control:

B1. All issues where the dynamic behaviour during active power control is affected need to consider the possible implementation of the CL-Windcon Plant Control as proposed within this project. This includes the following functionalities mainly in the wind turbine but also on plant level:

a. Control strategies for re-connection after faults

b. Ramp-up after zero voltage situations (switch-off)

c. Ramp rate control

d. Frequency response (see following item 5)

e. Reductions of active power due to running into the limit of reactive power change and accepted higher priority to reactive power per grid code

B2. Changing the electric active power to compensate a frequency deviation compared to 50 Hz (FSM and LFSM-O) shall override any of the CL-Windcon Plant Control functions. This has to be tested, assessed and certified.

B3. Changing the electric active power depending on a corresponding reduction signal from the electric system operator (e.g. due to line congestions or operation outside the specified electric values) shall override any of the CL-Windcon Plant Control functions. This has to be tested, assessed and certified.

B4. Changed electric power load flows due to the CL-Windcon Plant Control in the internal grid in the wind power plant should be considered during electric simulations for project certification if needed. This should be mentioned in the corresponding standards.

B5. Priorities of the different controllers should be implemented in the standards, defining priorities for different functionalities in different cases.

B6. All standards dealing with the Existing Plant Control need to consider possible implications by the CL-Windcon Plant Control, too.

B7. Simulation model validation of the CL-Windcon Plant Control needs to be properly implemented into the applicable standards for simulation model validation of the Existing Plant Control. This also means that the corresponding changes in control strategy in the wind turbine control as proposed in this project also needs to be implemented in the electric simulation models of the wind turbine units per [2], [4] and [8] and in the standards which those refer to.

B8. Impact of grid code compliance on structural integrity needs to be assessed.

The following Table 10 gives an overview in which design standards changes should be implemented as listed in columns denoted with Bx. Standards are listed in lines along with reference to the respective documents in the Bibliography.

Table 10: Recommended changes in existing design standards or drafts

	B1. Changes in dynamic behaviour (active power control)	B2. Changes regarding frequency response (LFSM-O)	B3. Highest priority for system operator input signal	B4. Simulations to consider different load flows (electric)	B5. Priorities between controllers	B6. Consider CL-Windcon Plant Control and implement this	B7. Consider CL-Windcon Plant Control for validation of existing model	B8. Impact on structural integrity
[1] IEC 61400-1 (safety)					x			
[2] IEC 61400-27-2 (simodel. valid.)	x					x	x	
[3] FGW TG3 (testing)	x	x	x			x		
[4] FGW TG4 (simmod. validation)	x					x	x	
[25] IEC 61400-27-1 - generic models						x	x	

	B1. Changes in dynamic behaviour (active power control)	B2. Changes regarding frequency response (LFSM-O)	B3. Highest priority for system operator input signal	B4. Simulations to consider different load flows (electric)	B5. Priorities between controllers	B6. Consider CL-Windcon Plant Control and implement this	B7. Consider CL-Windcon Plant Control for validation of existing model	B8. Impact on structural integrity
[5] DNVGL-SE-0124 (certification)	x	x	x	x	x	x	x	
[6] DNVGL-ST-0125 (assessm. test)	x	x	x	x	x	x	x	
[7] FGW TG8 (GCC certification)	x	x	x	x	x	x	x	
[8] IEC 61400-21-2 (plant meas.)	x	x	x	x		x		
[9] IEC FDIS 61400-21-1 (testing)	x	x	x			x		
[13] VDE-AR-N 41xx (grid code)	x	x	x	x	x	x	x	
[14] EN50549-x (assessm. test)	x	x	x	x	x	x	x	
see section 3.1								x

7 DESIGN LOAD CASES

In the load calculation the loads for the design of the main parts of a wind turbine are calculated. Later, site specific load calculations are carried out to validate a turbine design for specific site conditions. Different load situations are described in design load cases (DLCs). A load calculation has the goal to simulate the loads acting on the real wind turbine as precise as possible. Therefore, it is important to implement the control and protection system as used in the real wind turbine in the load simulation. Normally, all wind turbines in a wind park show the same behaviour and no individual control strategies are implemented. With the controller strategies introduced with CL-Windcon this has changed. Hence, the increased complexity has also to be reflected in the load simulation.

In chapter 7.1 related standards are discussed. Chapter 7.2 reviews CL-Windcon deliverables with regards to the standards. Chapter 7.3 provides comments on load cases based on the introduced controller strategies. Practical recommendations on load simulations as well as on design evaluation are given in chapter 7.4 and chapter 7.5.

7.1 Related standards DNVGL-ST-0437 [15] and IEC 61400-1 [1]

The requirements for site-specific load case definition acc. IEC 61400-1 [1] are stated therein in section 11.10 "Assessment of structural integrity by load calculations with reference to site-specific conditions" and Annex B "Design load cases for special class S wind turbine design or site suitability assessment". The requirements for site-specific load case definition acc. DNVGL-ST-0437 [15] are stated in section 4.4 "Load case table for onshore and offshore loads" and in section 4.6 "Design load cases for extended design situations".

IEC 61400-1 [1] section 11.10 and DNVGL-ST-0437 [15] section 4.8.2 state similarly with respect to fatigue load cases "Fatigue load calculations shall be …". This implies that the complete list of fatigue relevant DLCs acc. to IEC 61400-1 [1] Table 2 must be simulated: DLC1.2, DLC2.4, DLC3.1, DLC4.1, DLC6.4, with frequencies/durations acc. to section 7.4.3.4 footnote 7 / section 7.4.4 footnote 9 / section 7.4.5 footnote 10. DNVGL-ST-0437 [15] states equivalent.

IEC 61400-1 [1] section 11.10 and Annex B and DNVGL-ST-0437 [15] section 4.8.2 state similarly that (copy from IEC 61400-1 [1] section 11.10): "… the following ultimate design load cases shall be assessed as minimum: DLC 1.1, DLC 1.3, DLC 6.1, and DLC 6.2. […] If relevant, other load cases than in design situations 1), 6), and 7) in Table B.1 should be considered. Design situations 2), 3), 4), 5), and 8) in Table B.1 only need to be considered when the control system behaviour and transport, assembly, maintenance and repair procedures are site-dependent.” Table B.1 list all DLCs of Table 2 under site-specific external conditions “S”. The following DLCs are possibly relevant for CL-Windcon:

- DLC1.6 ETM-s Wake effects
- DLC1.7 NTM-s Ice formation / wake

7.2 Review of CL-Windcon WP 1 – 4 with regard to standards

The following CL-Windcon deliverables have been found to be relevant for this review:

- “DELIVERABLE REPORT 4.1: Assessment of controller key performance indicators & Guidelines on controller application for the management of existing wind farms [16]

The DLC table is included and explained as shown below and commented. The coordinate system used in [16] is identical to DNVGL-ST-0437 [15] Appendix A. For the DLC definition no specific reference could be identified (could be IEC 61400-1 [1] or DNVGL-ST-0437 [15]).

The table and text (indicated with underline) is copied from CL-Windcon-Deliverable 4.1 [16] sections 3.3 and 3.4 are commented as given below:

Table 1. List of DLCs to evaluate the wind farm control performance at wind turbine level. F: fatigue U: ultimate load; ADC: actuator duty cycle.

DLC	Operation	Wind condition	KPIs	Other conditions	Safety factor
DLC 1.1	Power prod.	NTM $[V_{in} : V_{out}]$	AEP, ADC, F		1.0
DLC 1.2	Power prod.	NTM $[V_{in} : V_{out}]$	U		1.35
DLC 1.3	Power prod.	ETM $[V_{in} : V_{out}]$	U		1.35
DLC 1.4	Power prod.	ECD V_r, $V_r \pm 2$, V_{out}	U		1.35
DLC 1.5	Power prod.	EWS $[V_{in} : V_{out}]$	U		1.35
	Power prod. + faults	NTM $[V_{in} : V_{out}]$	U	Grid loss + pitch freeze	1.10
DLC 2.2	Power prod. + faults	NTM $[V_{in} : V_{out}]$	U	Grid loss + brake failure	1.10
	Power prod. + faults	NTM $[V_{in} : V_{out}]$	U	Pitch runaway	1.10
DLC 2.3	Power prod. + faults	EOG V_r, $V_r \pm 2$, V_{out}	U	Grid loss	1.10
DLC 6.1	Parked	EWM - Wind dir. -8, 0, 8 deg	U		1.35
DLC 6.2	Parked + Fault	EWM - Wind dir. 0:30:330	U		1.35

- <u>Not all load cases are considered</u>:

  Consequently, all design driving load cases should be calculated or a pre-study should be carried out to show that some load cases are not design drivers.

- The wind farm control is to be considered active only in a range of wind speed (i.e. up to a given speed). In absence of further specifications the range 4 - 15 m/s is considered: CL-Windcon Plant Control wind speed range should be simulated as implemented in the real wind turbine.
- Some failures (e.g. pitch freeze, pitch runaway, . . .) of DLC 2.2 to be selected on the basis of their relevance: must be extended to DLC2.1 (ULS), DLC2.2 (ULS), DLC2.4 (FLS+ULS) with ULS = ultimate load analysis and FLS = fatigue load analysis; see IEC 61400-1 section 11.10 and Annex B) to be selected based on turbine and wind power plant FMEAs
- Wind rose selected according to FINO3 measurements: it is assumed that the "wind rose" includes sector-wise wind direction probabilities, Weibull distribution, turbulence intensities, and possibly deterministic gusts as e.g. EOG, ECD, EWS)

7.3 Conflicts of CL-Windcon to standards and possibly gaps & needed amendments of standards due to CL-Windcon

A recommendation is made for an updated load case catalogue considering CL-Windcon Plant Control based on site wind conditions.

Assumptions:

It is assumed that the following information is available:

- a given site-specific wind conditions (=wind rose + all site-specific wind speeds + all site-specific gusts that can be determined + all site-specific TI distributions) and
- a defined CL-Windcon Plant Control (in this case as an example) applying yaw misalignment for wake redirection and following requirements of active power control for GCC and
- an existing FMEA analysis covering also the CL-Windcon Plant Control

Recommendation for Design Load Cases Catalogue:

Based on DNVGL-ST-0437 [15] and IEC 61400-1 [1], it is recommended to simulate at least the DLCs listed below, considering the above listed information for site-specific wind conditions, CL-Windcon Plant Control and FMEA.

These load cases shall be simulated for the wind turbines carrying out any CL-Windcon Plant Control action, as well as for wind turbines being affected by any CL-Windcon Plant Control action.

- **Fatigue load analysis (FLS):**
    - DLC1.2 NTM-s
    - DLC2.4 NTM-s (operation with failure and additionally with / without yaw misalignment and GCC active power control and also considering FMEA for CL-Windcon plant control)
    - DLC3.1 NWP-s / DLC4.1 NWP-s
    - DLC6.4 NTM-s (considering yaw misalignment if it is still active)
    - possibly further DLCs of IEC 61400-1 Table B.1 and DNVGL-ST-0437 [15] Table 4-4 (site-specific design load cases), if relevant
    - assumptions are required for the probability / duration of fatigue load cases for each specific situation:
        - With yaw misalignment
        - Without yaw misalignment
        - Without upstream wake impingement
        - With upstream full / partial wake impingement
        - GCC active power control
        - Combinations
        - Considering the probability / duration of each situation

- **Ultimate load analysis (ULS):**
    - DLC1.1 NTM-s
    - DLC1.3 ETM-s
    - DLC1.4 ECD-s
    - DLC1.5 EWS-s
    - DLC1.6 ETM-s Wake effects
    - DLC2.1 NTM-s (Normal control system fault acc. to IEC 61400-1 [1] section 7.4.3 and DNVGL-ST-0437 [15] section , 4.5.2 considering FMEA for CL-Windcon plant control)
    - DLC2.2 NTM-s (considering also FMEA for CL-Windcon Plant Control)
    - DLC2.3 EOG-s / ETM-s

- DLC2.5 NWP-s
- DLC3.1 NWP-s / DLC4.1 NWP-s (*)
- DLC3.2 EOG-s / DLC3.3 EDC-s / DLC4.2 EOG-s (DLC4.2 often design driver) (*)
- DLC5.1 NTM-s
- DLC8.1 NTM-s (maintained turbine influenced by running turbines under CL-Windcon Plant Control)
- possibly further DLCs of IEC 61400-1 [1] Table B.1 and DNVGL-ST-0437 [15] Table 4-4 (site-specific design load cases), if relevant
- For ULS analysis all DLCs with turbine in operation must be calculated for the case of yaw misalignment (maybe even in steps between 0deg yaw misalignment and max yaw misalignment)
- (*) normal start up and shut down cases might be omitted, in case the CL-Windcon Plant Control excludes normal start up and shut down combined with CL-Windcon Plant Control actions (e.g. yaw misalignment)
- DLC6.1 / DLC6.2 / DLC6.3 EWM-s (**)
- DLC7.1 EWM-s (**)
- DLC8.2 EWM-s (**)
- possibly further DLCs of IEC 61400-1 [1] Table B.1 and DNVGL-ST-0437 [15] Table 4-4 (site-specific design load cases), if relevant (**)
- (**) for these DLCs the wind turbines are not in operation, but idling or locked; site-specific wind conditions must be considered but probably not the CL-Windcon Plant Control

New or updated design load case due to e.g. increased yaw error or e.g. possible cyclic collective pitch movements shall be added. This may cause the fatigue on the structure and shorten the design life time of the structure of the wind turbine.

7.4 Practical recommendations to load simulations

As a pre-requisite, it must be ensured that applied calculation methods, being suitable for present load calculations on turbine level are feasible also for CL-Windcon Plant Control strategies, as e.g. high yaw misalignments for wake redirection.

According to internal project communication, previous measurement have shown that significant deviations exist between measured and simulated loads for cases with yaw misalignments in the order of 40deg. For the load simulations, a code was applied using the Blade-Element-Method (BEM). This might indicate that the BEM may have problems in simulating correct loads for high yaw misalignments. The reason might be three-dimensional effects due to inflow along the blade for large yaw misalignments. This problem of BEM is well known.

7.4.1 Concept flow chart for wind farm load simulations

A flow chart is suggested demonstrating load simulations for wind power plants, i.e. site-specific design assessments (SSDA). The following assumptions are made:

- the wind power plant layout (wind turbine parameters, number and position of single wind turbines, etc.) and external conditions (wind rose distribution with all relevant data) is given
- pure offshore effects (e.g. waves, different water depths, etc.) are excluded
- for the conventional approach without CL-Windcon Plant Control:
    - the main aim is to identify the most loaded single wind turbine
    - it might not be possible to determine the most loaded wind turbine a priori, so finally more than one turbine must be simulated
- for the approach with CL-Windcon Plant Control:
    - possibly all single wind turbines of a wind farm must be simulated in order to determine an optimized economic operation of the entire wind power plant
    - a clustering might be possible (1st row, 2nd row, etc)
- no economic effects are considered here (cost of energy including wear, maintenance, energy output optimization, etc.)

In Figure 6, in the blue upper left box (conventional input for SSDA) the required input for wind power plant load simulations without CL-Windcon Plant Control is listed. In the red upper right box (additional input for SSDA with CL-Windcon Plant Control) the additional input is listed for wind power plant load simulations considering CL-Windcon Plant Control. The upper box stands for any new tool that describes external conditions, e.g. wind speeds and turbulences within steered wakes.

The second red box stands for the modified load case catalogue, as proposed section 7.3. The last red box stands for the applied CL-Windcon Plant Control strategy as input for the wind turbine and CL-Windcon Plant Control system, including any required parameter settings for any single turbine.

The two blue boxes below list the load analyses for extreme loads (ULS) and fatigue loads (FLS), which are identical for the cases with and without CL-Windcon Plant Control.

7.4.2 Refined concept flow chart for wind farm load calculation with wind farm control

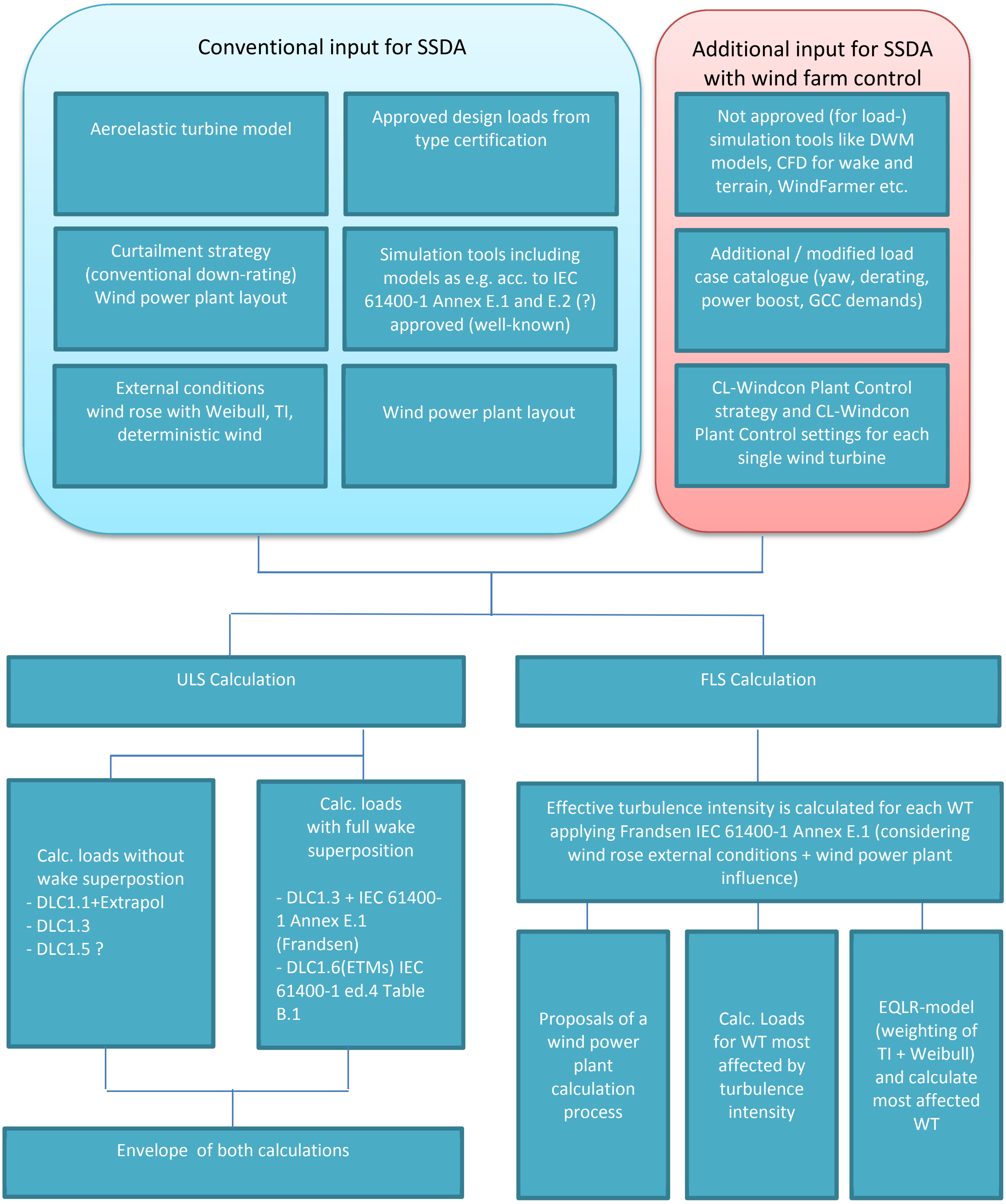


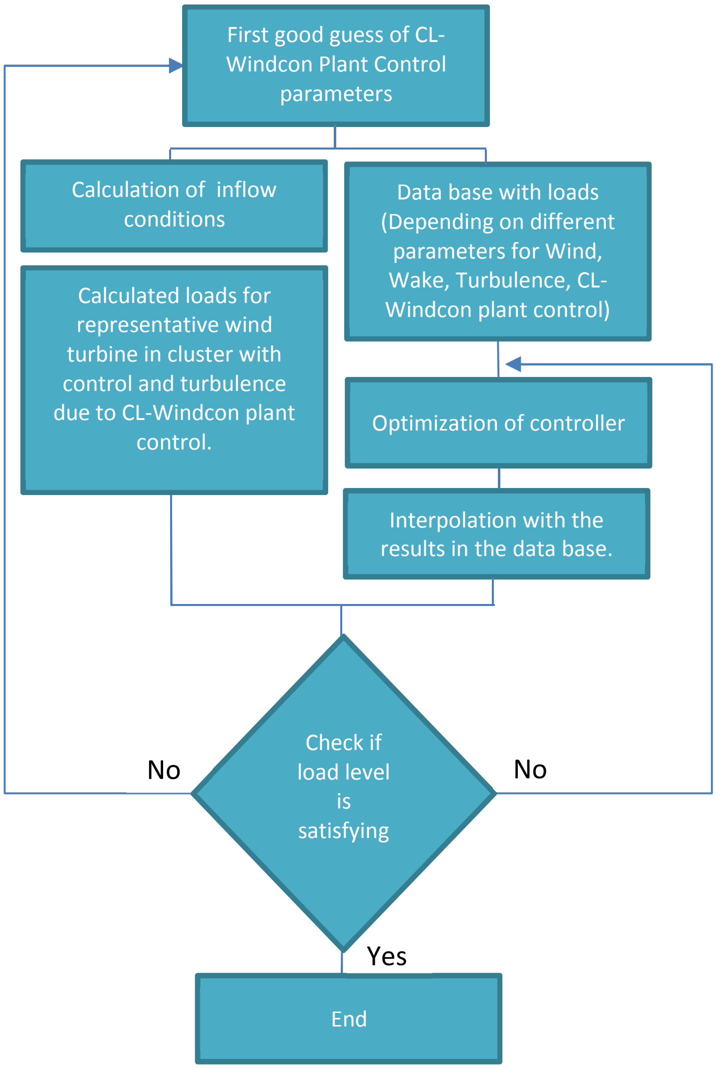
Figure 6: Site-Specific Design Assessment for without CL-Windcon Plant Control and the additional input necessary for CL-Windcon Plant Control

The load calculation of a wind power plant, especially offshore, is a processing intensive work. Usually, the wind power plants are clustered and only individual representative wind turbines are calculated. The ambient turbulence as well as the wind power plant effects are included in the load simulations.

More complex is the simulation in case CL-Windcon Plant Control is included in the simulation. The purpose of CL-Windcon Plant Control is to reduce loads or optimize power output. This is done e.g. by de-rating and wake steering. The increased complexity of the wind power plant behaviour is followed by an increase of complexity in the wind power plant simulation. The proposed load case definition presented in section 7.3 shows the load cases which have to be taken into account for a site-specific load calculation with regards to CL-Windcon Plant Control. But the implementation of wind power plant load calculation with CL-Windcon Plant Control is still under development and depends strongly on the tools and the processing power.

In the following graph a suggestion of an implementation is presented. Further thoughts on this topic are given in “Combining induction control and wake steering for wind farm energy and fatigue loads optimisation” [17]. The approach shown in the left thread of Figure 7 calculates the wind power plant loads based on the pre-calculated wake and turbulence conditions. Whereas the right thread shows the calculation of a load database for different CL-Windcon Plant Control settings and turbulence intensities. Later this data base is used to optimize the CL-Windcon Plant Control parameters to calculate the wind power plant loads. It should be noted that sufficiently validated models for either of the threads are not known.

Figure 7: Proposals of a wind power plant calculation process



7.4.3 Validation of wind power plant load calculation process (general approach)

As mentioned in section 7.4.1 for the upper red box in Figure 6 and also in section 7.4.2, significant uncertainties exist due to not sufficiently validated new models for the determination of external conditions and simulation of load simulations applying CL-Windcon Plant Control. Based on the information available, it seems difficult for the near future to have those new models validated in the required accuracy range for commercial applications.

Such uncertainties might be decreased during thorough validation within e.g. research projects, where all single new or modified models for determination of external conditions and simulation of load simulations are tested separately against measured data and then combined to the entire process. This process might be very time and money consuming.

Instead of a a-priori-validation of those models, a validation is suggested which is carried out during operation of the (commercial) wind power plant under investigation. During the Site-Specific Design Assessment (SSDA) the new or modified models for determination of external conditions and simulation of load simulations are only assessed on a plausibility basis, but not finally approved. Since final approval of the new modules is outstanding, not all the planned benefits of the new modules are realized for the operational limits of the wind power plant. For example, the life time is reduced from the planned full life time down to a reduced value, which compensates for the uncertainty in load simulation.. The issued SSDA or Project Certificate (PC) includes conditions within the modified in service module that the validity of the new modules shall be approved by measurements during the first years of operation of the realized wind power plant. If these measurements (external conditions, loads, SCADA data, etc.) show that all new models have determined correct calculations, e.g. the life time is extended to the initially planned life time. In case the new models have underpredicted the loads, the realistic loads must then be calculated based on the measured values. Actions must be taken either to meet the initially planned life time (e.g. curtailment), or the life time is reduced according to the measured loads.

By carrying out a number of such projects, a step-by-step validation of the new models can be carried out, leading to the full approval of the new models. The section below describes this modified in service module step-by-step.

7.4.4 Modified in service module for SSDA / project certificate including CL-Windcon Plant Control

1. Assess CL-Windcon Plant Control on theoretical basis by plausibility checks, do not approve unknown or new simulation model in detail, because that is probably not possible
2. Issue of SSDA including CL-Windcon Plant Control
    a. in case the customer wants to “invest” the load reduction into extended life time (> 20 years): SSDA will state a life time of somewhere between the conventional life time and the life time desired by the customer -> determine a conservative life time (based only on plausibility checks!), but better than conventional, the customer gets something but not yet 100% of what is desired
    b. in case the customer wants to “invest” the load reduction into smaller spacings between single turbines or into lower-dimensionized turbines (e.g. IEC class III instead of IEC class II) with a life time of 20 years (the minimum lifetime for a

SSDA / project certificate is 20 years, with reference to IEC 61400-1 [1] Sec. 6.2) and DNVGL-ST-0437 [15] section: SSDA will state a life time of 20 years but with the condition that the “in service module” must demonstrate that the assumptions / simulations for the CL-Windcon Plant Control can be verified; otherwise the wind power plant will be curtailed in order to meet the life time of 20 years without having the expected but not realized effects of the CL-Windcon Plant Control

3. Project certificate includes “in serviced module” with:
    a. requirement of measurements of loads and external conditions for e.g. first 5 years of wind power plant operation
    b. compare with initial simulations for SSDA
    c. if comparison is ok (which minimum requirements for “ok”?), then
        i. for case 2a: rest of desired life time will be issued, or whatever comes out from the measurement vs. simulation comparison
        ii. for case 2b: wind power plant can operate un-curtailed, or whatever curtailment is necessary to meet life time of 20 years

7.5 Practical recommendations to Design Assessment

The state-of-the-art Design Assessment (DA) of WT does not consider wind power plant effects, except for optional load cases as listed in e.g. IEC 61400-1 [1] Table B.1 and DNVGL-ST-0437 [15] Table 4-4, see section 0 above. State of the art Design Assessment (DA) consider stand-alone turbines only. Wind power plants on the other hand are covered by Site-Specific Design Assessments (SSDA).

However, it is recommended to include any wind power plant effects (including CL-Windcon Plant Control), already into the DA, as far as possible. These wind power plant effects might be the application of any specific wind turbine controller features (including the possibly to be updated control system), grid code requirements, as well as applied simulation codes and methods. The specific set of external conditions and CL-Windcon Plant Control parameters might be chosen to cover a typical but generic wind power plant. The project specific external conditions and CL-Windcon Plant Control parameters will then be covered in the Site-Specific Design Assessments (SSDA).

8 CONCLUSION

The CL-Windcon Plant Control approach has been assessed with respect to certification, in the area of “control”, “grid code compliance” and “loads”. While there are a lot of findings in detail, it can be stated that most of the CL-Windcon actions are already covered by current standards. There are only a few critical control actions or turbine states that need further attention and possible amendments of standards. Operation under extreme yaw misalignment is expected to be the most sensitive case here. However, there are also some challenges as the new CL-Windcon Plant Control interferes with Existing Plant Control (grid code compliance), there is limited experience in extended non-optimal turbine operation and applied software tools are not validated for the CL-Windcon Plant Control environment, to give some relevant examples.

One benefit is, that the integration of CL-Windcon Plant Control into the existing certification scheme can be often realized in a simple way by just prioritizing the existing control and protection function. An example is the prioritization of the individual wind turbine control over CL-Windcon Plant Control for certain limiting parameters of the turbine like active power under grid fault conditions or switching off the new controls in certain wind farm operational states like “start up” or “shut down. A precondition for this is that there is enough time to switch off from CL-Windcon Plant Control mode to normal operation mode.

But also unplanned situations must be considered: especially fast control action is necessary to preserve the safety of the turbine for grid stabilization in fault cases with no time to bring the turbine to normal operation first. Therefore, it must be proven, that all external or internal demands can be fulfilled safely even under CL-Windcon Plant Control operation.

As done in the risk analysis (FMEA) for certification purpose wind turbines under CL-Windcon Plant Control can be distinguished in two groups of wind turbines: the “group I” where a CL-Windcon Plant Control is executed and the other “group II”, that is only affected by the first group’s activity (e.g. by modified inflow). In most cases a modified certification approach is only necessary for the first group of turbines while the situation remains unchanged for “group II”. The underlying picture here is that no new flow situations might be generated by collective wind farm control that couldn’t also occur under free operation and that the time of partial wake operation for each turbine is more reduced under CL-Windcon Plant Control than enlarged. Particular risks seen in the assessment are safe operation during grid faults, operation in nonaligned wind direction, negative impact onto the WTs internal control loops and the general lack of experience with wind farm operation under CL-Windcon Plant Control. However, no risks are seen that cannot be controlled by extra model analysis or measurements.

For the "control system" compliance it is important to guarantee that CL-Windcon Plant Control will only be active during the normal operation and not during the safe mode operation which is the status of the turbine if certain safety limits are exceeded. All major functionalities to switch off CL-Windcon Plant Control or to prioritize turbine safety functions over CL-Windcon demands need to be proven before the wind farm starts operation. It must also be proven that the CL-Windcon modes don't lead to excessive vibration during operation and all control actions are still safe under communication failures.

One major request from the grid code compliance analysis is that the certification of CL-Windcon Plant Control shall not contradict the certification of the existing GCC control. It must be proven that during operation all GCC demands are still safely fulfillable. This will influence current test schemes, where wind turbines in future must prove their functionality within voltage shortage also during large yaw misalignments.

Within the load analysis it is recommended not only to concentrate on those load case definitions that include wakes. It seems to be necessary to calculate all load cases also under CL-Windcon conditions that are not part of the normal operation. As currently the CL-Windcon states are not defined in particular, the calculation effort might be significantly increased. Recommendations are made in this deliverable in order to highlight which aspects need to be considered, however, further assessment to minimize the amount of additional calculations are needed.

It will probably be necessary to consider new load cases (e.g. extreme yaw misalignments) that cannot be defined before the CL-Windcon control patterns are defined in detail. This will be a task for the future standardization work. While it might be easy to prove that certain design limits are not exceeded, it might be much more difficult to prove that new vibrational states with increased fatigue loads are prohibited, especially during wake mitigation techniques. An update of existing design tools and design validation standards might be mandatory.

Within the site-specific design analysis (SSDA), it might be only possible to issue a preliminary certificate, as important design validation tools are currently not validated yet. The obligation will be to prove the assumptions of the SSDA during operation. For the wind farm operator this might be a serious hurdle within the realization of CL-Windcon Plant Control methods. A certification with a fall back option to “normal” operation might be a preliminary solution. This “in service” obligation will probably only be necessary until more experience exists with CL-Windcon in real operation.

In this deliverable the analysis of the impact on the certification could only be done at a high level, it needs a more detailed description of the exact controls to be implemented that goes beyond present analysis. It seems to be crucial for practical realization that adapted design tools and models not only in the scientific area exist but also within industry and certification. A step wise introduction and more practical experience with CL-Windcon Plant Control will allow for smart improvement and adaptation of certification procedures or schemes and overcome “In service” restrictions that shall only be an interim solutions in the beginning phase. The involved certification bodies will interactively support further activities to enable a successful realization of closed loop control actions.

9 REFERENCES

[1] IEC 61400-1:2019 Edition 4, Wind energy generation systems Part 1: Design requirements, Switzerland

[2] IEC CDV 61400-27-2:2018, Wind energy generation systems - Part 27-1: Electrical simulation models - Model validation, Switzerland

[3] FGW TG3: 2019, Technische Richtlinien für Erzeugungseinheiten, -anlagen Teil 3 (TR3) Bestimmung der elektrischen Eigenschaften von Erzeugungseinheiten und -anlagen, Speicher sowie für deren Komponenten am Mittel-, Hoch- und Höchstspannungsnetz, Revision 25, 01.09.2018, including FAEE-resolution for Technical guideline TG 3 Rev. 25, 22.01.2019, both issued by FGW e.V. Fördergesellschaft Windenergie und andere Dezentrale Energien, Berlin, Germany

[4] FGW TG4: 2019, Technische Richtlinien für Erzeugungseinheiten, -anlagen Teil 4 (TR3) Anforderungen an Modellierung und Validierung von Simulationsmodellen der elektrischen Eigenschaften von Erzeugungseinheiten und -anlagen, Speicher sowie für deren Komponenten, Revision 09, 01.02.2019, FGW e.V. Fördergesellschaft Windenergie und andere Dezentrale Energien, Berlin, Germany

[5] DNVGL-SE-0124: 2016, Service Specification, Certification of grid code compliance, Edition March 2016, DNV GL AS, Norway

[6] DNVGL-ST-0125: 2016, Standard, Grid code compliance, Edition March 2016, DNV GL AS, Norway

[7] FGW TG 8 - Certification of the electrical characteristics of power generating units and systems in low-, medium-, high- and extra-high voltage grids, Rev 9, 1.2.2019, FGW e.V. Fördergesellschaft Windenergie und andere Dezentrale Energien, Berlin, Germany

[8] Future IEC 61400-21-2 expected for 05-2020, Approved plan to prepare it: 88/533/RVN, Wind turbines - Part 21-2: Measurement and assessment of electrical characteristics - Wind power plants, 2015, Switzerland

[9] IEC FDIS 61400-21-1:2019, Wind energy generation systems - Part 21-1: Measurement and assessment of electrical characteristics - Wind turbines

[10] CL-Windcon Deliverable Report D2.1 “Minimal loading wind turbine de-rating strategy and active yaw controllers”, Draft Final 2017-10-31

[11] Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators, Official Journal of the European Union, L112/1, 27.4.2016.

[12] CL-Windcon Deliverable Report D2.2 “Methodology for active load control”, Draft Final 28.02.2018

[13] VDE-AR-N 41xx German Grid Codes, VDE, 2019, Frankfurt, Germany

[14] EN 50549-1, Requirements for the connection of generators above 16 A per phase to the LV distribution system or to the MV distribution system; CENELEC, Europe, draft status

[15] DNVGL-ST-0437 Standard, Loads and site conditions for wind turbines, Edition November 2016, DNV GL AS, Norway

[16] document CL-Windcom-Deliverable4.1 (draft) “DELIVERABLE REPORT Assessment of controller key performance indicators & Guidelines on controller application for the management of existing wind farms”, not dated, CL-Windcon

[17] Bossanyi E. “Combining induction control and wake steering for wind farm energy and fatigue loads optimisation”; Science of making torque from wind 2018

[18] CL-Windcon Deliverable Report D1.1 “Definition of reference wind farms and simulation scenarios”, Draft Final 2017-04-26

[19] CL-Windcon Deliverable Report D4.2 “Hardware and infrastructure conditions for energy capture and fatigue improvements”, Draft Final 2019-03-31

[20] IEC 60812:2018, Failure modes and effects analysis (FMEA and FMECA)

[21] EN ISO 13849-1:2016, Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design

[22] DNVGL-ST-0438: 2016, Standard, Control and protection systems for wind turbines, Edition April 2016, DNV GL AS, Norway

[23] IEC 61400-22: 2010, Standard, Wind turbines – Part 22: Conformity testing and certification, Edition 1.0 May 2010, Switzerland

[24] IEC 61400-13:2015, Standard, Wind turbines - Part 13: Measurement of mechanical loads, Switzerland

[25] IEC 61400-27-1:2015, Standard, Wind turbines – Part 27-1: Electrical simulation models - Wind turbines, February 2015, Switzerland

[26] EN 50308:2004, corrected 2005 Wind turbines – Protective measures – Requirements for design, operation and maintenance

[27] DNVGL-SE-0190: 2015, Project certification of wind power plants, Edition December 2015, DNV GL AS, Norway

[28] IEC 61400-25-5, Standard, Wind energy generation systems - Part 25-5: Communications for monitoring and control of wind power plants - Compliance testing

[29] IECRE OD-501:2018-05 Operational Document, Type and Component Certification Scheme (Ed 2.0)

[30] IECRE OD 501-5: 2017-09, Operation document, Conformity assessment and certification of Control and Protection System by RECB (Ed 1.0)

[31] IECRE OD-502:2018-10 Operational Document, Project Certification Scheme (Ed 1.0)

[32] DNVGL-SE-0441:2016-06 Service Specification, Type and component certification of wind turbines, DNV GL AS, Norway

10 APPENDIX A, FMECA

No	Asset	Operation condition	Component	Failure mode	**Potential cause of failure** (risk # in section 4.1 with further explanations)	Probability of Occurrence	Potential effect of failure	Severity	Detection method	Detectability	Risk priority number (RPN)		Remark
1	wind turbine (WT)	power production down-rated	structural components	overload due to oscillations	non-optimal operation conditions (1.1)	1	extensive fatigue damage	3	vibration monitoring	2	6		
2	WT	non-aligned to wind direction	structural components	mechanical overload	turbine operates longer in this condition, than assumed during design (2.1)	3	extensive fatigue damage or damage due to excessive ultimate load	3	vibration monitoring, visual inspections	4	36		Additional load cases need to be considered.
3	WT	non-aligned to wind direction	structural components	mechanical overload	prolonged operation outside simulation software's validation envelope (2.2)	3	extensive fatigue damage	3	vibration monitoring, visual inspections	4	36		
4	WT	non-aligned to wind direction	structural components	mechanical overload	bug in WT's software controlling yaw angle (2.3)	2	extensive fatigue damage	3	vibration monitoring, visual inspections	4	24		
5	WT	non-aligned to wind direction, occurrence of grid disturbance	electrical main components	switch off unintendedly	fault-ride-through parameters tuned for different operation condition (2.4)	3	loss of fault-ride-through capability	3	none	5	45		
6	WT	periodical collective pitch movements	pitch system's mechanical components	mechanical overload	turbine performs more pitch movements (higher pitch mileage), than assumed during design (3.1)	2	excessive wear at pitch drive, pitch gear and pitch bearing	4	inspections at maintenance	3	24		Additional load case need to be considered.
7	WT	periodical collective pitch movements	structural components	mechanical overload	bug in WT's software controlling pitch angle (3.2)	2	failure of main component	3	vibration monitoring, rotor blade bending monitoring (if applicable)	4	24		
8	WT	periodical collective pitch movements	structural components	mechanical overload	wake mitigation action influences control loops negatively (3.3)	3	extensive fatigue damage	3	vibration monitoring	4	36		Additional load case need to be considered.
9	wind park (WP)	all	WP's controller	no or no proper reaction upon grid disturbance	"New Plan Control" influences "Existing Plant Control" negatively (5.1)	2	loss of fault-ride-through capability	3	none	5	30		
10	WP	WP control active	WT's structural components	fatigue damage	wind farm control activities without positive effect (5.2)	3	accelerated fatigue damage to some turbines	3	wind farm monitoring	4	36		
11	WP communication	WP control active	WTs	malfunction of WTs	communication error between WF controller and WT controller (6.1)	3	WT operates not as intended	2	supervision measures in WF communication system	1	6		
12	WP communication	WP control active	WTs	malfunction of WTs	communication loss between WF controller and WT controller (6.2)	3	WT operates in self-control mode	1	supervision measures in WF communication system	1	3		
13	WT	power production	WT control	malfunction of WT	priority problems regarding WP control commands (7.1)	2	WT stop with failure mode	2	alarm in remote control centre	2	8		
14	WT	power production	WT control	no or no proper reaction upon grid disturbance	priority problems regarding WP control commands (7.1)	2	loss of fault-ride-through capability	3	none	5	30		