TotalControl

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

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Definitions/Abbreviations

ABL	Atmospheric boundary layer
Asset	term used in the context of wind farm projects to describe the object in focus. Here the term refers either to wind turbines, wind farm or wind farm communication.
Authorized Certifier	“Authorised certifier” means an entity that issues equipment certificates and power-generating module documents and whose accreditation is given by the national affiliate of the European cooperation for Accreditation (‘EA’), established in accordance with Regulation (EC) No 765/2008 of the European Parliament and of the Council [1].
C&P	Control and protection of WT or Wind Farm
CC	Component Certificate /Component Certification
DEL	Damage Equivalent Load
DLC	Design Load Case
DSO	Distribution system operator, responsible for electric power distribution grid in medium (20kV) or high voltage (110 kV)
DWM	Dynamic Wake Meandering Model
ECD	Extreme Coherent Gust with Direction Change
EOG	Extreme Operating Gust
EqC	Equipment Certificate, also known as unit certificate, Type Certificate GCC
ETM	Extreme Turbulence Model
EWM	Extreme Wind Speed Model
EWS	Extreme Wind Shear
F	Fatigue
f	Electric power system frequency (grid frequency) in Hz
FACTS	FACTS (also known as STATCOM [2]) is an acronym for flexible AC transmission system. FACTS is an evolving technology-based solution envisioned to help the electric utility industry to deal with changes in the power delivery business [3]
FMEA	Failure Mode and Effect Analysis
FRT	Fault Ride-Through (covering both, UVRT and OVRT)
GCC	Proof of evidence regarding conformity with grid code requirements, also called Grid Code Compliance, see Section 5
GCC features	Functionalities required by grid codes, see Section 0
GCC actions	Intended reaction of the wind turbine or its components following the triggering of a specific GCC feature as required by the grid code in order to achieve grid code compliance. E.g. a power reduction triggered by the GCC feature LFSM-O while system frequency reaches values above 50,x Hz.
Grid Code	a document that sets out the procedures and requirements relating to the activities of connection, management, planning,

	development and maintenance of the national electrical transmission and distribution system, as well as dispatching and metering etc. Usually issued by SOs.
ILA	Integrated Load Analysis
LFSM-O	Limited frequency sensitive mode for over frequency situations, i.e. f>50 Hz. Active power is reduced depending on over frequency with a droop as P(f) function by control. See D5M in Section 0
LVRT	Low Voltage Ride Through (replaced by UVRT)
NC RfG	EU wide grid code, see [1] in Section 8
NTM	Normal Turbulence Model
NWP	Normal Wind Profile
MLC	Measurement Load Case
ms	Milliseconds; 1 ms = 10^{-3} s, thousand ms are one second
PC	Project Certificate / Project Certification (normally related to a wind farm)
PoC	Point of connection, the electrical grid connection point of a wind farm
RANS equations	Reynolds Averaged Navier Stokes equations
RECB	Renewable Energy Certification Body, see IECRE [4]
SCADA	Supervisory control and data acquisition (subsystem of the wind farm controller)
S_k	Short-circuit power, the product of the electrical current in the short circuit at a point of a system (i.e., the electric power system or grid) and a conventional voltage, generally the operating voltage
SO	System Operator. Operator of the electric power system (the grid). Can be TSO or DSO.
SSDA	Site-specific design assessment
System and relay protection	Electrical protection systems protecting the electric power system from constant fault operation outside the electrical design ratings
TC	Type Certificate / Type Certification (normally related to a type of WT)
ToT	Test of Wind Turbine Behaviour
TSO	Transmission system operator, SO of electric power systems for transporting electrical energy, may be high (110 kV) or extra high voltage (220 or 380 kV)
t_{WM}	Time period for cyclic pitch activities for wake mixing
U	Ultimate strength
UVRT	Standardized term in IEC 61400-21 for a sudden voltage dip followed by a sudden voltage swell. Formerly called LVRT which term is still in use in some countries
V_{WF-FC_in}	Cut in wind speed for mode "operation with WF-FC"
V_{WF-FC_out}	Cut out wind speed for mode "operation with WF-FC"
WFC	Wind Farm Control
WF-FC	Wind Farm Flow Control (wind farm level control optimising loads and energy yield)

WF-GC	Wind Farm Grid Control is the part of wind farm control which is implementing grid code related aspects (also known in other standards as plant control, PGS controller, PGP controller, system controller, central control)
WFC-active / WF-FC-active	Systems (e.g. WTs) that actively contribute to WFC by controlled actions
WFC-passive / WF-FC-passive	Systems (e.g. WTs) that do not contribute to WFC
WF-CS	Wind Farm Control System
WT	Wind turbine, also known as unit or power-generating module
WT-CS	Wind Turbine Control System
+yaw, -yaw, 0yaw	operation with WF-FC yaw misalignment in positive / negative direction / without WF-FC yaw misalignment
α_{WM}	Amplitude of cyclic extra pitch angle for wake mixing
δ	Yaw offset demand (Demanded yaw misalignment), see Figure 3
ε	Yaw error (angle between WT axis and demanded orientation of WT axis), see Figure 2 and Figure 3
θ	Yaw misalignment (horizontal deviation of the wind turbine rotor axis from the wind direction, IEC-61400-1 [5] section 3.77), see Figure 2 and Figure 3

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EXECUTIVE SUMMARY

Wind farm control (WFC) is establishing an upcoming evolutionary step in wind farm design. This report analyses how certification of wind farms applying this new technology can comprehensively be performed.

In section 1 an introduction to certification of wind turbines and wind farms is given, addressing relevant certification schemes and standards. This is done by focussing on the Type and Project Certification requirements of both structural integrity and grid code compliance (GCC).

Section 2 provides a qualitative risk assessment of a generic wind farm setup applying WFC. The failure modes and effects as well as the respective criticalities determined can be guidance for a new design.

A gap analysis showed that the applicable standards lack a significant number of requirements for WFC certification. This affects the control and protection system and the load assumptions of the wind turbines respectively wind farms. In section 3, the specific features of a control and protection system applying WFC in a wind farm setup are analysed and supplements to the requirements are proposed. It is referred to the extended complexity of the control system and its potential criticalities regarding system stability. Several control loops with mutual dependencies may interfere with each other, impacted by additional sensor measurements.

Section 4 discusses present limitations regarding load definition and calculation. Wake models available at present are partly considered insufficient. While tools for wind farm simulation still require more thorough validation, approaches to proceed under the given conditions are provided. Furthermore, section 4 provides guidance on how to define design load cases for WFC.

Section 5 is dedicated to the aspects of GCC in WFC. GCC features relevant to WFC are described with their impact on WT and wind farm design as well as contradictory GCC requirements within different EU countries are presented. Priorities conflicting with respect to the power system, WT control and protection system as well as with optimisation goals are discussed. Certification requirements are proposed.

Requirements for testing of wind turbines applying WFC are summarized in section 6. This includes measurements of loads, power performance as well as the safety & function tests in the framework of the wind turbine's Type Testing. The listing is furthermore supplemented by requirements for GCC test which comprises the test plan itself, fault-ride-through testing, measurements of the controllability, power quality as well as commissioning.

INTRODUCTION

Achieving the Glasgow Climate Pact goal of limiting the global temperature rise to 1.5°C in order to prevent the worst impacts of climate change on human life requires enormous efforts worldwide. One technology which can be leveraged to contribute to this goal is the production of electricity from renewable energy. It is not only desirable to increase the share of wind energy in the total electrical power mix; there is also strong focus on optimising the operation of a wind power plant in terms of maximising energy output at the lowest possible levelized costs.

Optimisation of a wind power plant can make use of wind farm control (WFC). In a holistic way WFC covers different approaches of controlling, operating, and maintaining the individual wind turbine as well as the whole wind farm in an optimised manner. In the current state-of-the-art, without WFC each individual wind turbine is controlled in such a way that it extracts the maximum energy possible from the wind in a "greedy" way. This results in the remaining wind energy supply for the wind turbines further downstream as well as the respective electric energy production being reduced. Whereas with WFC, the performance of the individual wind turbine is sacrificed to the benefit of an improved production of the wind turbines downstream. This allows for the optimization of the wind farm as a whole power plant and is expected to show significant performance enhancements. It is therefore no surprise that WFC is gaining interest in research and industry while first wind turbine OEMs are offering their products to the market.

Due to the multidisciplinary challenges with WFC the full introduction to the market has not yet taken place as WFC is still on the way to gaining qualification towards a desirable stage of bankability [6]. Many technical aspects in aerodynamic, aeroelastic, control and electrical system modelling require further development.

Certification of a new wind energy technology plays a key role for its acceptance by financial institutions. It confirms safety and reliability which is essential for the successful operation of the asset. As WFC significantly impacts the way a wind farm is controlled and operated, relevant aspects of WFC need to be considered within certification. So, the economic aspects of energy production, the key interest of wind farm owners and financial institutions, come indirectly into the focus of the certification of wind farm design.

This report analyses the present certification landscape for its' WFC readiness. As new technology is dealt with, available certification standards ensuring structural integrity of wind turbines and wind farms are not yet fully prepared to require appropriate verification. Sections of this report will propose distinct certification requirements addressing aspects of the wind turbine's control and protection system and the loads which are yet missing for WFC in applicable standards. Other "components" of the WT certification like rotor blades, structures or the electrical system are only affected indirectly, i.e. by the design loads and require design according to those loads.

Furthermore, this report discusses the extent to which the certification of grid code compliance aspects is affected by WFC. Additional certification requirements are proposed which aim at closing potential gaps in present certification standards to ensure grid code compliance of wind turbines and wind farms under WFC.

WFC comprising a toolbox of different new technologies is expected to enter the market gradually. Still the expected performance needs to be proven. Single elements of WFC may first be applied and tested in existing wind farm as a retrofit before a wind farm will be especially designed for WFC in pre-construction. It is also expected that first wind farms will be operated using open-loop WFC technologies before more complex closed-loop control design will be utilised. Later, WFC may feature digital twin technology for online load calculation and re-distribution of lifetime between the wind turbines of the farm to further improve optimised operation.

The requirements and procedures proposed in this report are expected to provide guidance for certification to above mentioned cases in a comprehensive way. They may be used as a draft for implementation into international certification standards by IEC and DNV.

For less complex approaches of WFC parts of this reports might not be applicable and the extent of necessary certification activities may be reduced based on individual consideration.

1. Wind Farm Control in Certification

1.1. Definition

Wind Farm Control (WFC) is an umbrella term that is used in different contexts and applications. In general, WFC can be defined as the cluster of models and methods that operate a whole wind farm in an optimised way. In Table 1different types of WFC are displayed. Wind farm flow control (WF-FC) comprises control techniques that individually impact the aerodynamic flow at each wind turbine. The aim is to optimize the mechanical loads utilization and energy yield of the whole wind farm. Techniques of WF-FC are presented in section 2.1.

Wind farm grid control (WF-GC) addresses how the wind farm with its individual wind turbines is coupled to the electrical grid in two aspects. First, the compliance of the wind farm with applicable grid codes, which is not new, but the combination of WF-GC with other types of WFC may require further consideration. Second, new kind of services are expected to be marketed in future in the context of WFC. Ancillary services may provide technical capabilities of a wind farm which are beneficial for the electrical grid to which the wind farm is coupled. An introduction into ancillary services is given in [7] and [8].

Strictly speaking techniques like noise and shadow control can also be influenced by applying WFC. They stem from legal obligations in the process to achieve a building permission.

A more detailed modelling of a whole wind farm in the context of WFC provides the opportunity to discretize the individual turbines, monitor their performance and plan their respective maintenance or even component change.

All before mentioned techniques used under the umbrella term WFC aim at optimizing the wind farm as a whole power plant. The underlying optimisation goals are versatile and often competitive. Energy production shall be maximised under certain restrictions regarding lifetime, while mechanical loads as well as operation and maintenance costs shall be minimized. Often the minimisation of the levelized cost of energy (LCOE) integrates all these aspects to one common goal.

This report focusses on WF-FC and WF-GC as marked in teal colour in Table 1. Wind turbines and wind farms operating these WFC techniques require certification according to applicable design guidelines.

Table 1 – Types of Wind Farm Control

	Wind Farm Control (WFC)				
	WF flow control (WF-FC)	**WF grid control (WF-GC)**		**Operation & Maintenance**	
Elements of WFC	Load and energy yield optimisation	Compliance with GCC requirements	Ancillary services	Legal obligations	Maintenance optimisation
Techniques of WFC	e.g. ▪ wake steering ▪ axial induction control ▪ wake mixing ▪ (curtailment)	e.g. ▪ power ramp rate limitation ▪ curtailment (f-response, LFSM-O) ▪ reactive power control ▪ fault ride through	e.g. ▪ delta control ▪ power limitation ▪ black start capability ▪ island operation	e.g. ▪ noise control ▪ shadow control ▪ other? (bats)	e.g. ▪ planning of maintenance hours in low wind season ▪ planning of component change before failure
Certification (Type / Project)	attests conformity of the mechanical, structural, and electrical design with the related standards	attests conformity with grid code compliance requirements	-	-	-

1.2. Certification schemes and standards for wind energy systems

In the following sections, it is listed which technical standards, comprising design and certification requirements in wind energy generation systems already exist. Furthermore, it is listed which certification schemes for wind turbines and wind farms exist, regarding both structural integrity and grid code compliance. The choice of listed technical standards is restricted to documents which are expected to have an impact on WFC.

Proving conformity of wind turbines or wind farms with technical standards has to be performed strictly per certification schemes by certification bodies accredited to IEC 17065 [9]. This includes proving conformity of wind farms with grid codes (also known as grid code compliance). This ensures the achievement of sufficiently high levels of quality and confidence in such certificates.

Certification schemes describe exact measures required for assessing compliance of products (WT) or installations (projects) with given requirements, the success criteria to be applied, and the measures to be performed before evaluation and certification can happen. Certification bodies accredited per IEC 17065 [9] are forced to fully follow those certification schemes when issuing certificates.

1.2.1. Technical standards for the design and testing of wind turbines

The following listed below are existing technical standards for the design and testing of wind turbines:

- **IEC 61400-1**:20005 Edition 3
- **IEC 61400-1**:2019 Edition 4 *Wind energy generation systems Part 1: Design requirements* [5]
- **IEC 61400-3-1**:2019 *Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines* [10]
- **IEC TS 61400-3-2**:2019-04 *Wind energy generation systems – Part 3-2: Design requirements for floating offshore wind turbines* [11]
- **IEC 61400-13**:2015-12 Wind turbines – Part 13: Measurement of mechanical loads [12]
- **IEC 61400-21-1**:2019 Wind energy generation systems – Part 21-1: Measurement and assessment of electrical characteristics – Wind turbines [13]
- **DNVGL-ST-0437**:2016 *Loads and site conditions for wind turbines* [14]
- **DNV-ST-0438**:2016 *Control and protection systems for wind turbines* [15]
- **DNV-ST-0076**:2021 *Design of electrical installations for wind turbines* [16]

1.2.2. Certification schemes for wind turbines

The following listed below are related certification schemes for wind turbines:

- **IECRE-OD-501**:2018 *Type and Component Certification Scheme* [17]
- **IECRE OD-501-4**:2017 *Conformity assessment and certification of Loads by RECB* [18]
- **IECRE OD-501-5**:2017 *Conformity assessment and certification of Control and Protection System by RECB* [19]
- **IEC 61400-22**:2010 *Wind turbines – Part 22: Conformity testing and certification* [20]
  Note: This standard is expired and replaced by IECRE-OD-501 (for wind turbines) and IECRE-OD-502 (for wind farms). However, it still is in use in certification contracts.
- **DNV-SE-0441**:2021 *Service Specification, Type and component certification of wind turbines* [21]

1.2.3. Technical standards for the design of wind farms

Most technical standards for wind turbines focus in detail on *wind turbine* design. *Wind farm* design, mainly regarding loads, is considered to some . Other aspects of wind farm design are covered vaguely in these technical standards.

However, there is a set of standards on communication in wind farms:

- **IEC 61400-25** (all parts), Wind turbines – Part 25: *Communications for monitoring and control of wind power plants* [22]

1.2.4. Certification schemes for wind farms

The following listed below are related certification schemes for wind turbines

- **IECRE OD-502**:2018-10 Operational Document, Project Certification Scheme [23]
  Note: Section 7.2.2. *Project design basis evaluation* mentions WFC in the list of options, as do figures 1 and 2. Requirements for WFC certification are not stated.
- **IEC 61400-22**:2010 *Wind turbines – Part 22: Conformity testing and certification* [20]
  Note: This standard is expired and replaced by IECRE-OD-501 (for wind turbines) and IECRE-OD-502 (for wind farms). However, it still is in use in certification contracts.
- **DNV-SE-0190**:2021-09 Service Specification, Project certification of wind power plants [24]
  Note: Section 8.13 *Wind farm control* states rough requirements for the certification of WFC.

1.2.5. Certification Schemes for Grid Code Compliance

Apart from Equipment certificates (see Section 5.7.6) and Project Certificates (Section 5.7.7) component certification also exists. For WF-GC, a corresponding component certificate as described in Section 5.7.8 can be requested.

Certification for GCC will need to make a decision regarding the scope by listing the applied grid codes in case of WT level certification (product certification) to be provided by the manufacturer who usually will order GCC certification. If a component certificate of a WF-GC together with the product certificate of a specific WT type shall be used for project certification for a specific Wind Farm (site-specific certification) the grid code applied will be the one valid at the connection point (PoC) of the Wind Farm, or the detailed requirements requested by the operator of the corresponding grid i.e., the relevant System Operator (SO).

Within European Union, grid code compliance is mostly covered by Equipment Certificates per NC RfG i.e., EU 2016/631 [1]. Details are described in Section 5.7. However, NC RfG itself cannot be regarded as a certification scheme, neither the two EN standards [25] nor [26] can as they are neither providing details regarding assessment nor evaluation nor certification.
Existing and publicly available certification schemes are listed in Table 2 and Table 3.
Other certification schemes on grid code compliance exist in several private certification companies but have not been shared with the public i.e., they are not publicly available.
Further international certification schemes are under development and listed in Table 4.

Known national certification schemes are listed below in Table 2, sorted by countries and usually only being applicable in the countries of origin.

Table 2 – Publicly available national Certification Schemes for GCC

Country	Title (translated to English)	Reference
Germany	Technical Guidelines for power-generating units, modules as well as storage and for their components Part 8 (TR8)	[27]
Spain	Technical conformity supervision standard per EU Regulation 2016/631 for power-generating modules (NTS 2.1)	[28]

Furthermore, there is one known certification scheme for international application which is publicly available, and one which can partly be used, listed in below Table 3.

Table 3 – Publicly available internationally applicable Certification Scheme for GCC

Number	Applicability	Title	Reference
DNV-SE-0124	No limitation	Certification of grid code compliance	[29]
prEN 50549-10	Can be used as part of a certification program	Requirements for generating plants to be connected in parallel with distribution networks — Part 10: Tests demonstrating compliance of units	[30]

In future, another international certification scheme will be available [31] from IECRE [4]. As with other certification schemes issued by IECRE this document will also be called OD (operational document) followed by a number (to be decided). The status in October 2021 was still drafting. To date it seems that this certification scheme will only cover product and component certification (no site-specific certification is planned to be included for the time being). Regarding WF-GC certification this future document will most probably refer to the existing WT standards from the IEC 61400 family, such as [32], [13] and [33].
Furthermore, an updated edition of the existing Service Specification DNV-SE-0124 [29] will be available in 2022 [34].
An overview can be found in below Table 4.

Table 4 – Drafting of international certification schemes on Grid Code Compliance

Preparation by	Applicability	Timeline	Topic	Reference
IECRE WG 10	Products	unclear	Prepare guidance for acceptance criteria for grid code compliance certification by issuing new ODs for harmonized certification, testing and simulation model validation in the field of grid code compliance with references to IEC standards	[31]
DNV	No limitations	2022	Update of DNV-SE-0124	[34]

1.3. Certificates for wind turbines and wind farms applying WFC

In this deliverable two different streams of certification for WTs and wind farms are addressed. The first attests to conformity of the civil engineering, mechanical, structural and electrical design with the related standards – it focuses on the structural integrity of the wind turbine or wind farm design. Applicable certification schemes and standards are dealt with in sections 1.2.1 to 1.2.4. Certificates that can be achieved as a result of structural integrity certification are listed in the following section 1.3.1.

The second stream of certification is intended to attest to conformity with grid code requirements to WTs and wind farms. The relevant certification schemes and standards are listed in section 1.2.5, while related certificates for GCC are listed in the following section 1.3.2.

1.3.1. Certificates on wind turbine and wind farm structural integrity

1.3.1.1. Type Certificate

Type certification covers the third-party verification of design, testing and manufacturing of a component or a software package in serial production and for multi-purpose application. In the wind industry it is common practice that a wind turbine type owns a type certificate according to IEC or DNV standards. With regards to WFC, the type certificate covers the compatibility of the wind turbine for a range of predefined WFC strategies.

The assessment includes an independent load calculation, a verification of the model validation performed, and comparison with tests (see prototype level). Verification of the wind turbine structural components is an inherent part of the design assessment. Further assessments comprise the assessment of the electrical system as well as the safety and control system. Furthermore, the design quality control shall be covered by a certified quality management system complying with ISO 9001.

1.3.1.2. Site-Specific Design Assessment

The site-specific design assessment (SSDA) of a wind farm applying WFC proves that its design is fit for application in the environment of a specific site. The wind farm with its individual wind turbines can deal with wind farm related parameters like individual wind conditions, turbine layout and wake effects under WFC. It is based on an existing type certificate for the individual wind turbines while site-specific load assumptions considering the effects of WF-FC are assessed. Furthermore, corresponding control related design changes are addressed which have not been considered in type certification before. A measurement campaign according to section 8.13 in DNV GL-SE-0190:2020 can reduce the uncertainty associated with the application of new load simulation approaches for WF-FC.

1.3.1.3. Project Certificate

A successfully completed project certificate corresponds to a system regarded proven in an operational environment. For the planning, the installation, and the operation of a wind farm, project certification is recommended. It stipulates that the risks arising from site assessment, design basis, design, manufacture, transport, installation, commissioning, operation and maintenance are considered.

The conditions of a specific site and the compatibility with the type certified turbine are checked.

The validity of the project certificate is limited to the design lifetime of the farm stated in the project certificate. Maintenance of the project certificate is conditional on periodic in-service evaluations.

1.3.1.4. Component Certificate

Certification schemes for wind turbines like IECRE-OD-501 [17] and DNV-SE-0441 [21] (see section 1.2.2) define what is meant by "Component Certificate".

As example the related definition from DNV-SE-0441 section 1.4.1 is sited as follows:

Component Certificate (CC)	*A certificate issued by a certifying body when it has been demonstrated that a product type in question, here a wind turbine component, assembly or system, complies with the applicable regulations*

Thus, WFC for a given wind farm can in principle be certified as a "Component", which would consist of software with or without related hardware.

However, at present no "regulations" (e.g., standards) are in place to issue such Component Certificate. Further down in this report we suggest additions to standards. Inclusion of these additions into the relevant standards can clear the path to WFC certification and finally to a Component Certificate for WFC. A challenge for a WFC Component Certificate will be to define appropriate interfaces to a generic wind turbine and wind farm setup.

1.3.2. Certificates on Grid Code Compliance

For grid code compliance two general state of the art certification levels are commonly accepted: unit- and project certification. Sections 1.3.2.1 through 1.3.2.3 deal with unit certification, also known as Type- or Equipment-Certification. Sections 1.3.2.4 and 1.3.2.5 deal with site-specific certification of wind farm installations.
These certificates do not cover structural integrity issues. Focus of all grid code compliance certification levels is on preventing instabilities and blackouts in the grid (i.e., the electric power system) the wind farm is connected to.

1.3.2.1. Prototype Certificate GCC

Before a wind turbine can be connected to the grid for testing purposes e.g., FRT testing, a general approval regarding the ability to fulfil the grid code requirements has to be performed by a third party (approved Certification Body). WFC should be part of this to prove that those functionalities will not be in contradiction to typical GCC-features.

1.3.2.2. Type Certificate GCC

The Type Certificate GCC, also called unit certificate (for Germany) or Equipment Certificate (for EU), gives confirmation that relevant local requirements (grid codes) for the wind turbine type are met. Usually this also means, that a simulation model for GCC is certified after being validated by

the Certification Body against standardized test results. The type certificate will reference the GCC-class assigned and specify the grid codes which the wind turbine type complies with.
Wind turbines being prepared for the use of WFC would need to be tested per FGW TG3 or at least would need to prove, that the requirements covered by the type certificate GCC are still met, even when WFC will be applied. The same needs to be performed for proving that the changes WFC will do with the simulation model will not jeopardize the grid code requirements proven by the validation. Simulation model specifications and methods for validation against measurements are given in FGW TG4 [35] or in IEC 61400-27 [32]. FRT tests are described in Section 6.4.2.1, measurements from those tests are used for validation unless the certification procedure applied requires different tests.

1.3.2.3. COMPONENT CERTIFICATE FOR GCC

Component Certification is a wide field regarding both, components which can be certified, and the certification procedures and grid codes they can be certified against. Within this Section, the certification schemes in question are those listed in Section 1.2.5 together with the relevant grid codes. Components to be certified in this Section are mainly WF-GC systems including hardware and software.
In theory, component certification regarding grid code compliance could also refer to other components in WTs and wind farms. However, usually those components (e.g., main frequency converters, pitch systems, generators, and reactive power compensation units) need to go through a full FRT test-campaign and hence will almost never become certified without a WT type under test. Having a full WT type under test, those components are usually part of that WT type and do not need an extra component certificate regarding GCC. On the other hand, it is very difficult to transfer measurement results for a component tested within the one type of WT to another type of WT, since design, interfaces and control systems of WT types differ quite heavily from one type to the other.
Taking Germany as an example, installing WF-GC to the wind farms is state of the art and are well described in existing standards ([25], [26], [27], [36], [13], [32], [37]. Unfortunately, national naming (even when translated to English) differ quite significantly. An overview on national or standard-specific naming is given in below table Table 5.

Table 5 – State of the art of WF-GC

Naming of WF-GC in European and national standards		Country	Reference
EZA-Regler	PGS controller	Germany	[27]
EZA-Regler	PGP controller	Germany	[38], [39]
-	Plant control	International	[32], [29]
CCI (Controllore Centrale di Impianto)	Central Plant Controller	Italy	[37]

For manufacturers of WFC or WF-GC or for any of those products listed in above table, a corresponding certification is mandatory e.g., in Germany. The WFC as discussed within the total control project should, at least once, run through such component certification to prove grid code compliance.

Alternatively, any WFC used will be certified as part of the WT type and again as part of the site-specific installation (i.e., the Wind Farm) in a project certificate.

1.3.2.4. PROJECT CERTIFICATE GCC

The project certificate GCC, also called system certificate, states compliance of a wind farm with the requirements of relevant grid codes. Evidence must be provided for the specific site by dynamic and static simulations using the validated simulation model certified by the corresponding Equipment Certificate (also called unit certificate) GCC for the WT types (units) used. The Project Certificate has different names, in Germany it is called system certificate (Anlagenzertifikat) and provides necessary preconditions for the settings of the grid connection installations and for each individual turbine installed. This project certificate refers to electrical characteristics at the grid connection point and has to be provided prior to energization of the wind power plant (EON per NC RfG [1] terminology – Energisation Operational Note).

1.3.2.5. DECLARATION OF CONFORMITY FOR GCC

After the wind power plant has been energized and commissioned (or together with field commissioning), an independent inspection is needed as required in FGW TG8 [27] in Germany to prove that the wind farm has been built as certified (by project certificate / system certificate) and that settings have been implemented as required by the Project Certificate GCC. At this point in time plausibility tests with the WFC should also be performed to prove practical functionality (see Section 6.4.3). The state of the art WF-GC per FGW TG8 [27] is part of that already, implementation of a full WFC is not covered by that yet (see Section 5.7.2).

1.3.3. TECHNOLOGY QUALIFICATION

Depending on the complexity of a new WFC technology intended to be certified it might be helpful not to directly enter the regular process towards e.g., Type Certification. In advance a qualification program ("Technology Qualification" according to DNVGL-RP-A203 [57]) can be performed in co-operation between the supplier and the certification body. The necessary steps for verification and the requirements e.g. towards Type Certification are individually established. This concept considerably eases the later certification process, as the critical questions are duly handled at an early stage. The Technology Qualification concludes with the Statement of Feasibility for the new WFC technology.

2. QUALITATIVE RISK ANALYSIS, FMECA

The following chapter was taken from CL-Windcon delivery D4.7 "Review on Standards and Guidelines, Deliverable Report," [40] section 4. It was further developed and adapted to the needs of the TotalControl project.

2.1. Identification of risks from WFC

WFC (Wind Farm Control) features are analysed with respect to guidelines stating WT (Wind Turbine) design requirements. To do so, the related risks to the WTs, the wind farm, the quality of power delivery and the operation are analysed. Section 2.2 gives a formal FMECA risk analysis, while this subclause discusses the risks and related mechanisms.

2.1.1. AXIAL INDUCTION CONTROL

Induction control is performed by down-rating selected WTs (WFC-active) to allow other turbines in the wind farm (WFC-passive) to increase their energy yield.
1.1: There is in principle a risk for WFC-active WTs, 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 WFC-passive WTs, as WTs are made and optimised for maximum energy yield. WFC-passive WTs run in their natural operation environment.

Table 6 – Risk for axial induction control

	WT affected	risk
1.1	WFC-active WTs	non- optimal operation conditions
1.2	WFC-passive WTs	none

2.1.2. WAKE STEERING

Wake steering is performed by yawing selected WTs (WFC-active) out of the wind by up to e.g., ± 30 ° away from optimal alignment to the wind direction. This is done to optimise the direction of the wake behind the turbines. Wake steering allows other WTs (WFC-passive) located downwind of group 'WFC-active' to increase their energy yield, because the wake is steered away from them.
2.1: WFC-active 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 WFC-active 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 the 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. Simulation codes might deliver uncertain load simulation results (see also Guidance note at the end of section 6.1.1.1).

2.3: In standard WT design the yaw movements are controlled by the WT controller with the aim to align the wind turbine with wind direction. This is a closed loop feedback control. It normally does not have any interfaces for receiving external commands. Wind farm controller access to the WT yaw control, introduced in WFC applications, is a novelty. The related changes to the WT's control software need to be made carefully. It must be ensured, that the WT never operates outside the allowable yaw angle range. The risk here is that an important matter may be overlooked, 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 during grid disturbances. Therefore, WTs need to perform fast control actions to stay online. These actions are tuned for ordinary alignment to the wind. The risk is that the turbines might switch off if grid disturbance happens at times of large yaw misalignments.

2.5: Wind *direction* measurement on WTs is done by wind senor(s) on the roof of turbine's nacelle. In that location wind direction measurement is influenced by the flow disturbances from the rotor and above the nacelle. Therefore, as part of prototype testing of WTs, calibration of wind direction measurement is done. In the past these calibrations were not performed for the large yaw misalignments used for WFC. The risk here is that the WT may run in unknown yaw misalignment because of deficient sensor calibration.

2.6: Wind *speed* measurement on WTs is done by wind senor(s) on the roof of a turbine's nacelle. In that location wind speed measurement is influenced by the flow disturbances from the rotor and above the nacelle. Therefore, as part of prototype testing of WTs, calibration of wind speed measurement is done. These calibrations in the past were not performed for the large yaw misalignments used for WFC. In WFC application the wind speed in the wind farm is an important input parameter. It might be taken from the wind speed signal measured at the first-row turbines. As these turbines might be subject to wake steering actions (WFC-active), accurate wind speed measurement may be periled, which in turn could influence WFC actions negatively.

2.7: We do not see any risk on the WFC-passive turbines, as WTs are made and optimised for maximum energy yielding. WFC-passive 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 is always the case in wind farms. However, partial wake conditions due to WFC activities must be considered within the design load cases appropriately, see section 4.4.

Table 7 – Risks for wake steering

	WT affected	risk
2.1	WFC-active 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		turbine operates in unknown yaw misalignment, because of pure wind vane calibration
2.6		turbine's wind speed signal is inaccurate, because of pure wind speed sensor calibration
2.7	WFC-passive WTs	none

2.1.3. Wake mixing

Wake mixing can driven by periodically modulating the collective pitch angle by some degrees and thereby modulating rotor thrust. The period time (in the range of 0.5 to 1.5 minutes) and the amplitude of variation (up to ±5 ° pitch angle) needs to be optimised for given rotor diameters and wind speeds. J.A. Frederik in his thesis "Pitch control for wind turbine load mitigation and enhanced wake mixing" [41] suggests using individual pitch control ("helix approach") rather than collective pitch control for wake mixing. Thus, both collective pitch control and individual pitch control can be used for wake mixing, however collective pitch control for this purpose is further developed and tested.
This is performed by selected WTs (WFC-active) to reduce the wake behind them and thus allows other turbines (WFC-passive) located downwind of WFC-active WTs to increase their energy yield.

3.1: There is in principle a risk for WFC-active WTs. The periodically pitching activity represents extra loading on the pitch system, as it considerably increases the 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 angle 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. Wind farm controller access to the WT pitch control, introduced in WFC applications, is a novelty. The related changes in WT's control software need to be done carefully. It must be ensured that the WT never operates outside 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 the WT's control software.

3.3: It is important to control WT dynamic behaviour 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 apart from other measures controlled by the control loops for pitch angle and generator torque. Additionally, now pitch angle adjustments are used to perform wake mixing actions. Therefore, in principle the dynamic behaviour of WTs' components could be influenced negatively.

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

Table 8 – Risks for wake mixing technique

	WT affected	**risk**
3.1	WFC-active WTs (cyclic pitching)	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	WFC-passive WTs	none

2.1.4. COMBINATION OF AXIAL INDUCTION CONTROL AND WAKE STEERING

We do not see any additional risk by combining features of axial induction control and wake steering. The risks are comparable to the application of each feature separately. Thus the sum of the risks described in sections 2.1.1 *Axial induction control* and 2.1.2 *Wake steering* is applicable.

2.1.5. WIND FARM CONTROLLER

To apply WFC features, the required functions and control loops need to be included in the wind farm control hard- and software. The wind farm controller traditionally hosts the *WF-GC* functionalities. The newly introduced *WF-FC* (Wind Farm Flow Control) features can potentially conflict with the WF-GC functions. Details are given in Section 5 below.

5.1: Wind farm reaction upon grid disturbances must always be performed to fulfil the contract between wind farm 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 WF-FC may impair FW-GC.

5.2: WFC features may 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 measure. There is the risk of adding extra fatigue damage to some turbines without balancing it with related rise in earnings.

5.3: As pointed out in section 3.6 below control mechanisms in wind farms are complex and highly integrated. WFC adds additional complexity. Instabilities or malfunctioning of control loops cannot be ruled out for reasons as mutual dependency of control tasks (section 3.6.1), influence of WFC action on wind sensors (section 3.6.2) and/or closed loop WF-FC instabilities (section 3.6.3). These items come together with the risk that integration of WFC features causes undetected problems.

Table 9 – 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
5.3		malfunctioning through undetected problems with mutual dependency of control loops, negative influence of WFC on wind sensors or controller instabilities

2.1.6. WIND FARM COMMUNICATION

Communication between wind farm controller and WT controller is an essential part of open and closed loop wind farm control. This of course also is valid for the communication between wind farm 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 and avoid operating 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 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 10 – 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

2.1.7. PRIORITIES IN WIND TURBINES' CONTROL SYSTEM

The safe and reliable operation of the individual WT shall not be compromised by WFC features. The WT control system shall make sure that the WT always is kept inside the allowable operation parameters. In case of conflict, these have priority over any signals from the wind farm Controller.

7.1: One risk for the WT is malfunctioning because of problems with the priority of WT control over WFC.

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

Table 11 – Risks about priorities in wind turbines' control system

	WT affected	risk
7.1	all	WT malfunction because of priority problems regarding WT-CS versus WF-CS
7.2		WT non-proper reaction upon grid disturbance because of priority problems regarding WT-CS versus WF-CS

2.2. Qualitative risk analysis, FMECA

FMECA (Failure Mode, Effects and Criticality Analysis) method as per IEC 60812 [42] 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 wind farms. In future wind farm applications, it is recommended to perform a component level detailed FMECA (see also section 3.2.2.3 (5) d) WT related, and section 3.3.3.2 f) wind farm related).

In order to generate an FMECA the numbers for the criticality analysis need to be defined. This definition is shown in subsection 2.2.2. The FMECA is given in section 2.2.2 and the conclusion is drawn in section 2.2.3.

2.2.1. Failure modes and effects

The risks identified in section 2.1 were analysed and further commented using the FMECA method.

As suggested in IEC 60812 [42] the following columns are used:

Asset	term used in the context of wind farm projects to describe the object in focus. Here the term refers either to wind turbines "WT", wind farm or "wind farm communication".
Operation condition	state of the WT or wind farm 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 2.1
Potential effect of failure	impact of the failure on the WT or wind farm
Detection method	the way, how the failure would be detected before damage occurs

The related aspects were worked out and are presented in section 2.1. Conclusion is drawn in section 2.2.3 below.

2.2.2. Criticality analysis

The criticality analysis was performed following annex B of IEC 60812 [42].

Criticality analyses 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 (Table 12, Table 13,
Table 14 and
Table 15).
A conclusion is drawn in section 2.2.3 below.

Table 12 – 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

Table 13 – 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

Table 14 – 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

Table 15 – Risk priority number

Risk priority numbers (RPN)																										
Occurance		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Severity		1					2					3					4					5				
Detection	1	1	2	3	4	5	2	4	6	8	10	3	6	9	12	15	5	8	12	16	20	5	10	15	20	25
	2	2	4	6	8	10	4	8	12	16	20	6	12	18	24	30	10	16	24	32	40	10	20	30	40	50
	3	3	6	9	12	15	6	12	18	24	30	9	18	27	36	45	15	24	36	48	60	15	30	45	60	75
	4	4	8	12	16	20	8	16	24	32	40	12	24	36	48	60	20	32	48	64	80	20	40	60	80	100
	5	5	10	15	20	25	10	20	30	40	50	15	30	45	60	75	25	40	60	80	100	25	50	75	100	125

Table 16 – FMECA

No	Asset	Operation condition	Component	Failure mode	Potential cause of failure *(risk # in section 2.1, See there for further explanations)*	Probability of Occurrence	Potential effect of failure	Severity	Detection method	Detectability	Risk priority number (RPN)	Remark
1.1	wind turbine (WT)	power production down-rated	structural components	overload due to components' oscillation	non-optimal operation conditions (1.1)	1	extensive fatigue damage	3	vibration monitoring	2	6	
2.1	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	Large yaw misalignment to be considered in WT load simulation.
2.2	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	
2.3	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	
2.4	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	
2.5	WT	non-aligned to wind direction	structural components	mechanical overload	turbine operates in unknown yaw misalignment angle, because of pure wind vane calibration (2.5)	2	extensive fatigue damage or damage due to excessive ultimate load	3	vibration monitoring, visual inspections	4	24	Wind vane calibration procedure at prototype testing of WT needs to be adapted.
2.6	WT	non-aligned to wind direction	wind speed sensor	inaccurate signal	turbine's wind speed signal is inaccurate, because of pure wind speed sensor calibration (2.6)	3	WFC fooled because of insufficient accuracy of wind speed signal	3	Comparison with wind speed sensor other than on WTs, if there is any	4	36	Wind speed sensor calibration procedure at prototype testing of WT needs to be adapted.
3.1	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	Extra pitch milage to be considered in WT load simulation.
3.2	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	
3.3	WT	periodical collective pitch movements	structural components	mechanical overload	wake mixing action influences control loops negatively (3.3)	3	extensive fatigue damage	3	vibration monitoring	4	36	
5.1	wind farm	all	wind farm's controller	no or no proper reaction upon grid disturbance	WF-FC influences WF-GC negatively (5.1)	2	no adaquat reaction on grid disturbances	3	none	5	30	
5.2	wind farm	wind farm control active	wind farm'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	
5.3	wind farm	wind farm control active	wind farm's structural components	fatigue or extreme load damage	malfunctioning through undetected problems with mutual dependency of control loops, negative influence of WFC on wind sensors or controller instabilities (5.3)	3	accelerated fatigue damage to some turbines	3	wind farm monitoring	2	18	
6.1	wind farm communication	wind farm 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	
6.2	wind farm communication	wind farm 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 / wind farm monitoring	1	3	
7.1	wind farm	power production	WT control	malfunction of WTs	priority problems regarding wind farm control commands (7.1)	2	WT stop with failure mode	2	alarm in remote control centre	2	8	
7.2	wind farm	power production	WT control	no or no proper reaction upon grid disturbance	priority problems regarding wind farm control commands (7.2)	2	loss of fault-ride-through capability	3	none	5	30	

2.2.3. CONCLUSIONS FROM THE FMECA

The risks identified in section 2.1 were listed in the FMECA, which is presented in Table 16. Here, a conclusion is given:

2.2.3.1. CASES WITH RPN = 45

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)". Description of this risk see section 2.1.2 para 2.4. The reason for this is mainly, that this failure mode is virtually not possible to detect before the grid disturbance might happen in given operation condition or if implemented in FRT tests per Section 6.4.2.1 with the maximum yaw misalignment. In a wind farm design, this must be considered, e.g., by assessing the corresponding GCC type certificate (see Sections 1.3.2.2 and 5.7.6) and the corresponding certification reports if such yaw misalignment has been tested to withstand FRT testing (as suggested in Section 6.4.2.1).

2.2.3.2. CASES WITH RPN = 36

Line 2.1 refers to the case, that a WT or a group of turbines might operate longer in non-aligned yaw orientation, than allowed for in design. Description of this risk see section 2.1.2 para 2.1. Also, this would be difficult to be detected. In any wind farm design, this must be considered thoroughly.

Line 2.2 refers to the case that non-aligned wind turbine might operate out of the validation scope of the simulation software, which was used during WT design. Description of this risk see section 2.1.2 para 2.2. Also, this needs to be considered thoroughly during wind farm design, because it would be difficult to detect in the operation phase.

Line 2.6 refers to the case that non-aligned wind turbine might result in inaccurate wind speed signal, which might be used for WFC as input value. Description of this risk see section 2.1.2 para 2.6. In turn this could lead to faulty WFC actions. Countermeasure would be proper calibration of wind speed during WT Type Testing.

Line 3.3 is on possible negative influence of WFC feature 'wake mixing' on the control loops of the WT. Description of this risk see section 2.1.3 para 3.3. This can be counteracted by extended WT simulations and testing.

Line 5.2 is on the overall effect of WFC features. In case of failure, there could be no such positive effect. Description of this risk see section 2.1.5 para 5.2. To gain confidence on the effect of the WFC activities, operational data of the wind farm need to monitored and related statistics need to be drawn up during operation of the wind farm.

2.2.3.3. CASES WITH FMECA = 30

Line 5.1 refers to the possible case, that prioritisation inside wind farm's controller does not work proper. Description of this risk see section 0 para 5.1. This could lead to malfunction in case of grid disturbances. Countermeasure here would be thorough testing of wind farm's controller.

Line 7.2 refers to a similar possible failure case. Description of this risk see section 2.1.7 para 5.2. Priority mismatch in WT's controller. Countermeasure here would be thorough testing of WT's control system.

2.2.3.4. Overall conclusion

Overall result of the FMECA analysis is, that risks to WTs and wind farms introduced by WFC features, are expected to be handled by state-of-the-art counter measures in WT design and wind farm design as well as monitoring and processing of wind farm operational data. From this a proposal is derived to consider capabilities for WFC features during WT's design phase, in order to directly design them "WFC-fit" (see section 3.1. Table 19 "– Two steps approach" page 38).
Consequently, it is suggested to also reflect WFC requirements better in standards in the areas of WT Control and Protection, Design Load Case definition and Testing.

3. CONTROL AND PROTECTION SYSTEMS

3.1. General

In terms of Control and Protection (C&P) System the wind farm consists of the main systems

- *Wind turbine control system* (WT-CS) — hard and software for control and protection functions of the WT
- *Wind farm communication* — cables (or wireless systems) for routing signals between WT-CSs and WF-CS
- *Wind farm control system* (WF-CS) — hard and software for all control functions on wind farm level

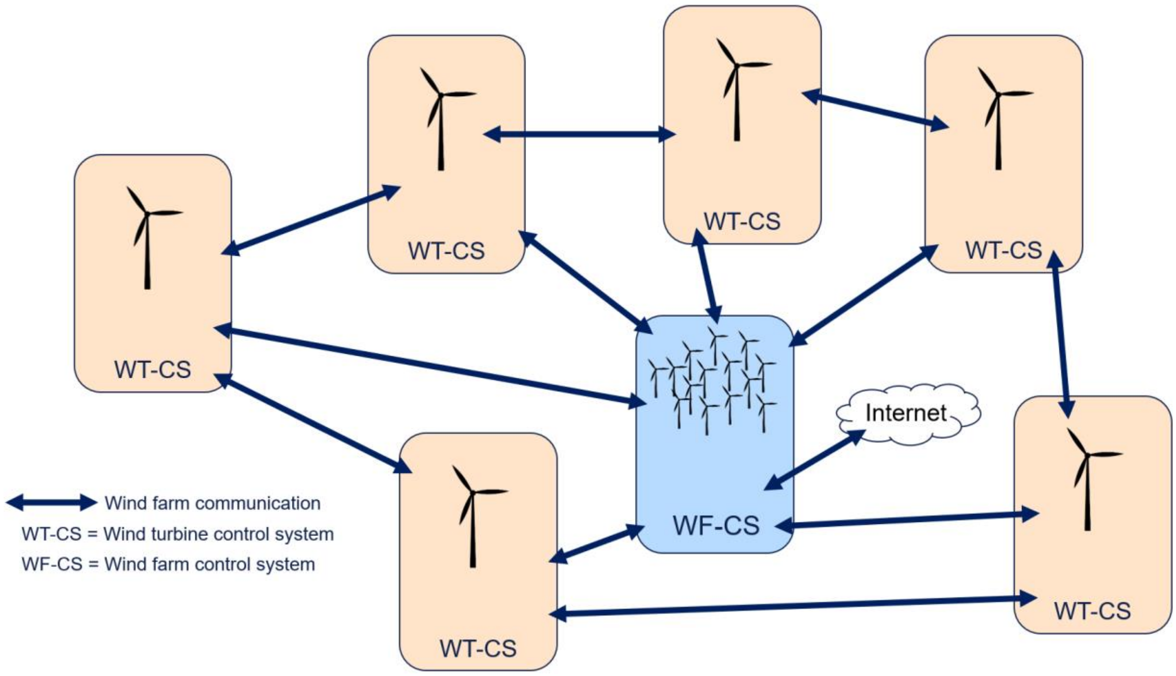

Figure 1 – WT/Wind farm control systems

Traditionally WFC (wind farm control) focussed on the grid connection properties of the wind farm to fulfil grid code requirements and/or sell ancillary services (see [27] and [13]). This control focus is referred to as *WF-GC* (Wind Farm Grid Control).
Now WFC is extended to additionally optimise the overall performance of the wind farm by conducting wind turbines' operation from the wind farm control system. This control focus is referred to as *WF-FC* (Wind Farm Flow Control).
Through WF-FC, the influence of the wind farm control system (WF-CS) on the WTs' operations is increasing. New functions such as axial induction control, wake steering and wake mixing require active involvement of the WF-CS in the WT control processes.

Table 17 below lists main functions of a wind farm indicating for both the WT-CS (wind turbine control system) and the WF-CS (wind farm control system) their involvement in the respective functions.

Table 17 – Functions in WT-CS versus WF-CS

The function is …	… in WT-CS	… in WF-CS		
		… independent of WFC	… part of WF-GC	… part of WF-FC
Operate wind turbine safely	x			
Start/Stop of wind turbine	x	x		
WT yaw control	x			x
WT pitch control	x			x
WT and wind farm power control	x		x	x
React upon grid voltage dip or swell	x			
Data collection/storage	x	x		
Communication to internet (e.g., remote control centre, customer)		x		
Communication to system operator			x	

WT-CS	Wind turbine control system
WF-CS	Wind farm control system
WFC	Wind farm control (also see Table 1)
WF-GC	Wind Farm Grid Control (also see Table 1)
WF-FC	Wind Farm Flow Control (also see Table 1)
x	Functions introduced for WF-FC only

State of the art WTs and wind farms are equipped with the ability to perform WF-GC functions as e.g., fast reactions on grid voltage dips and swells, voltage, system frequency, active and reactive power, voltage and current control. Therefore, we assume that related hard and software is in use and well proven already.

In contrast WF-FC is making "new" functions available. They are indicated in blue in Table 17 above. Thus, in the following we focus on discussing the ability of WTs and wind farms for featuring WF-FC, as we consider these to be in a *state of research* and as such content of this paper.

Table 18 below lists capabilities, which are necessary for WTs and wind farms in order to perform WF-FC functions. These capabilities focus on the two functions 'WT yaw control' and 'WT pitch control', which are not newly introduced, but for WF-FC are newly influenced from the wind farm control system.

Table 18 – Required capabilities

No	Asset	System	Capability	Remark
1.	WT	Structural design	WT's design must be capable of dimensioning loads and/or activities from WF-FC	
2.	WT	Communication	Receive commands for yaw and pitch control from WF-CS and report back actual values on yaw orientation and pitch position in high resolution	1)
3.	WT	Communication	Receive power generation commands from WF-CS and report back actual values on power generation in high resolution	
4.	WT	WT-CS	Perform yaw and pitch actions as commanded from WF-CS	
5.	WT	WT-CS	Perform power generation as commanded from WF-CS	
6.	WT	WT-CS	Keep activities upon comments from WF-CS inside the design limits considered in the design of the WT	
7.	Wind farm	WF-CS	Generate yaw and pitch control commands for each WT to perform WF-FC functions	
8.	Wind farm	WF-CS	Generate power generation control commands for each WT to perform WF-FC functions	
9.	Wind farm	WF-CS	Host the WF-FC software and related data storage	2)

xxx Capabilities related to a function introduced for WF-FC only

Remarks:

1) A sensor for nacelle yaw orientation relative to tower is needed at each WT taking part in WF-FC yaw control activities. These sensors might not be part of the standard WT design.

2) Wind sensors additional to those on the wind turbines might be necessary for WF-FC (e.g., measurement buoy, upward looking LIDAR). These sensors might not be part of standard wind farm design.

In the sections below codes and standards in the wind turbine branch are analysed with respect to C&P to find out if the required capabilities of Table 18 are considered already. Suggestions for amendments are made where necessary. Focus is given on the blue marked capabilities related to WF-FC.

To analyse the related design and certification work flow we look at it in two steps as shown in Table 19.

Table 19 – Two steps approach

WT design/ certification	TC	typically, executed by the wind turbine manufacturer. It ensures the **readiness of WT design for WFC** including related WT certification
Wind farm design/ certification	PC	may be executed by the wind farm developer. It incorporates **WFC features in wind farm design** including related wind farm certification

These two steps are covered in the two sections to follow:

WT design/certification	Section 3.2 "Proposal for certification requirements. WT C&P certification"
Wind farm design/certification	Section 3.3 "Proposal for certification requirements. Wind farm C&P certification"

3.2. Proposal for certification requirements. WT C&P certification

3.2.1. GENERAL

It is obvious that most technical standards for wind turbines focus in detail on *wind turbine* design. The related design and certification procedures in *wind farm* certification refer to technical standards of wind turbines or other systems. Now, that WFC plays a more important role in wind farm design and portions of the wind turbine's control is moved into the WF-CS (wind farm control system), it makes sense to think about the impact of these changes on existing and possible new standards for WT certification.

In the following content of related codes and standards is discussed along the requirements suggested to be added for WFC around C&P (control and protection) systems of WTs.

3.2.2. TECHNICAL STANDARDS FOR THE DESIGN AND TESTING OF WTS

3.2.2.1. EXTENDED YAW MISALIGNMENT

In non-WFC application the "yaw misalignment θ" is typically around ± 8 ° or less in normal ambient conditions. The WT's yaw system would work constantly to minimise this misalignment reasonably.

In WFC operation the yaw misalignment may be enlarged by demand from the wind farm control system. This "yaw offset demand, d" can be ± 30 ° or more. In such situations the WT's yaw system will no longer *minimise* the yaw misalignment, it will *adjust* it reasonably to the demanded misalignment angle. That is, minimising the "yaw error, ε". Hence, the yaw error ε (say ± 8 °) adds to the yaw offset demand d (say + 30 °), resulting in a yaw misalignment, q, in this example of + 38 ° to + 22 °.
The yaw misalignment θ in such operating condition would be up to ± 38 ° in normal ambient conditions, as the yaw error ε will be added on top of the yaw offset demand d.

We suggest the definitions of *yaw offset demand* d, *yaw error* ε and *yaw misalignment* θ as per following Figure 2 and Figure 3.

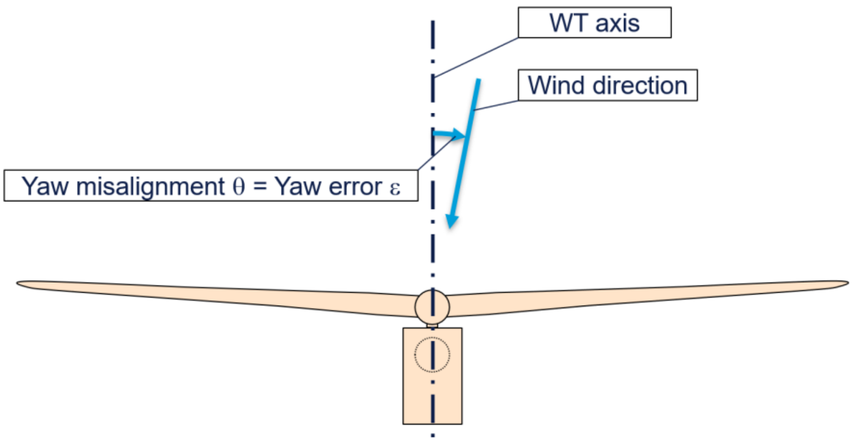

Figure 2 - Definition of yaw angles (WFC-passive)

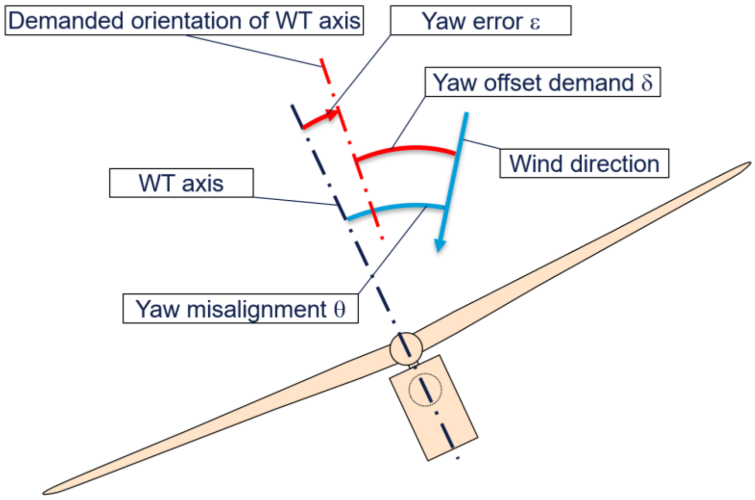

Figure 3 – Definition of yaw angles (WFC-active)

Verbal definitions of these angles are given in table of Definitions / Abbreviations at the beginning of the document.

3.2.2.2. Additional pitch system activities

To apply 'wake mixing' the wind turbine's collective pitch angle is modulated back and forth by some degrees. This modulates the rotor thrust at the same time. The time period of such activity lies typically in the range of 0.5 to 1 minute and the amplitude of variation is up to ±5 ° pitch angle. In a wind farm this is performed by selected WTs (WFC-active) where the wake should be reduced.

Related pitch activities contribute to pitch system wear in addition to the wear caused by other activities from collective and individual pitch operation. Thus, these extra pitch activities for wake mixing need to be considered in WT design.

We suggest the definition of *amplitude of cyclic extra pitch angle for wake mixing* α_{WM} and *time period for cyclic pitch activities for wake mixing* t_{WM} (see following Figure 4).

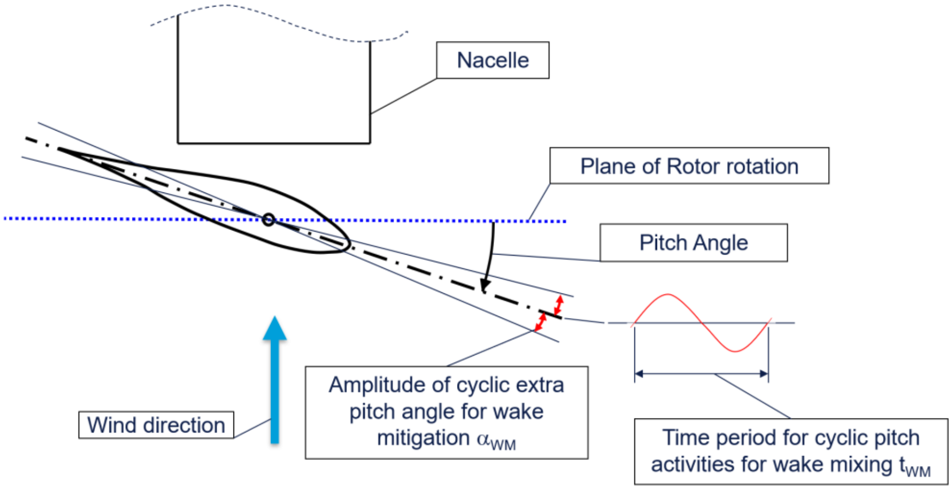

Figure 4 - Amplitude of the cyclic extra pitch angle

Verbal definitions of α_{WM} and t_{WM} are given in the table of Definitions / Abbreviations at the beginning of the document.

3.2.2.3. SUGGESTIONS FOR WT C&P SYSTEM RELATED ADDITIONS TO STANDARDS

The list of technical standards is given in section 1.2.1 above.
For the control system both offshore WT standards IEC 61400-3-1 (bottom fixed) [10] and IEC TS 61400-3-2 (floating) [11] refer to **IEC 61400-1** [5]. Thus, the discussion here is referenced to the latter standard and to both **DNVGL-ST-0437** [14] and **DNV-ST-0438** [15].
Standard DNV-ST-0076 (electrical installations) [16] is not discussed here, as this section focuses on C&P systems.

For testing discussion is referring to **IEC 61400-13** [12].

We suggest amending the standards by adding the following requirements:

(1) **Definitions**

a) The definition for δ, ε and θ regarding **yaw misalignment** should be entered in the standards:

δ Yaw offset demand (Demanded yaw misalignment), see Figure 3

ε Yaw error (angle between WT axis and demanded orientation of WT axis), see Figure 2 and Figure 3

θ Yaw misalignment*) (horizontal deviation of the wind turbine rotor axis from the wind direction), see Figure 2 and Figure 3

*) "Yaw misalignment" is defined in section 3.77 of IEC-61400-1 [5].

For clarity both Figure 2 and Figure 3 should be included in the standards.

b) The following definitions for additional **pitch activities** should be entered in the standards:

α_{WM} Amplitude of cyclic extra pitch angle for wake mixing

t_{WM} Time period for cyclic pitch activities for wake mixing

For clarity Figure 4 should be included in the standards.

(2) **Definition of WFC scenarios**

a) The extra **yaw activities** for WFC shall be defined when designing the wind turbine. Related definitions should contain values for expected *yaw offset demand* δ and expected operation time in this condition.

b) The extra **pitch activities** for WFC shall be defined when designing the wind turbine. Related definitions should contain values for expected *amplitude of the cyclic extra pitch angle* α_{WM} and expected *time period for cyclic pitch activities for wake mixing* t_{WM} as well as expected operation time in this condition.

These definitions shall be available during certification module Design Basis (WT). See also 3.2.3.2 (1).

(3) **Load case definition / load simulation**

a) The extra yaw misalignment as well as the extra pitch activities defined as per (2) shall be included in the load case definition as well as in the load simulations.

b) The transients in and out any WFC operation condition shall be included reasonably in the load case definitions and load simulations.

(4) **Requirements on WFC functions for C&P certification**

For the certification of WTs for C&P systems we suggest the following requirements regarding WFC:

a) Protection functions which are designed to protect the WT and/or its components shall be processed in hard- and software located in or at the respective wind turbine. Such protection functions always shall overrule any signals from outside the WT. Also, they shall be designed to protect the WT from faulty or inappropriate outside signals.
Additionally, the protection functions shall protect the WT against any possible failures in control procedures introduced for WFC.

b) The control system of the WT shall be able to control the WT's operation independent of any communication from outside the WT.

In case outside signals influence the WT's behaviour (this can be for WFC or for operation along a sensor outside the WT), the communication to the sender of the signals shall be monitored permanently (e.g., by "heartbeat").
In case of communication failure, WT shall return to its own control functions which are independent of any WFC or sensor outside the WT.

(5) **Documentation for WT C&P system certification**
The documentation / information as listed below shall be part of the design documents for certification of wind turbines (WTs) for C&P systems.

a) Interface definitions at wind turbine terminals for communication related to WFC. The WT must be able to both receive and transmit relevant data.
E.g., the following:

Definitions, how WT receives:

i. *Active power* demand
ii. *Yaw misalignment offset* demand δ
iii. *Cyclic collective pitch offset* α_{WM}, and *cycle time* t_{WM} demands
iv. Other demand values as far as applicable, as maybe for *ancillary services*

Definitions, how WT transmits:

v. Wind speed
vi. Pitch angle
vii. Rotational speed
viii. Rotor azimuth position
ix. Active power
x. Wind direction
xi. Yaw position

b) Definition of control procedures for WFC
These procedures shall define how the WT performs control actions upon demand from outside. These actions are e.g., extended yaw misalignment, additional pitch system activities and/or reduced operation.

c) Definitions of control procedures for the transients in and out of WFC actions defined in b)

d) Amend WT's existing fault analysis (mostly a FMEA) by inclusion of WFC procedures inside WT's control system and their possible faults, also considering possible prioritisation problems between WF-FC and WF-GC (see 2.2.3.3 "Line 7.2.").

e) Definition of protection functions to be design as per (4) a).

f) Define additional tests for the *Safety and Function Tests / Test of Turbine Behaviour*. These tests need to be added to the test plan:

   i. Tests to prove the control procedures of b), the transients of c) as well as the protection functions of e).

   ii. Test to prove the wind direction signal calibration up the angle of maximal yaw misalignment defined as per 3.2.3.2 (1) (Design Basis) below.

   iii. Test to prove the wind speed signal calibration up the angle of maximal yaw misalignment defined as per 3.2.3.2 (1) (Design Basis) below.

(6) **Testing of WT (referring to IEC 61400-13 only)**
Additional MLCs (measurement load cases) shall be added to the table *MLCs during steady-state operation*. These MLCs shall prove the load simulations as (3) above.
See also section 6.1.1.1 "Load Measurements for Type Certification considering WF-FC".

3.2.3. Certification schemes for wind turbines

3.2.3.1. General

The list of certification schemes for WTs is given in section 1.2.2 above.
As standard IEC 61400-22:2010 [20] is expired no suggestions for additions to this standard are made. Thus, the discussion here is referenced to

- **IECRE-OD-501** (certification scheme TC/CC) [17],
- **IECRE OD-501-4** (certification of loads) [18],
- **IECRE OD-501-5** (certification of C&P) [19] and
- **DNVGL-SE-0441** (certification scheme TC/CC) [21]

The certification of wind turbines commonly is conducted as WT *Type Certification*, leading to the WT *Type Certificate*.

The purpose of Type Certification is to confirm that the wind turbine type is designed, documented and manufactured in conformity with design assumptions, specific standards and other technical requirements. Demonstration that it is possible to install, operate and maintain the turbines in accordance with the design documentation is required.

WT type certification comprises different modules. Out of these the modules

– *Design Basis Evaluation / Design Basis*,

– *Design Evaluation / Design* and

– *Type Testing / Test*

are discussed below.

3.2.3.2. DESIGN BASIS EVALUATION / DESIGN BASIS (WT)

"Design Basis" is defined as:

"The design basis shall identify all requirements, assumptions and methodologies, which are essential for the design and the design documentation … ."

IECRE OD-501 [17] section 7.2.

With respect to wind turbine design for WFC this shall include the design requirements to prepare the wind turbine design for WFC. We suggest the following additional requirements.

The certification schemes list information, which shall be part of the Design Basis documentation. Regarding C&P for WFC we suggest adding to this list:

(1) **Specification of conditions, which the WT may experience in WFC** situations (e.g., de-rated operation, extended yaw misalignment or additional pitch system activities), including allowable operating time in each condition. The anticipated number of transients in and out these conditions shall also be specified.

(2) These conditions and transients in and out shall also be reflected in the **definition of load cases**.

<u>Explanations to (1):</u>

The WT manufacturer shall include definition of special conditions, which the WT could experience in WFC situations, including allowable operating time in each condition.
E. g. the following:

i. **Extended yaw misalignment**: yaw misalignment up to xx °
(e.g., '+yaw': δ = +30 ° average for 15 % of operation time,
'-yaw': δ = -30 ° average for 15 % of operation time,
100 transients in and 100 transients out for each '+yaw' and '-yaw' misalignments,
extreme misalignment θ = ± 45 ° as trigger value for high misalignment switch off)

ii. **Additional pitch system activities** for Wake Steering or Wake Mixing
(e.g., Additional Individual Pitch activities for wake steering: ± 2 ° for 20 % of operation time,
Additional Collective Pitch activities for wake mixing: α_{WM} = ± 4 ° in cycles of t_{WM} = 45 sec for 20 % of operation time)

iii. Requirements for **Induction Control** are partly to be addressed here.
Induction control reduces power on the active wind turbines and as such thrust.
These reductions are already part of WT design, as it is done maybe for noise reduction or maybe for technical reasons in the WT itself (e.g., reduced mode because of technical issues e.g. overheating of components).
Therefore the design of reduced operating procedures is not part of WFC related design and thus not discussed here.
However, the transients in and out induction control might be run through much more frequently in WFC applications, than without WFC. Therefore, they might

introduce extra loading on wind turbine's components, which requires them to be included in load simulations.

Requirements in turbine design for **operation in the wake** of another turbine positioned upwind are not discussed here, as WTs must withstand such wakes also in state-of-the-art wind farms.

Explanations to (2):

The module *Design Basis Evaluation / Design Basis* contains the **definition of design load cases**. Definition of some load cases might be influenced by WFC features.
Regarding the C&P system, potential failures in control need to be covered by protection functions and/or load cases. Thus, the definition of load cases depends on the control system design and how possible failure cases are dealt with.

Therefore, the WT manufacturer shall include the parameters of extended yaw misalignments and/or additional pitch system activities in the definition of related load cases.

At the moment we do not expect any additional failure load cases which originat from WFC features. We expect the WT load case table as per state-of-the-art wind turbine design to be sufficient. WFC features are included by choosing appropriate parameters.

3.2.3.3. Design Evaluation / Design (WT)

The purpose of design evaluation is to examine whether the wind turbine type is designed and documented in conformity with the design basis. Design Evaluation comprises different elements. Among those are *Control and Protections System* and *Loads and Load cases*, which are discussed below.

For WFC we suggest the following requirement, which the WT manufacturer shall include in the design documentation:

- ➔ The definitions of additional tests for the *Safety and Function Tests / Test of Turbine Behaviour* as listed in 3.2.2.3 (5) f) above shall be added to section "Test plan" in IECRE OD-501-5 [19].

The WFC specific requirements on C&P for module *Design Evaluation / Design* need to be added in the technical standards for design. This is discussed in section 3.2.2 above and has no influence on the certification module *Design Evaluation / Design* in the WT certification schemes.

For certification schemes module *Design Evaluation / Design* we do not suggest any other additions for C&P.

3.2.3.4. Type Testing / Test (WT)

The purpose of type testing is to provide the data needed to verify power performance, aspects that are critical to safety and need additional experimental verification, and any other aspects that cannot be reliably evaluated by analysis. Type testing comprises different elements. Among those are *Load Measurements* and *Safety and Function Tests / Test of Turbine Behaviour*, which have to do with C&P systems.

We do not suggest any additions to the certification schemes for module *Type testing / Test*, as it is suggested that WFC related changes are made in the respective technical standards, see section 3.2.2 above.

3.3. Proposal for certification requirements. Wind farm C&P certification

3.3.1. General

As stated in sections 1.2.3 and 3.2.1 above, most technical standards for wind turbines focus in detail on *wind turbine* design. *Wind farm* design is reflected to some extent regarding loads. Other aspects of wind farm design are covered vaguely in technical standards.
The related design and certification procedures in wind farm certification refer to technical standards of wind turbines or other systems instead. Now, that WFC plays a more important role in wind farm design and portions of wind turbine's control is moved into the WF-CS (wind farm control system), it makes sense to think about impact of these changes on existing and possible new standards.

In the following content related codes and standards are discussed along with the requirements suggested to be added for WFC around C&P (control and protection) systems.

3.3.2. Technical standards for the design of wind farms

The only technical standard for wind farms we know of are series of standards **IEC 61400-25** [22] on communication. Other technical requirements on wind farms are stated in the standards for wind turbines or their components, and for C&P are dealt with in section 3.2 above.

We do not suggest any additions to any technical standards for the design of wind farms regarding C&P for WFC.

3.3.3. Certification schemes for wind farms

3.3.3.1. General

The list of certification schemes for wind farms is given in section 1.2.4 above.

As standard IEC 61400-22:2010 [20] is expired no suggestions for additions to this standard are made. Thus, the discussion here is referenced to

- **IECRE OD-502** (certification scheme PC) [23] and
- **DNV-SE-0190** (certification scheme PC) [24]

Both standards mention WFC.

IECRE OD-502
WFC is mentioned in OD-502 section 7.2 *Project design basis evaluation* as well as in the related figures 1 and 2. It is part of the list of optional items, which can be included in the project design basis. Requirements specific to WFC are not given.

DNVGL-SE-0190
SE-0190 section 8.13 *Wind farm control* describes requirements on the certification of WFC. A procedure is outlined how to include WFC in SSDA and how to proceed, if the tools used for simulation of WFC specific loads are not validated yet.

The certification of wind farms commonly is conducted as wind farm *Project Certification*, leading to the wind farm *Project Certificate*.

Project Certification shall confirm for a specific site that type-certified wind turbines and other wind farm assets meet requirements governed by site-specific external conditions (wind, wave and current, soil, electrical grid, ...) and are in conformity with applicable local codes and other requirements relevant to the site.

Project certification may also confirm that installation and commissioning are in conformity with specific standards and other technical requirements, and that the wind farm assets are operated and maintained in conformity with relevant manuals.

Wind farm Project Certification comprises different modules/phases. Out of these the modules/phases

- *Project Design Basis Evaluation / Design Basis*,
- *Integrated Load Analysis Evaluation / SSDA*,
- *Other installations design evaluation / Design*
- *Commissioning Surveillance / Commissioning; Operation and Maintenance Manuals*
- *Project Characteristics Measurements / In-service* *and*
- *Maintenance of Project Certificate*

are discussed below.

We suggest amending the standards for C&P system related issues by adding following requirements:

3.3.3.2. Project Design Basis Evaluation / Design Basis (wind farm)

As pointed out in section 3.2.3.2 above for the topic WTs, the purpose of the *design basis* is to identify all requirements, assumptions and methodologies, which are essential for the design and the design documentation.

"The purpose of *design basis evaluation* for wind farms is to examine that the project design basis is properly documented and sufficient for a safe design and execution of the project." (IECRE OD-502 [23] section 7.2.1)

With respect to wind farm design this shall include the design requirements for WFC.

The certification schemes list information, which shall be part of the Design Basis documentation. Regarding C&P for WFC we suggest adding to this list:

The wind farm developer shall include the following in the Design Basis documentation:

a) Specification of WFC functionalities
b) Definition of assets and components used for WFC
c) Definition of WFC control functionalities and/or control loops
d) Specification of anticipated operation times in WFC conditions
e) Wind farm specific definitions of communication interfaces between WF-CS (wind farm control system) and WT-CS (wind turbine control system)
f) Descriptions of possible malfunctions in the WFC functions and how they can be detected during commissioning of the functions and in the wind farm operation phase. The technique used for this can be an FMEA as per IEC 60812 [42].

   Possible malfunctions to be considered may be e.g.,

   - WFC activities without positive effect. See 0 "Line 5.2"
   - Malfunction in the WF-CS because of conflict between WF-FC and WF-GC. See 2.2.3.3 "Line 5.1"

g) Specifications on measures on cybersecurity in the communication networks along IEC 62443 [43] series of standards
h) Prove that WFC features fall inside the definitions of WT's design specification. This can be part of the integration process of WT's type certificate into find farm project certification.

3.3.3.3. Integrated load analysis evaluation / SSDA (wind farm)

The purpose of the Integrated Load Analysis is to examine whether the site-specific loads and load effects on the integrated wind turbine structure, including the rotor-nacelle assembly plus the support structure and supporting soils, are derived in conformity with the project design basis.

SSDA (Site Specific Design Assessment) is the certification phase in DNVGL-SE-0190 [24] in which the Integrated Load Analysis is performed.

We suggest the following requirements. The wind farm developer shall:

(1) Include WFC operations in the Integrated Load Analysis (ILA).

(2) Define requirements for testing and/or monitoring in order to prove WFC measures' effectiveness during wind farm operation.

Explanations to (1):

One of the reasons for performing the ILA is to prove that wind turbine loads are not exceeding the design loads from WT Type Certification. Thus, by including WFC operations in the ILA it can be shown that the effects from WFC on turbine loading are acceptable.

Explanations to (2):

The purpose of this testing/monitoring is to provide related reporting for certification module/phase *Project Characteristics Measurements / In-service*. and/or for the *Maintenance of Project Certificate*.

3.3.3.4. OTHER INSTALLATIONS DESIGN EVALUATION / DESIGN (WIND FARM)

The purpose of *Other installations design evaluation* is to evaluate the design of other installations than wind turbines. Such other installations include the wind farm substation, in which the wind farm control system (WF-CS) is located. The other installations shall be evaluated for compliance with the standards and other specifications in the approved project design basis as well as with site-specific loads and conditions.

Design is the certification phase in DNVGL-SE-0190 [24] in which the design evaluation of the substation is performed.

The certification schemes list requirements, which shall be part of the *Other installations design evaluation / Design* validations.

Regarding C&P for WFC we suggest adding to this list:

➔ The control software of the WF-CS shall be evaluated along DNV-ST-0438 [15] section 2.9 or IEC 61400-1 [5] section 8.

3.3.3.5. COMMISSIONING SURVEILLANCE / COMMISSIONING; OPERATION AND MAINTENANCE MANUALS (WIND FARM)

The purpose of commissioning surveillance is to verify that the wind farm and its installations are commissioned in conformity with the relevant manuals included in the design documentation.

We suggest following requirements. The wind farm developer shall:

(1) Commission all functions as defined in 3.3.3.2 a) (Project Design Basis)

(2) Test the communication interfaces defined in 3.3.3.2 e) (Project Design Basis)

(3) Perform the tests for commissioning as defined in 3.3.3.2 f) (Project Design Basis)

3.3.3.6. PROJECT CHARACTERISTICS MEASUREMENTS / IN-SERVICE (WIND FARM)

The purpose of *Project Characteristics Measurements* within project certification is to establish performance-related characteristics of a specific wind farm at a specific site, in addition to the measurements done for a single turbine within the type certification.

In-service is the term used in DNVGL-SE-0190 [24] for the certification phase containing all certification activities in the operation period of the wind farm.
Testing and monitoring to prove WFC effectiveness can be performed inside this certification module/phase.

We suggest following requirements. The wind farm operator shall:

(1) Perform all tests and monitoring as defined in 3.3.3.3 (2) (Integrated Load Analysis).

(2) Perform measurements and tests which might be necessary for validation of the simulation tool used in find farm design. See 6.1.1.2.

3.3.3.7. MAINTENANCE OF PROJECT CERTIFICATE (WIND FARM)

For the maintenance of the Project Certificate certain activities of the certificate holder are required. Among these activities is an annual report issued by the certificate holder to be submitted to the certification body.

We suggest following requirements to be added to the requirements on the annual report.
The certificate holder (mostly the wind farm operator) shall include in the report:

(1) Report on WFC activities. List of actions taken and duration in the different WFC operation condition.

(2) Descriptions of possible malfunctions in the WFC functions detected in the wind farm operation phase. Methods of how such malfunctions can be detected were defined during certification module *Project Design Basis*; see 3.3.3.2 f).

3.4. Operational envelope

When introducing or optimising WFC features in a wind farm, close attention must be paid that the wind turbines (WTs) are not operated outside their allowable load envelope. Potential hazards are e.g.:

- overloading of WTs' components because of prolonged operation with large yaw misalignment,
- excessive wear at the pitch system because of increased pitch activities, and/or
- overloading of structural components related to thrust variations from WFC activities.

Usually, wind farm optimisation is done by the company operating the wind farm. Inside such company knowledge from the design process of the wind turbine may be little. Thus, when introducing WFC measures without co-operation of the wind turbine manufacturer, it might be difficult to judge whether the WTs are operated inside the allowable operational envelope. In other words: How to find the optimum tuning of WFC actions considering on the one hand extra loads on the WTs and on the other hand extra energy yield through WFC measures?

Addressing this conflict, it is proposed that the design process of WTs should include WFC measures and specify, which operational conditions are allowed for the wind turbine. This is explained in section 3.1. See Table 19 "– Two steps approach".

It is expected that the allowable operation conditions for WFC measures can be defined precisely in the WT's documents. Such specifications can be delivered to the wind farm operator together with the turbines. Also, it seems possible to include related specifications in the WT certification process and with that confirm by the Certification Body, that related specifications took part in the WT design process.

There might be cases, where wind farms consist of WTs for which WFC measures were not included in the design process. In such cases a substantial verification of WTs' suitability without re-visiting related load simulations and without a validation by testing will be very difficult. In terms of certification this would be part of certification module/phase *Integrated load analysis evaluation / SSDA*.

3.5. Digital Twin

A data driven possibility to support decisions in maintenance and operation of wind farms is to run digital twins of some or all wind turbines in the wind farm. Such digital twins receive input from WTs' control system and process them in a simulation software running live in parallel to the WTs. Thus, real turbines' operational life is "mirrored" in the simulation. Output from digital twins may be fatigue strength consumption, reasonable maintenance intervals or other information. So, they can be used to support discussions with operators.

A digital twin in principle consists of the elements shown in Figure 5 below.

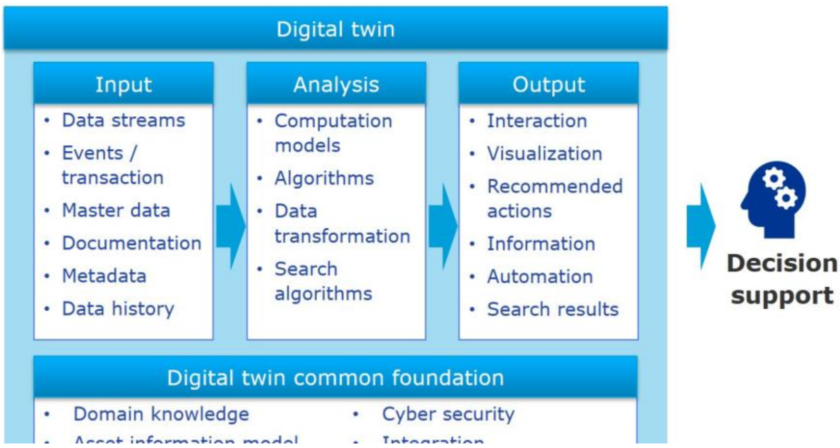

Figure 5 - Elements of a digtal twin
(Source: DNV-RP-A204:2021-09 [44], Figure 2-1 page 17)

A third-party validation of the digital twin can be beneficial to support confidence in its output data. Such validation would typically be made along the DNV service document *DNV-RP-A204 Qualification and assurance of digital twins* [44] from which also Figure 5 was taken.

Depending on the computational model and simulation software used, the digital twin can e.g., deliver component load data accurate enough to monitor the fatigue status of the hardware. This in principle can support controlling WFC measures.

Standards or other regulations on digital twins are not specific to wind turbine or wind farm application. Therefore, we are not suggesting any additions or changes to them regarding WFC.

3.6. Overall wind farm system stability

3.6.1. MUTUAL DEPENDENCY OF CONTROL TASKS

Control processes in wind farms are complex. WTs are constantly adapting their controls on

a) **ambient conditions** like wind speed, wind turbulence, allowable noise and shadow emissions, possible icing ...
   and
b) WTs' **components conditions** like temperature of main components, well-functioning of all technical systems
   and
c) conditions of, and demands from the **electrical grid** (or from the relevant network operator), to which the PoC of the wind farm is connected to. E.g., limitations or response requests regarding active power, reactive power, grid disturbances, voltage dips or swells, system frequency f etc.

To accomplish these control tasks, state-of-the-art wind farms contain control systems in each of the WTs (WT-CS) and one control system for the wind farm in one of the WTs or in the wind farm's substation (WF-CS). These control systems are connected through the wind farm communication system. See Figure 1 "– WT/Wind farm control systems". Functions in these systems work along a clear hierarchy of priorities to accomplish overall well-functioning.

Thus, WFC measures need to be integrated into already integrated complex systems. Even more WFC activities will influence other existing control loops. Such as:

- **Yaw control**
  In absence of WFC, each of the WT-CSs aligns the yaw orientation of the wind turbine with the wind direction.
  During WFC activities, the WFC-active turbines might control yaw orientation to align to the demanded orientation rather than to the wind direction.
  See section 3.2.2.1 Figure 2 and Figure 3.

- **Pitch control**
  In absence of WFC, each of the WT-CSs controls each of the pitch movements for the optimum balance between energy yield and component's loads. This might include individual pitch control in closed loop control with load sensors.
  During WFC activities, the WFC-active turbines might additionally control the pitch movements for wake mixing. This might include wake mixing by individual pitch control ("helix approach").
  See section 3.2.2.2 Figure 4 for collective pitch control and section 2.1.3 for both collective and individual pitch control.

- **Power control**
  In absence of WFC, each of the WT-CSs controls active power production (via pitch and speed control) to achieve optimum yield. At the same time the reactive power production of the wind turbine might be controlled to minimise losses in wind farm's electrical installations or / and to control voltages at different points within the wind farm or at the PoC.
  During WFC activities, the WFC-active turbines might down-rate active power. This will also influence voltages at different points in the wind farm and in turn the power factor and should be aligned with reactive power control (and especially voltage control). See also section 5.4.2 below.
  Note: Significant influence from reactive power control on performance or mechanical loads of the WTs are not expected. Thus, WT's active power control can be independent of reactive power control; in contrast to – as described – reactive power control which is not independent of voltage control.

It is important for the overall function of the wind farm, that WFC measures do not negatively affect any existing control mechanisms. At the same time the question arises how robust the different control loops and mechanisms are in terms of possible disturbance from other loops.

How can interfaces be defined sufficiently? How can mutual dependencies be recognised and visualised? Can possible instabilities result in suboptimal behaviour, or even in interaction with the electrical grid outside the wind farm? Can structural integrity be endangered?

An overall complete combined testing of wind farm controls and effects seems impossible, as the number of combinations of different conditions is enormous.

Computational simulation of wind farms normally is done in "two worlds".
On the one hand, effects in the electrical grid of the wind farm, at WT and transformer terminals and at the PoC are simulated in power system software with very short time steps (in the range of ms, e.g. PowerFactory, PSSE).
On the other hand, aerodynamic and mechanical effects are simulated in specialised software with larger time steps of 20 Hz to 1 Hz (e.g. Bladed, LongSim).
Overall effects and dependencies are thus difficult to capture by simulation.

As shown in Deliverable D4.1 of TotalControl "Control algorithms for primary frequency and voltage support" [2], simulation of aerodynamic and mechanical effects can be done in closed loop setup with the simulation of effects in the electrical grid by coupling the related software packages. In D4.1 [2] this was done with the focus on the behaviour of a large grid including its wind farms. Future research might focus on wind farm internal effects to better understand the mutual dependencies of control tasks and possibly negative interactions.

When including WFC in a wind farm on site, the wind farm developer is recommended to closely monitor the turbines' and grid's behaviour to detect any possible oscillations in good time.

For the topic *mutual dependencies of control tasks*, no changes in or additions to any standards are recommended.

3.6.2. Wind sensors

Wind speed and wind direction in a wind farm are often measured on the "first row wind turbines", which – depending on momentarily wind direction – are located most upwind. At those wind turbines the operational wind sensors are used to calculate the wind farm's wind speed and direction.
The sensors for both wind speed and wind direction are typically located on the roof of WTs' nacelles behind the rotor. Thus, they are disturbed by the aerodynamic effects from operation of the rotor. To compensate such negative effects, wind speed and directions signals are normally calibrated during WT prototype testing.

This calibration can however be corrupted by WFC measures like wake steering. Such corruption may contribute to control problems or even instabilities.

Therefore, it is suggested to include the WFC measures in the calibration procedures of wind speed and wind direction signals. See section 3.2.2.3 items (5) f) ii and iii.

3.6.3. Closed loop WF-FC

Wind farm flow control (WF-FC) measures can in principle be conducted in a closed control loop. The wind farm control system could initiate actions such that the intensity of these actions is controlled depending on measured reactions from the field. In such closed loop control the frequency of control actions might be very low (in the magnitude of 10 minutes to ½ hour, see FarmConnners Delivery D2.1 [7] figure 10). The measured reactions could be loads on downstream WFC-passive turbines or rise/drop of active power yield, maybe even signals from wind sensors in the wind farm.

Any closed loop control in principle involves the risk of controller instability. Normally, in control loops such instabilities are ruled out by adequate tuning of the control parameters. This tuning would be very difficult here, as experience is rare.

We would expect such closed loop WFC to be challenging, because the measurable reactions are little and will probably be hidden in signal noise. In fact, we are not aware of any WFC now being conducted in closed loop control.

Therefore, is appears difficult at this point to relate closed loop WFC to requirements in standards. Thus, we do not suggest any standards or changes in standards for closed loop WFC.

3.7. Interface WT design ↔ wind farm design

Certification of *wind turbines* (WTs) is often done by issuing Type Certificates to types of wind turbines. See sections 1.3.1.1 and 1.3.2.2. On the other hand, certification of *wind farms* is often done by issuing Project Certificates to wind farms. See sections 1.3.1.3 and 1.3.2.4. Thus, the interface between these two sorts of certificates is important.

Additionally – as pointed out in section 3.4 "Operational envelope " – naturally WFC measures would be initiated by the wind farm operator whereas the wind turbines are designed by the wind turbine manufacturer. Thus, the interface between the two stakeholders is important.

To address these interfaces, we suggest considering WFC measures in the WT design process. See section 3.2.2.3 above.
Also, we suggest including specification of the WTs' WFC capabilities in WTs' specification. See section 3.2.3.2 para (1). These suggestions are referred to as "Two step approach". See section 3.1. See Table 19.

Key for the interfaces mentioned above is the specification of the capabilities of wind turbine for WFC measures. This specification shall be prepared by the WT manufacturer and provided to the wind farm operator for the design of the wind farm.

We expect that such specification describes as clearly as possible, which WFC measures were considered in the design of wind turbines and to which extent. As a minimum it should include relevant data from certification module/phase WT *Design Basis Evaluation / Design Basis*, see section 3.2.3.2 bullet (1) including section Explanations to (1). In practical terms, this means the operator should know the thresholds for any operational parameter which can be adjusted for WFC.

4. Design Loads

4.1. General

The determination and certification of design loads is part of the certification module / phase "Design Evaluation" according to the certification schemes for Type Certification as listed in section 1.2.2 and for Project Certification as listed in section 1.2.4. Applicable standards for the design and testing of wind turbines are listed in section 1.2.1, and for wind farms in section 1.2.3. The Design Evaluation is split into several components, the relevant ones with respect to the design loads are "Design Basis", "Load Evaluation" and "Type Testing".

Within the Design Basis, all required Design Load Cases (DLC) are firstly based on the applicable standards (see sections 1.2.1 and 1.2.3), secondly on the site-specific conditions such as wind & wave, and wind farm layout, and thirdly also on the control and protection systems which might apply WFC-actions. The DLC definitions under WFC requirements are discussed in section 4.4.

The determination of design loads is being done by applying highly specialised simulation tools. These tools usually generate time series of loads, based on an aeroelastic model. These (aeroelastic) models need to execute potential WFC-actions. The load simulation models can be supported by tools determining wake propagation within a wind farm ("wake tools"). For the application of WF-FC actions, these wake tools need to be upgraded. Any of these tools (simulation and wake modelling) require a thorough validation, commonly being done by simulation vs. measurement comparisons. The determination of design loads by applying different tools including their validation is described in the sections 4.1.1 to 4.3.

The numerically determined design loads, as well as the power performance and some general functionality of the wind turbine control and safety system are validated within the certification module / phase "Type Testing". The focus of these standardized measurements followed by validation is to verify the applied model of the wind turbine under certification. See also section 6.

4.1.1. Load simulation in wind farms according to IEC 61400-1 ed. 3.

The loading level of a wind turbine inside a wind farm is determined to a significant extent by the wake effects that it undergoes. That means that loading does not only depend on the ambient conditions characterizing the site but also on the relative location of the neighbouring wind turbines.

4.1.1.1. Wake model

From a certification point of view, the wake effects have been historically reduced to an increase of the turbulence intensity felt by the downstream wind turbine. From the different possibilities that can be found in the literature, in IEC 61400-1 3rd edition [45] it was decided to prescribe a model for the wake-induced added turbulence intensity based on Frandsen's approach [46]. The model chosen for the added turbulence intensity is engineered to fit wake turbulence measurements at both near and far-wake regions. Assuming a linear relation between turbulence and stress cycles, and that fatigue damage can be described by a linear SN-curve with the Wöhler exponent m, an m-dependent effective turbulence intensity is defined such that it causes the same fatigue as the varying quantity. Following Annex D.1 of [45], this effective turbulence intensity can be written as:

$$I_{eff,m}(V_{hub}) = \left\{\int_0^{2\pi} p(\theta|V_{hub}) I^m(\theta|V_{hub}) d\theta\right\}^{\frac{1}{m}}$$

where V_{hub} represents the wind speed at hub height, $p(\theta|V_{hub})$ stands for the probability density function of wind direction conditioned on the wind speed, and m represents the Wöhler (SN-curve) exponent for the considered material. The turbulence intensity of the combined ambient and wake flows from wind direction θ can be written as:

$$I(\theta|V_{hub}) = \sqrt{I_c^2(\theta|V_{hub}) + I_{add}^2}$$

where $I_c = E[I] + 1.28\sigma_I$ stands for the characteristic ambient turbulence standard deviation and the wake-added turbulence is represented by $I_{add} = \left(1.5 + \frac{0.8d}{\sqrt{C_T}}\right)^{-1}$. As described in Annex D of Amendment 1, an additional wake effect originating inside large, densely packed, wind farms is also considered in the model.

4.1.1.2. Application to wind farms

One of the main advantages of this approach is its applicability. Without much computational effort, it is possible to quickly calculate the effective turbulence intensity expected at each position within the wind farm for different Wöhler exponents. For this purpose, the input required is reduced to: wind farm layout, wind rose, sector-wise wind distribution, and turbulence intensity.

As stated in Sec. 11.9 of [45], if this omnidirectional effective turbulence intensity is exceeded by the turbulence intensity considered in the certification at all positions, then there is no need to perform additional fatigue calculation.
If that is not the case, then a load calculation is necessary, and the simulation of the different design load cases required by the standards at each position may become a time-consuming task.

In order to optimize this process two options are generally followed.

a) Representative wind conditions. Use the wind conditions, including the aforementioned effective turbulence intensity, to find representative conditions that cover the whole wind farm. Once these are identified, only simulations for these are needed. The simplest approach is to consider the envelope of all wind conditions. This straightforward strategy, though, may lead to rather conservative loads. An alternative may imply the consideration of the envelope of only specific combinations of different wind properties, e.g. the effective turbulence intensity and the wind speed distribution at each position. This method is also very fast and may be used to reduce the number of simulations to be performed without being over conservative. Nevertheless, caution has to be taken when using these alternative approaches: The assumptions involved in the determination of the most loaded turbines imply some relationship between the wind conditions considered and the corresponding expected loads are not always satisfied for all conditions and all sensors.

b) Load estimation. The second option is based on the estimation of loads at each WT position without recurring to direct simulation every time. This can be achieved by using surrogate models. This offers some advantages with respect to the "wind-based" approach: firstly, one expects a better match with the expected actual loads since the analysis directly involves loads; secondly, one obtains at once values for different sensors. The only requirement is to have control on the uncertainties inherent to the numerical methodology as well as from the use of variants in the database that differ from the ones expected at the site.

The main limitation of the wake model proposed is twofold: first, the model does not attempt to describe the physics involved in the wake phenomenon like the wake deficit or meandering; and second, the model can be only applied to analysis of fatigue loads. The wind conditions required for calculating ultimate loads in the presence of wake are either omitted, "it shall be demonstrated that the site specific horizontal shear due to partial wakes does not exceed EWS" Sec. 11.9, or only vaguely mentioned "The site specific extreme turbulence may be represented by the maximum centre wake turbulence in the most severe direction", Sec. 11.9 of [45].

4.1.2. Load simulation in wind farms according to IEC 61400-1 ed. 4.

In order to overcome these problems, an additional wake model was proposed in IEC 61400-1 ed. 4. [5], alternative to Frandsen's model, namely the Dynamic Wake Meandering Model (DWM).

4.1.2.1. Wake model

One of the main purposes of DWM is its attempt to describe the main features of the wake evolution without becoming too computationally time-consuming. So, instead of reducing the wake effect to an empirical increase of the turbulence behind the upstream wind turbine, DWM describes the changes in the mean flow field over the wind farm as well as the changes in the turbulence intensity and turbulence structure compared to ambient conditions.

The DWM model is based on the assumption that wakes can be considered as passive tracers consecutively released from upstream wind turbines and subsequently Taylor advected downstream under the influence of large scale turbulence structures in the lateral and vertical directions [47].The DWM is composed of three ingredients, see Annex E.2 [5]:

- A model of the wake deficit formulated in the meandering frame of reference, based on the thin shear layer approximation of the Navier-Stokes equations in their rotational symmetric form with the pressure term disregarded, and assuming an eddy viscosity approach for the Reynold stresses [48] and [49].
- A stochastic model of the downstream wake meandering process, based on the fundamental presumption that the transport of wakes in the atmospheric boundary layer can be modelled by considering the wakes to act as passive tracers driven by the large-scale turbulence structures.

- A model of the self-induced wake turbulence described in the meandering frame of reference, accounting for the conventional mechanically generated turbulence. This is caused by the wake shear, as well as from the blade shed and trailed vortices mainly in terms of tip and root vortices gradually breaking down downstream of the wake generating rotor. Thus, this turbulence contribution is considered independent of the ambient turbulence.

Apart from the description of the three main ingredients of the DWM, the Annex E.2 also provides a prescription about how to deal with wake superposition.

4.1.2.2. Application to wind farms

As already mentioned, one of the main objectives of introducing the DWM model is to capture the main characteristics of the wake evolution. As a consequence, it allows for a more consistent analysis of both fatigue and ultimate loads for wind turbines within a wind farm. As can be seen in Table 20, three different design load cases with explicit influence of wake are introduced in IEC 61400-1 4th ed.: DLC1.2 (F), DLC1.6 (U) and DLC1.7 (U).

Table 20 – Extract of design load cases table from [5],

Table B.1 – Design load cases

Design situation	DLC	Wind condition[41]	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM_s $V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM_s $V_{in} < V_{hub} < V_{out}$	Wake effects	F	*
	1.3	ETM_s $V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD_s $V_{hub} = V_r - 2$ m/s, V_r, V_r +2 m/s		U	N
	1.5	EWS_s $V_{in} < V_{hub} < V_{out}$		U	N
	1.6	ETM_s $V_{hub} = V_r \pm 2$ m/s and V_{out}	Wake effects	U	N
	1.7	NTM_s $V_{in} < V_{hub} < V_{out}$	Ice formation Wake effects	U	N
	1.8	NTM_s $V_{hub} = V_r$	Earthquake plus grid loss	U	N

The price to pay for using a more realistic wake model is more time-consuming simulations when compared to application of Frandsen's model. Performing detailed wake simulations for all positions is extremely challenging. Alternative strategies are therefore necessary.

One of the most promising possibilities consists in using surrogate models. It is important to keep in mind that, although the use of surrogate models may turn out to be crucial to speed up the load calculation process, it entails an inherent level of uncertainty associated with the numerical methodology as well as the consideration in some cases of variants that may differ from those expected at the site. A clear understanding and quantification of this uncertainty is required. From a certification point of view, this shall imply the submission of a detailed description of the

theoretical basis underlying the methodology used, a proper validation of the surrogate tool against measurements and/or standard aeroelastic tools, as well as a sensitivity analysis which allows for a quantification of the uncertainty associated to the use of the tool.
An alternative way to use surrogate models is to consider them on a relative approach, namely, not to determine absolute loads at the different positions but to identify the expected most loaded turbines and then perform detailed aeroelastic simulations only to this sub-set of wind turbines.

In addition, it is important to mention that in many cases the focus is put on the estimation of fatigue loads. However, wake-induced extreme loads may play an important role in driving some components.
Of particular importance are the 50 year load values expected from the load extrapolation analysis (DLC1.1). Whereas in the framework of 61400-1 ed. 3, load extrapolation has been basically used in the past as a way to calibrate DLC1.3, the use of more and more sophisticated control features makes it harder for DLC1.3 to exceed the extrapolated loads. From a certification point of view, it is expected that the extrapolated loads will not be used to calibrate DLC1.3 but they will have to be directly included in the overall load evaluation as another load case. This will lead to the requirement to extend the load extrapolation analysis to additional sensors -not just the blade root bending moments and blade deflection- and to a more realistic estimation of the 50-yr loads within a wind farm. This implies the consideration of wake loads in DLC1.1, i.e. the wake-induced loads obtained in second-row WTs, in the estimation of the 50-yr values. Alternatively, a proof that the simpler use of ambient conditions is a conservative approach and the wake effects can be neglected is required.
Besides considering the NTM/ETM-based ultimate DLCs, it is crucial to establish the need –as well as the possibility– to simulate the wake effects in combination with rest of ultimate DLCs such as DLC1.4 or DLC1.5. It is of paramount importance to elucidate the mitigating or enhancing role of the wake on the second-row WT loads when the first-row WTs are affected by these extreme wind conditions.

With respect to the DWM model, it is important to mention that, although it represents a great advance in the process to find a realistic description of the wake phenomenon which at the same time is computationally manageable, the model as currently defined in the IEC presents some limitations:

- In spite of the extensive model validation carried out in the latest years, it is still not completely clear whether the current values of the parameters defining the different empirical functions are representative enough for all situation, or if they are significantly dependent of the wind turbine characteristics as well as the environmental conditions, as suggested in [50].
- It does not include the effect of the atmospheric stability but just assumes neutral atmospheric stratification. The atmospheric stability has an important influence on the mean wind shear, turbulence intensity and turbulence structure, mainly the large-scale turbulence structure, due to the contribution of buoyancy forces to the turbulence generation. With respect to DWM, the atmospheric boundary layer stability is expected to have a significant impact on the wake meandering [51].
- The model suggested in the IEC assumes no yaw misalignment. However, as it will be discussed in the next section, the consideration of WFC may lead to the need to consider

wake effects under significant yaw misalignment. A validated implementation of this situation into the DWM is required.

- The effects of complex topography are not accounted for in the model. In the case of onshore projects located on complex terrain, an adjustment of the existing DWM to these specific conditions and the corresponding validation may be required.
- Given the intrinsic assumptions of the model, it is not clear to which extent DWM can be extended to consistently describe the combination of wake effects (second-row WTs) with the presence of extreme conditions such as deterministic gusts acting on the first-row WTs). Further investigation in this direction is necessary.

4.2. Load simulation in wind farms in the presence of WFC

The presence of WFC is expected to have a significant impact in the load simulations within a wind farm. In Section 2.1 three major WFC strategies were introduced:

- Axial induction control
- Wake steering
- Wake mixing

In the axial induction control approach, the control settings, e.g. blade pitch and generator torque, are adjusted to influence the axial-induction factor of the wind turbine. By reducing the axial induction of the upstream turbine both its power production and rotor thrust diminish. As a consequence, the wind speed decrease expected within the wake becomes less severe and therefore the power production of the downstream turbine increases with respect to the non-derated case [52] and [53].
Yaw control is performed by yawing selected WTs out of the wind by up to approximately ±30° away from optimal alignment to the wind direction. This has a crucial effect on the wake evolution: the wake centre line does not propagate in the wind direction as in the case of no yaw misalignment, but it becomes deflected. As a consequence, the wake can in principle be steered away from the downwind WT position.
In contrast to the previous control strategies, which focus on static setpoint optimization of wind farms, in [54] a dynamic induction control approach based on LES and adjoint gradient optimisation was introduced. In that study, individual turbines were used as dynamic flow actuators that influence the wind-farm boundary layer flow so that the overall wind-farm power extraction is optimised. A qualitative analysis of instantaneous flow fields led to the observation of quasi-periodic shedding of vortex rings from the first-row turbines in the optimal control case [55]. This flow feature was successfully mimicked using simple sinusoidal thrust actuation of the first row. Increasing the wake mixing with the free-stream wind flow can also be achieved by periodically modulating the collective pitch angle by some degrees and thereby modulating the rotor thrust. Both the period and the amplitude of the pitch can be optimised to reduce the wake generated [56]. Similar effects are expected by using dynamic individual pitch control [41] [56].

In the present discussion, we will concentrate on the yaw control and its implications on the wake evolution, as it currently represents the technology expected to provide the most benefit in combination with the least risks.

4.2.1. WAKE MODELS FOR WFC

While the two wake models proposed in the IEC 61400-1 – Frandsen (Ed. 3 [45] and 4 [5]) and DWM (Ed. 4) – are capable of handling de-rating strategy, none of them contains a prescription about how to describe the wake effects under large yaw misalignment. With this respect, attempts are currently being made to extend DWM to describe the wake steering.

4.2.1.1. GENERALIZATION OF DWM

The most important activity carried out currently to make DWM more flexible, so that it can realistically cover more and more situations, is centred in the implementation of atmospheric stability and large yaw misalignments in the DWM description, see work performed by DTU in [51].

The former can be achieved by considering the changes that atmospheric boundary layer (ABL) stability induces in the mean wind shear as well as in the turbulence intensity and structure. The turbulence generation is modified since buoyancy forces now add to the friction forces, with the former affecting mainly the large-scale turbulence structures. As a consequence, the mean wind shear is also modified. The result is a reduction of the shear in situations with unstable ABL due to the larger mixing. With respect to the wake, it is therefore expected that the ABL stability primarily affects the wake meandering, driven by large turbulent scales. The impact on the turbulence can be taken into account by replacing the Mann spectral tensor modelling of the turbulence scales responsible for the wake meandering with a turbulence modelling accounting for buoyancy [51].

In order to deal with the wake steering in the framework of DWM it is important to keep in mind that one of its main assumptions is the Taylor advection of continuously emitted wake deficit releases in the longitudinal flow direction. In case of yawed operation, the streamlines behind the upwind wind turbine are expected to be curved in the near wake regime and asymptotically approaching straight lines in the far wake regime. A mean deflection is defined as the streamline passing through the upwind turbine' rotor centre and determined with the help of linear Reynolds Averaged Navier Stokes (RANS) simulations based on Fuga flow solver [57]. Following the original model, the wake deficit is modelled as circular symmetric in a plane rotated by a yaw angle [51].

An alternative implementation of the wake deflection within DWM can be found in the description of NREL's software FAST.Farm [58]. By simple extensions to the passive tracer solution for transverse wake meandering, the wake-dynamics solution in FAST.Farm is extended to account for wake deflection and wake advection. The passive tracer solution enables the wake centreline to deflect based on the inflow skew, since in this case the wake deficit normal to the disk introduces a velocity component that is not parallel to the ambient flow. In addition, FAST.Farm uses atmospheric phenomena generated by a precursor LES simulation of the entire wind farm, as is currently implemented in the ABL-solver pre-processor of SOWFA. This precursor atmospheric simulation captures stability as well as complex terrain effects.

4.2.1.2. ALTERNATIVE WAKE MODELS

Besides the extensions of the medium-fidelity DWM model, there are other models that provide a description of the wake in the presence of wake steering.

On the one hand, there are the high-fidelity wake models, relying upon differential relations of fluid mechanics. High-fidelity wind farm models generally employ large-eddy simulations (LES), which solve temporally and spatially-filtered forms of the three-dimensional Navier-Stokes equations that only capture eddies of relevant scale.
One example of a high-fidelity simulation tool that is commonly used for wind farm controller evaluation is SOWFA (Simulator fOr Wind Farm Applications), developed by NREL [59]. It couples an LES-based flow field model (OpenFOAM) with NREL's Fatigue, Aerodynamics, Structures, and Turbulence (FAST) code. The aerodynamic interaction between the wind and turbine blades is modelled using actuator line potential flow theory, which captures additional flow phenomena such as blade root and tip vortices in comparison to LES-based tools that model turbines using actuator disc theory.
Another widely used tool is EllipSys3D, developed by DTU [60] and [61]. A comparison of the two actuator-line based tools showed a very good agreement with MEXICO and NEW MEXICO experiments in the near wake region with only some discrepancies in situations when 3D effects start to dominate [62]. About their applicability in the context of wake steering, see e.g. [63] and [64].
Other three-dimensional LES-based simulators developed specifically for wind farm applications include: SP-Wind, developed by KUL [65], which reduces the computational cost of simulations by modelling wind turbines using actuator disc theory; UTD Wind Farm [66]; or PALM (Parallelized LES Model) [67].

High-fidelity models are necessary to understand the underlying physics of wind turbine wakes, assess their controllability and reliably predict wind turbine and farm performance. However, due to their time-consuming simulations, they are not so suitable for the design and optimization of wind farm control systems. For that purpose, it is more useful to consider certain model approximations which allows for faster simulations.
One of these possibilities is represented by the Fuga model [68]. The Fuga model is a linearized CFD flow model that calculates wake effects in wind farms. The linearization is a result of a perturbation expansion using the drag force as the perturbation. Although the original version did not include a description of the effects in the case of yaw misalignment, the possibility to generalize it to yawed cases has been investigated in [57].
Other examples of medium-fidelity wake models are WFSim [69], which solves a two-dimensional form of the unsteady turbulent Navier-Stokes equations along a horizontal plane located at the hub height of the wind turbines within a wind farm; or FarmFlow (WakeFarm) [70], which simulates the wind turbine wakes by solving the steady parabolized Navier-Stokes equations in perturbation form in three dimensions.

On the other extreme, there are the so-called low-fidelity wake models, based on integral relations of fluid mechanics, where the rates of change of fluid momentum and mass must be conserved across a specified control volume, like the Park wake model [71], [72].The possibility to combine these models with effects of yaw misalignment analytically was done in [73]. A simple formula was proposed to predict the wake skew angle based on the momentum conservation and top-hat model of [71]. Using this approach, a formula for the yaw induced wake centre trajectory was derived by integrating this skew angle [74] and implemented in FLORIS model (FLOw Redirection and Induction in Steady-state). Two models have been recently proposed using a similar approach but considering a Gaussian distribution of the velocity deficit [75] and [76]. Another Gaussian wake model [77] has been coupled with a fast boundary layer model, the Three Layer Model, to enable faster study of wind farm response in different atmospheric conditions [78].

4.2.2. APPLICATION TO WIND FARMS

The fact that the wake model becomes more sophisticated makes the evaluation of wake effects more time consuming. As in the case of wake analyses within the framework of IEC 61400-1 3rd and IEC 61400-1 4th ed., optimization strategies in the presence of WFC have to be defined.

As previously mentioned, the use of surrogate models can be crucial to speed up the load estimation at different positions within the wind farm, and therefore can play a crucial role for wind farm optimization purposes.

In the context of DWM, several examples can be found in the literature and are currently validated. Reference [79], for instance, proposes a method based on creating a database, which contains the time and rotor-averaged wake effect at any point downstream of a wake-emitting turbine operating in arbitrary ambient conditions. This database is later used as a look-up table to estimate the operating conditions at all turbines in the wind farm.
A more sophisticated surrogate model, based on polynomial chaos expansion and artificial neural networks, is presented in [80]. The artificial neural network has been used to simulate several wind directions and wind speeds across the wind farms to quickly compute the power production and damage consumption with and without de-rating. This has been combined with probabilistic methods for assessing the fatigue life consumption of wind turbines in the Lillgrund wind farm [81].

A new method called LongSim [82] has been developed by DNV which involves combining the deterministic effects of wake profiles, shear, yaw misalignment, upflow etc. with the stochastic effects of rotationally sampled turbulence coupled with structural dynamics. The effects are calculated separately from models fitted to appropriate sets of Bladed runs, and then combined. The step of combining the load components derived from different effects clearly involves a significant approximation, but this is tested by comparing the outcomes against individual Bladed simulations for specific sets of conditions which Bladed is able to deal with. The wake model considered is very similar to the DWM model described in IEC 61400-1 but with some differences, e.g. the wake added turbulence follows the empirical description suggested by Quarton-Ainslie. In addition, it takes into account the wake advection as well as the possibility of deflection following the analytical prescriptions described in [73], [77] and [75].

Other surrogate models can be found that do not use DWM as wake model but are based on high-fidelity solvers. In [83], the optimization of wind farm control through wake steering using surrogate models based on EllipSys3D and the actuator line method to represent the turbine is considered. The turbine performance and response are calculated using the aeroelastic tool Flex5 and the surrogate is based on polynomial chaos expansion.

Although the great potential that surrogate models offer in the context of wind farm control, one cannot forget that they are also affected by uncertainties, especially related to their calibration, i.e. the data set used for training the model. This uncertainty associated to the input is propagated through the model and can significantly affect the output.

This together with the fact that none of them is explicitly recommended in the current standards, makes the need for a thorough validation, when used with certification purposes, crucial. In addition, it is important to note that, as happened in the case of IEC 61400-1, without WFC, surrogate models are usually conceived for fatigue load estimations and not for extreme.

4.3. Validation of load simulation software

4.3.1. Summary of simulation software with WFC available

Wind farm models consist of two main components:

- Turbine model, which predicts the interaction between the flow and the turbine structure.
- Flow model, which describes the flow properties in a wake or of the total flow field in a wind farm.

Examples of common aeroelastic software packages used in the industry that simulate the interaction between the flow and the turbine structure are Bladed, HAWC2, FAST, etc. These are BEM-based tools and are utilized for the calculation of loads in Type Certification-loads in first-row position. Bladed and HAWC2 have to some extent implemented DWM, so that loads in the second-row positions in the presence of wake can be calculated.

Fast flow models which take into account the interaction with wind turbines are FAST.Farm or LongSim. They allow for the calculation of loads induced by multiple wakes and perfectly suited for wind farm control optimization, as well as the identification of the most severely loaded turbines.

4.3.2. Software Validation against Measurements

The higher uncertainty associated to the new, WFC-induced conditions plus the fact that no specific prescription is described in the standards, makes the need for a thorough software load validation especially important. For this purpose, two approaches are defined: validation against measurements and code-against-code validation.

The main objective of the validation against measurements is the confirmation of the aerodynamic description of the WFC effects as well as its implementation in the different software packages under normal environmental conditions. Depending on the wake impact, three scenarios are defined: 'first-row', 'second-row' and 'multi-wake' validation. The first case examines free flow approaching the wind turbine in the first row of a wind farm depending on the actual wind direction. For the second case a wind turbine in the wake of one other turbine is assumed. The third case considers any wind turbine exposed to multiple wakes. This setup intends to break down the complexity of the validation task as far as possible. Thus, the focus can be set to most relevant cases applying more customary simulation tools while more challenging validation tasks for the multi wake case can be performed with increasing experience.

4.3.2.1. First-row validation

WFC-based first-row validation would basically represent an extension of the requirements described in IEC 61400-13, namely measurements on a standalone wind turbine, to include the new WFC features. It is expected to describe the WT behaviour of wind turbines located in the first-row of a wind farm, namely in the absence of wake effects.

The following information shall be provided:

1) Description of the aerodynamic model considered for the yaw misalignment and implementation in the aeroelastic code.
2) Setup of measurements and comparison between measurements and values predicted by the software. A detailed description of the sensors to be considered and situations to be covered can be found in Sec. 6.1 and 6.2.
   Additional situations to consider (yaw-transient). Check model behaviour continuity.
3) Conclusion stating the range of applicability, e.g. range of yaw misalignment, and possible limitations and uncertainties associated to the model.

4.3.2.2. Second-row Validation

As previously mentioned, one of the most important challenges is the difficulty to find a relatively simple (computationally affordable) and accurate description of the wake phenomena under large yaw misalignment.
In order to quantify the uncertainty associated to the existing models as well as to guarantee a specific level of conservativeness, it is decisive to add waked measurements to those defined in the previous section. The focus of the validation is the confirmation of the downwind flow description as well as the operational behaviour and loading level of the second-row WTs, i.e. under direct wake, in situations where the upstream wind turbine rotor is not aligned with the wind direction, under normal conditions.

As in the previous case, the following information is required:

1) Description of the wake model used in combination with large yaw misalignment of the first-row WT, as well as its implementation in the specific aeroelastic tool.
2) Setup of measurements and results of the validation. As described in Secs. 6.1 and 6.2, power production load cases should be measured and analysed for both fatigue and relevant extreme loads, applying different turbulence intensity levels. The results will be provided for both the upstream (first-row) and downstream (second-row) turbines. For this purpose, the following 2-WT scheme may be considered:
   Two WTs separated by a distance *d* and with a specific angle between the two turbines and the wind direction, *WT up-wind angle*, as shown in Figure 6. Under this situation, power production load cases for the two turbines are analysed assuming different yaw misalignments of the upstream turbine. Following the description given in Secs. 6.1 and

6.2., extreme and fatigue loads as well as the power performance for the two turbines have to be calculated and compared with the measurements.
The same analysis shall be performed for different *WT up-wind angles*, including positive and negative angles. The maximum value analysed must be such that a clear transition between wake to free streaming should be observed.

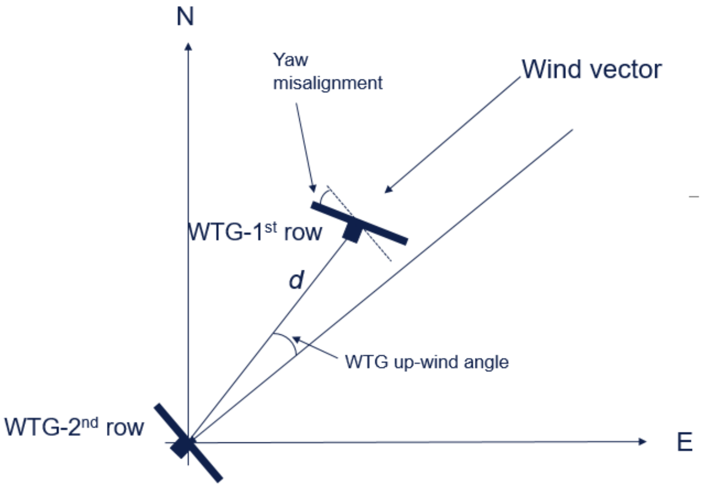

Figure 6 – Setup scheme for a 2nd-row validation.

The consideration of the following additional points is recommended:

- Dynamic characterization of the downwind turbine behaviour. Due to the different turbulence scales present inside the wake, it is important to verify that no resonances arise in the loads observed by the downwind turbine. This would be relevant for general wake effects but not necessarily for WFC.
- Given the dependence of the wake evolution on the atmospheric boundary layer stability, the inclusion of this parameter is recommended in the capture matrix.
- The stochastic nature of the turbulence and the wake meandering as well as the fact that the synthetic turbulence realization is usually based on only one point, may lead to high statistical uncertainties on load predictions. The use of nacelle-based lidars may play a crucial role in obtaining high spatial and temporal resolution inflow observations and therefore potentially in reducing these uncertainties [84] and [85].

Despite the validation potential of this scheme, the method proposed presents some important limitations:

- Only one turbine type (also controller) is analysed.
- Only one inter-turbine distance *d* is considered.
- The effect of multiple wakes is not directly investigated.
- The wind conditions considered will probably only correspond to the normal turbulence model.

In situations where investigations cannot be extended to cover these issues, a discussion on the uncertainties expected when transferring the conclusion derived to other turbines types, downstream distances, situations with multiple wakes or more extreme conditions shall be submitted.

4.3.2.3. MULTI-WAKE VALIDATION

One of the questions that need to be answered is the effect of the multiple wake superposition in the presence of WFC. Given the different wake-merging prescriptions found in the literature –linear, quadratic or the one proposed for heterogeneous background velocity fields [86]–, it is important to ascertain how well the different approaches behave when wake steering is considered.

For that purpose, in the context of validation a model description about the behaviour of the wake deflection shall be provided when both multiple wakes and WFC are present.
In cases where measurements involving the effect of the wake interaction -e.g. third-row WTs- are possible, studies shall be performed. They shall follow the description in the previous section while varying the yaw misalignment of the first- and second-row WTs, as described in Figure 7.

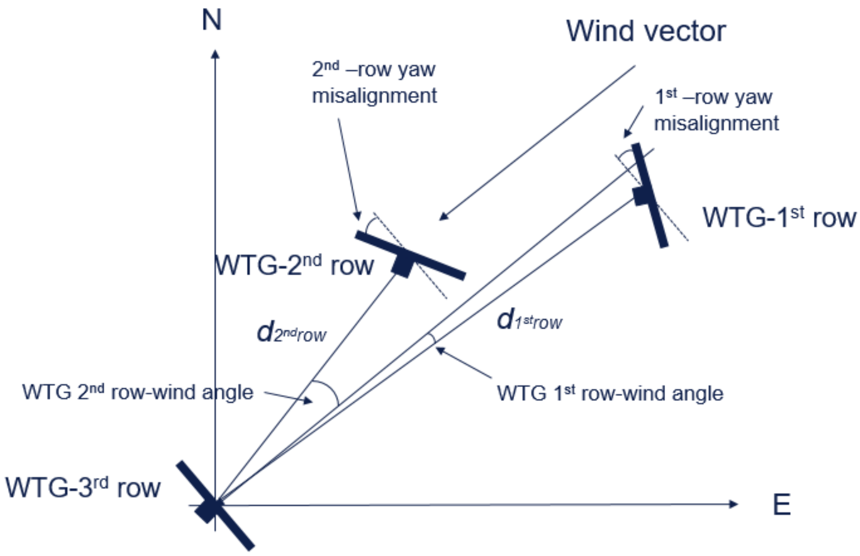

Figure 7– Setup scheme for a multi-wake validation.

The objective is to make a comparison between the loads and flow characteristics predicted at the 3rd row for different yaw misalignments settings of the 1st and 2nd -row turbines, as well as different wind directions and conditions.

4.3.2.4. WIND FARM SURROGATE MODEL VALIDATION

The validation of surrogate models basically follows the scheme described in the previous sections: first-row, second-row, and multi-wake validation. However, in this case additional information is required related to the intrinsic nature of the surrogate model considered:

1) Input. The definition of the variable space: which variables are to be included, their ranges, as well as potential dependencies between them [80].
2) Method. Description of the mathematical methodology that constitutes the basis for the surrogate model: interpolation in look-up tables, polynomial chaos expansion, artificial neural networks, etc.
3) Training. Description of the simulations used to perform the training.

In addition, a sensitivity analysis about the potential dependence of the results on the details of the training process will also be required. The objective is to quantify the uncertainty inherent to the surrogate method.

4.3.3. Validation Code against Code

As previously mentioned, the validation with measurements will only cover normal conditions. However, it is possible to identify situations where the absence of data can be a problem:

a) Normal environmental conditions but with few or no data. This includes on the one hand specific combinations of e.g. wind speed, turbulence intensity and atmospheric stability. On the other hand, this will be also the situation with common wind conditions but with layout properties which differ from those fixed at the measurement campaigns, e.g. different inter-turbine distance.
b) Extreme environmental conditions, such as extreme turbulence intensities, gusts or extreme wind speeds.

In these situations, when the lack of data prevents a measurement-based validation, it is recommended to use high-fidelity tools as reference models to compare with. An example of the second case, for highly transient wind speed ramps, can be found e.g. in [87].

In this case, the first step consists of reviewing the following additional information regarding the high-fidelity model considered:

- Model. Detailed mathematical description of the underlying physical assumptions of the model.
- Validation. A validation of the high-fidelity model with measurements for normal conditions.
- Comparison with BEM-based aeroelastic codes. For consistency reasons, a comparison with the tools commonly used in the industry for normal conditions, is required.
- Limitations. A discussion of the uncertainties and limitations associated to the tool, as well as to its possibility to accurately describe the situations to be covered. This is especially important in the case of transients.

In a second phase, the analyses suggested in Sec. 4.3.2 have to be considered for the situations specified in a) and b).

4.3.4. CONCLUSIONS ON VALIDATION ASPECTS

Numerous wind farm models and simulation tools can be found in the literature, which combine WFC with the wake-induced modification of the flow across a wind farm. Despite the great potential that these models offer in the context of wind farm optimization, it is important to keep in mind that are subject to uncertainties and limitations. Therefore, it is crucial to guarantee a thorough validation before its application for certification purposes.

In the previous sections, a scheme is proposed for software validation where different criteria are considered depending on the availability of measurements, the impact of wake, as well as the environmental conditions. This is summarized in Table 21.

Validation method	Layout	1st row WTG	2nd row WTG	Multiwake
Measurements	WFC (yaw misalignment)	Variable	Variable	Variable
	Layout	Standalone	2-WTGs, fixed distance	> 2-WTGs, fixed distances
	Wake	X	√	√
	Wind conditions	Normal	Normal	Normal
High-fidelity model	WFC (yaw misalignment)	Variable	Variable	Variable
	Layout	Standalone	2-WTGs, variable distance	> 2-WTGs, variable distances
	Wake	X	√	√
	Wind conditions	Normal & Extreme	Normal & Extreme	Normal & Extreme

Table 21 – Scheme of software validation using measurements and/or high-fidelity models.

On top of that, in situations where surrogate models are used or high-fidelity models are necessary as reference, additional specific requirements are defined, to guarantee that no biases are artificially introduced.

4.4. Design load cases

The present design load case catalogues, as listed in IEC 61400-1:2019 [5] (Table 2) and (Table B.1) or DNVGL-ST-0437 [14] (Table 4-3) and (Table 4-4), do not consider wind farm control explicitly. Offshore design load case catalogues as in IEC 61400-3-1:2019 [10] (Table 2) or IEC 61400-3-2:2019 [11] (Table 2) are similar. For a list of wind turbine and wind farm standards (but not limited to design basis and loads), see sections 1.2.1 and 1.2.4.
In IEC 61400-1:2019 (Table B.1) and DNVGL-ST-0437 (Table 4-4) "site suitability" or "extended" load cases are defined on a rather generic basis:

- IEC 61400-1:2019 lists DLC1.6 ETM-s "wake effects" and DLC1.7 NTM-s "wake effects" for ultimate load analysis,
- DNVGL-ST-0437 lists DLC1.2 "Wind farm influence (power production)" for fatigue and ultimate load analysis.

No further guidance is given, how wind farm control could be implemented. Wind farm control has different effects on the operation and thus also on the loading of single wind turbines in a wind farm. For that the term wind farm flow control WF-FC is applied. First, there are "WF-FC-active" wind turbines, i.e. wind turbines which carry out an action as e.g. wake steering by yaw offset demand. Commonly, these wind turbines are located upstream to the incoming wind direction. Secondly, there are "WF-FC-passive" wind turbines, i.e. wind turbines which are affected by e.g. wake steering. Commonly these wind turbines are located downstream to the incoming wind direction. A wind turbine may also be WF-FC-active, i.e. carrying out e.g. yaw offset demand or derating and at the same time being WF-FC-passive, i.e. affected by further upstream wind turbines. The few DLCs from IEC 61400-1 and DNVGL-ST-0437 listed above do not mirror all these different modes.

To consider WF-FC for load simulations, a more general approach for the DLC definition needs to be chosen. Instead of defining a few new DLCs, rather all (or nearly all) DLCs according to the present DLC tables IEC 61400-1:2019 (Table 2) / (Table B.1) or DNVGL-ST-0437 (Table 4-3) / (Table 4-4) need to be combined with WF-FC.

In the following text, a DLC table is presented and discussed which is based on the general DLC table of IEC 61400-1:2018 Table 2 and combines – where appropriate - all single DLCs with WF-FC.

4.5. Suggested load case table considering WF-FC

In general, as described above, all existing DLCs according to IEC 61400-1:2019 (Table 2) or DNVGL-ST-0437 (Table 4-3) need to be combined with WF-FC. WF-FC might be realized by very different control strategies and parameterizations. However, based on a few reasonable assumptions, the number of DLCs being affected by WF-FC might be reduced significantly.

Table 22 below lists all possible combinations of WF-FC and DLCs based on IEC 61400-1:2019 (Table 2).
Column 1 (DLC description and applied wind model), column 3 (type of analysis) are similar to the IEC table.
Column 2 lists some comments for the effect of WF-FC on that specific DLC. These comments are further elaborated in the text below the table and partly in section 4.5.2 for extreme loads and section 4.5.3 for fatigue loads.

It should be noted that Table 22 includes additional information and comments. It is not intended to be representative for a text proposal to be inserted into a standard. It considers only additional requirements for the DLC definition due to the application of WF-FC, with the modes "operation with WF-FC" and / or "operation without WF-FC". For a complete load simulation, the DLC definitions according to standards like IEC 61400-1:2019 (Table 2) or DNVGL-ST-0437 (Table 4-3) need to be considered as well.

Table 22 – Commented DLC table considering additional effects due to WF-FC

DLC + wind model	Comments with respect to WF-FC	Type of analysis
DLC1.1 NTM	Probabilities of occurrence to be considered for extrapolation	U for extrapolation
DLC1.2 NTM	Probabilities of occurrence to be considered for fatigue weighting	F / U*
DLC1.3 ETM	case 1: ETM without WF-FC case 2: ETM with WF-FC	U
DLC1.4 ECD	same approach as for DLC1.3	U
DLC1.5 EWS	same approach as for DLC1.3	U
DLC2.1 NTM	based on FMEA for WF-FC	U
DLC2.2 NTM	same approach as for DLC2.1	U
DLC2.3 EOG / NTM	same approach as for DLC1.3	U
DLC2.4 NTM	superposition of WF-FC (e.g. wake steering) and additional yaw offset demand may require special attention also for the fatigue loads	F / U*
DLC2.5 NWP	DLCs considering UVRT (formerly LVRT), in combination with WFC	U
DLC3.1 NWP	may be excluded if WF-FC is inactive during start-up – depends on the WF-FC strategy	F / U *
DLC3.2 EOG / ETM	see above for DLC3.1 or same approach as for DLC1.3	U
DLC3.3 EDC	see above for DLC3.1 or same approach as for DLC1.3	U
DLC4.1 NWP	may be excluded if WF-FC is inactive during normal shut-down – depends on the WF-FC strategy	F / U *
DLC4.2 EOG / ETM	see above for DLC4.1 or same approach as for DLC1.3	U
DLC 5.1 NTM	superposition of emergency-stop and WF-FC at NTM	U
DLC6.1 EWM	may be excluded if WF-FC is inactive during idling – depends on the WF-FC strategy	U
DLC6.2 EWM	see above for DLC6.1	U
DLC6.3 EWM	see above for DLC6.1	U
DLC6.4 NTM	see above for DLC6.1	F / U *

DLC7.1 EWM	may be excluded if WF-FC is inactive during parked conditions – depends on the WF-FC strategy	U
DLC8.1 NTM	may be excluded if WF-FC is inactive during maintenance – depends on the WF-FC strategy	U
DLC8.2 NTM	see above for DLC8.1	U

* Type of analysis "U" for these DLCs is not listed in IEC 61400-1:2019 (Table 2), but any fatigue load case needs also to be evaluated for extreme loads

4.5.1. Single DLC definitions

The following text describes, where appropriate, further specifications for DLCs from Table 22 for the modes "operation with WF-FC" and / or "operation without WF-FC" (acc. to column 2).
For the following DLCs it needs to be kept in mind, that "conventional", i.e. unwanted yaw misalignments need still to be considered, even if not mentioned for the affected DLCs. This means, that for the relevant DLCs the unwanted yaw misalignments needs to be modelled and for WF-FC features like wake steering an additional yaw offset demand has to be modelled on top of that.

4.5.1.1. DLC1.1 and DLC1.2

For the simulation and evaluation of load cases DLC1.1 and DLC1.2 all possible combinations of WF-FC and external conditions (e.g. wind speed, turbulence intensity, wind direction), and their probabilities should be considered, taking the wind farm layout into account. For this, the strategy and all possible features of WF-FC within regular power production mode should be taken into account. WF-FC features should be taken into account for both load decreasing, but also possible load increasing effects. This covers WF-FC features with the intention to influence the wind turbine loading, to increase power output and to meet GCC requirements. This includes also the mode "operation without WF-FC".
Load effects on both WF-FC-active wind turbines (as e.g. by active wake steering), as well as on WF-FC-passive wind turbines (as e.g. affected by wake steering) should be considered. The aim is to simulate the intended real-life operation of the wind farm under WF-FC features as closely as possible.
All possible single wind turbines within a generic wind farm (for Type Certification) or within a real wind farm (for Project Certification) should be considered. The most affected wind turbine (with regard to highest extreme loads for DLC1.1 or highest fatigue loads for DLC1.2) should be considered.
All of these single load simulations should to be evaluated by extrapolation according to DLC1.1 with respect to occurring extreme loads and their probability of occurrence.
All of these single load simulations should be evaluated as DLC1.2 with respect to occurring fatigue loads and their probability of occurrence.

4.5.1.2. DLC1.3, DLC1.4 and DLC1.5

This group of DLC's combines regular power production with extreme external conditions. These DLC's should be simulated and evaluated for extreme loads for both modes "operation without WF-FC" and "operation with WF-FC", because a wind farm being operated with WF-FC may also include single wind turbine being operated without WF-FC. The same applies for stand-alone wind turbines or small wind farms. These DLCs should be simulated and evaluated for both Type Certification and Project Certification, because the external conditions and the strategy and / or parameterization of the WF-FC may depend on the site-specific conditions, which might differ from generic Type Certification conditions.

It may be assumed that these DLC1.4 and DLC1.5 need to be simulated and evaluated only for "WF-FC-active" wind turbines in a wind farm. Most relevant effects will be seen in the first row of wind turbines in a wind farm caused by the external conditions "Extreme Coherent Gust With Direction Change" (ECD for DLC1.4) and "Extreme Wind Shear" (for DLC1.5). Wind turbines in further downstream rows may be affected only by extreme conditions being weakened by the upstream rows and their wakes.

Presently, no validated models for the interaction of deterministic gusts (as ECD, EWS, EOG etc.) and upstream turbine rows ("WF-FC-active") are known, resulting in modified deterministic gusts for downstream rows of turbines (state of research). Therefore, no further requirements for the simulation of downstream wind turbines ("WF-FC-passive") and deterministic gusts are proposed. However, further research and development of simulation models may change this position in future.

For DLC1.3 with "Extreme Turbulence Model" (ETM), two contrary effects happen in a wind farm: The general turbulence intensity level will be increased downstream due to wake effects, while the wind speed decreases at the same time. Whether downstream wind turbines are more or less affected than upwind turbines, especially under consideration of WF-FC, cannot be answered in general and might require site-specific considerations, supported by validated wake models and / or surrogate models.

The extreme wind models ETM, ECD and EWS and their probability of occurrence according to IEC 61400-1 have been defined without considering WF-FC. The probability of occurrence of the extreme wind models ETM, ECD and EWS together with a WF-FC-active wind turbine may be lower than the probability of occurrence of ETM / ECD / EWS together with a "regular" wind turbine not operating under WF-FC (according to IEC 61400-1), because WF-FC (e.g. yaw offset demand) may be active only for a fraction of time.

4.5.1.3. DLC2.1 AND DLC2.2

The group of load cases "Power production plus occurrence of fault" DLC2.1 and DLC2.2 should be analysed based on a Failure Mode, Effects and Criticality Analysis (FMECA) for WF-FC, see IEC 61400-1 section 7.4.3 and DNVGL-ST-0437 section 4.5.2. For the FMECA with regard to WF-FC see also section 2. All possible failure modes originating from the existence of WF-FC should be analysed. Dependent on the possible failure modes of the WF-FC, the load relevant DLCs need to be simulated for "WF-FC-active" and / or WF-FC-passive" wind turbines in a wind farm. It needs to be analysed, whether that wind turbine which is in failure mode experiences increased loads. And it needs to be analysed, whether this wind turbine affects another wind turbine leading to increased loads there.

Typical WF-FC modes might be yaw offset demand, derating and GCC features following the activation of specific GCC features as described further in Section 5.2. Thus, possible WF-FC fault situations might be e.g. "extreme (fault) yaw error", "yaw runaway", "wake steering" in combination with "generator short circuit", "erroneous wake steering towards a downwind turbine instead of away from it".

These DLCs should be simulated and evaluated for both Type Certification and Project Certification, because the external conditions and the strategy and / or parameterization of the WF-FC may depend on the site-specific conditions, which might differ from generic Type Certification conditions. However, it may be the case that the site-specific conditions and possible WF-FC faults of a project are completely covered by the Type Certificate.

Dependent on the possible failure modes of the WF-FC, these DLCs need to be simulated for "WF-FC-active" or WF-FC-passive" wind turbines in a wind farm. In case these failure mode situations do not cause an immediate shut down of the turbine, then they need to be considered as DLC2.4, see section 4.5.1.5.

4.5.1.4. DLC2.3

For the DLC power production and loss of electrical network in combination with Extreme Operating Gust (EOG), some aspects as for DLC1.3, DLC1.4 AND DLC1.5 apply, see section 4.5.1.2 above. This DLC should be simulated and evaluated for:

- both modes "operation without WF-FC" and "operation with WF-FC"
- Type Certification and Project Certification
- "WF-FC-active" wind turbines in a wind farm, i.e. with focus on the first row of wind turbines in a wind farm (as for DLC1.3, DLC1.4 AND DLC1.5)

4.5.1.5. DLC2.4

DLC2.4 is also based on the analysis of DLC2.1 and 2.2 for WF-FC-specific fault situations. If these WF-FC-specific fault situations do not cause an immediate shut down of the turbine, the likely duration of these situations should be considered in the fatigue evaluations. The possible WF-FC-specific fault situation "superposition of WF-FC (wake steering) and additional yaw error" may require special attention. This DLC is relevant for both Type Certification and Project Certification.

4.5.1.6. DLC2.5

The definition of DLC2.5 "event of low voltage ride through (UVRT)" depends strongly on the requirements of the system operator. Any WF-FC concept might interact with the load relevant effects by the UVRT requirements. As an example, a voltage dip with voltage recovery might lead to increased loads when combined with yaw offset demand.

Additionally, WFC may include GCC features which might need reflection in the definition of DLC2.5. As an example, a system frequency increase would require a corresponding wind farm power decrease by WFC-control. See also section 5.2.

4.5.1.7. DLC3.1 AND 4.1
In case WF-FC might be active during start-up / normal shut-down, the combination of normal start-up / normal shut-down situations, together with WF-FC needs to be considered for

- both modes "operation without WF-FC" and "operation with WF-FC"
- both extreme and fatigue loading
- Type Certification and Project Certification

However, dependent on the WF-FC strategy, WF-FC might not be active during start up and normal stop situations. This would leave out any combination of DLC3.x / 4.x with WF-FC.

4.5.1.8. DLC3.2, DLC3.3 AND DLC4.2
The combination of start-up / normal shut-down together with extreme wind conditions and with WF-FC needs to be considered for

- both modes "operation without WF-FC" and "operation with WF-FC"
- Type Certification and Project Certification
- "WF-FC-active" wind turbines in a wind farm, i.e. with focus on the first row of wind turbines in a wind farm (as for DLC1.3, DLC1.4 AND DLC1.5)

However, dependent on the WF-FC strategy, WF-FC might not be active during start up and normal stop situations. This would leave out any combination of DLC3.x / 4.x with WF-FC.

4.5.1.9. DLC5.1
The combination of emergency shut-down together with WF-FC needs to be considered for

- both modes "operation without WF-FC" and "operation with WF-FC"
- Type Certification and Project Certification, unless the site-specific conditions are completely covered by the Type Certificate conditions

4.5.1.10. DLC6.1, DLC6.2, DLC6.3, DLC6.4, DLC8.1, DLC8.2
For the load case groups "Parked (standing still or idling" (DLC6.1, DLC6.2, DLC6.3, DLC6.4) and "Transport, assembly, maintenance and repair" (DLC8.1, DLC8.2) the turbines are in stand still or idling. For those situations, it can be assumed that WF-FC is not active, or at least that WF-FC has no significant load effect on any WF-FC-active or WF-FC-passive wind turbine.

As a first approach, these DLC groups may be omitted for the consideration of WF-FC.

4.5.1.11. DLC7.1
Based on the FMEA for DLC2.1 and DLC2.2 it should be analysed, whether WF-FC-fault conditions during parking may occur, which are not covered by DLC7.1 "without WF-FC".

4.5.2. EXTREME LOADS

The simulation and evaluation of extreme loads relates closely to Table 22 and the descriptions of the single DLCs above. It is already listed there, whether DLCs need to be simulated for

- both modes “operation without WF-FC” and / or “operation with WF-FC”
- Type Certification and / or Project Certification
- “WF-FC-active” and / or “WF-FC-passive” wind turbines in a wind farm.

4.5.2.1. EXTRAPOLATION

The evaluation of DLC1.1 by extrapolation according to IEC 61400-1 (Table 2), sections 7.4.2 resp. 7.6.2.2 and Annex G mirrors the “loads resulting from atmospheric turbulence that occurs during normal operation of a wind turbine throughout its lifetime” (section 7.4.2). Consequently, WF-FC needs to be considered as close as possible to the real wind farm conditions. For all single DLC1.1 simulation (per grouped per wind bin) both possible modes “operation with WF-FC” and “operation without WF-FC” must be considered, including their probabilities of occurrence with respect to. duration for their weighting.

Since the wind direction differs during the entire lifetime, it can be assumed that each single wind turbine of a wind farm will be “WF-FC-active” for some time and be “WF-FC-passive” for some other time. This means, that each wind turbine may be carrying out WF-FC features as an upstream wind turbine (e.g. yaw offset demand) for some time, but also being affected by other upstream wind turbines for some other time (e.g. in case the wind direction has changed).

The extrapolation procedure may become significantly complex, since most situations will be multiplied by additional parameters like “operation with WF-FC” vs. “operation without WF-FC”. The mode “operation with WF-FC” will be further split up into “WF-FC-active” or “WF-FC-passive”, and again further split up into the different possible WF-FC features, like yaw offset demand and / or derating, etc. The split into all these different modes might lead to different populations, i.e. the extreme loads may group into separated branches. This needs to be done for the most extreme loaded wind turbine in the wind farm. The determination of this wind turbine might require the simulation and evaluation of several wind turbines or clusters. Possibly, simplified models and simplifying assumptions may be applied here to determine the extrapolated loads, as surrogate models. However, it needs to be shown that simplifications lead to equal or conservative loads.

For a Project Certification, all required parameters (external conditions, wind farm layout, WF-FC strategy and parametrization, etc.) are usually known and can be modelled. In principle, it needs to be simulated “what will happen over the lifetime” for this specific project. For Type Certification, assumptions need to be made in order to model a generic case which needs to cover typical but yet unknown projects with and without WF-FC and also stand-alone wind turbines. Here, an envelope for the design loads for “operation with WF-FC” and “operation without WF-FC” needs to be determined.

Some thoughts on the extrapolation procedure can also be found in section 4.1.2.2.

The same procedure needs to be carried out for the fatigue load simulation and evaluation of the most (fatigue) loaded wind turbine. However, the highest fatigue and extreme loads may occur for different wind turbines. See also section 4.5.3 for the fatigue loads.

4.5.3. FATIGUE LOADS

Similar to the extreme loads, the simulation and evaluation of fatigue loads relates closely to Table 22 and the descriptions of the single DLCs above. The simulation of fatigue loads needs to

- consider the different modes of the wind turbines and their duration "operation without WF-FC" and "operation with WF-FC"
- consider the different operational modes of the wind turbines and their duration of "WF-FC-active" wind turbines in a wind farm and "WF-FC-passive" wind turbines further downstream, dependent on the varying wind direction; wind turbines may change between those modes
- define an envelope for the design loads within the rather generic Type Certification
- be carried out for each Project Certification.

The simulation and evaluation of DLCs for fatigue loading according to IEC 61400-1 (Table 2), sections 7.4 and 7.6.3 and Annex H mirrors the loads resulting from "operation of a wind turbine throughout its lifetime". Consequently, WF-FC needs to be considered in conditions as close as possible to the real wind farm conditions.

This is nearly the same analysis as for the extrapolation based on DLC1.1, described in section 4.5.2.1 above. The definitions, the simulations and probabilities of occurrence with respect to. duration for their weighting for normal production are the same as for the extrapolation. Differences for the fatigue loads are:

- DLC1.1 is called here DLC1.2 for the fatigue loads (but the simulations maybe identical)
- additional fatigue load cases as DLC2.4, DLC3.1, DLC4.1 and DLC6.4 need to be considered
- the evaluation of these simulations is with respect to fatigue loads and not extrapolation

Both possible modes "operation with WF-FC" and "operation without WF-FC" must be considered for all fatigue DLCs (e.g. grouped per wind bin), including their probabilities of occurrence with respect to. duration for their weighting.

Since the wind direction differs during the entire lifetime, it can be assumed that each single wind turbine of a wind farm will be "WF-FC-active" for some time and be "WF-FC-passive" for some other time. This means, that each wind turbine may be carrying out WF-FC features as an upstream wind turbine (e.g. yaw offset demand) for some time, but being affected by other upstream wind turbines for some other time (e.g. in case the wind direction has changed).

The fatigue load analysis procedure may become significantly complex, since most situations will be multiplied by additional parameters like "operation with WF-FC" vs. "operation without WF-FC". The mode "operation with WF-FC" will be further split up into "WF-FC-active" or "WF-FC-passive", and again further split up into the different possible WF-FC features, like yaw offset demand and / or derating, etc.

Especially the simulation of the interaction of wake and wind farm turbulence may require significant increased effort due to the intended wake steering / influencing. New models and analysis tools for wake and wind farm turbulence and wake propagation might be required, see also sections 4.2.1 and 4.2.2. For the wake modelling based on present standards see also sections 4.1.1 and 4.1.2.

This needs to be done for the most fatigue loaded wind turbine in the wind farm. The determination of this wind turbine might require the simulation and evaluation of several wind turbines or clusters.

For a Project Certification, all required parameters (external conditions, wind farm layout, WF-FC strategy and parametrization, etc.) are usually known and can be modelled. In principle, it needs to be simulated "what will happen over the lifetime" for this specific project. For Type Certification, assumptions need to be made in order to model a generic case which needs to cover typical but unknown projects with and without WF-FC and also stand-alone wind turbines. Here, an envelope for the design loads for the modes "operation with WF-FC" and "operation without WF-FC" needs to be determined.

Besides the gain in annual energy production, WF-FC may offer a reduction of fatigue loads. This may pay of the increased simulation and evaluation effort. However, increased fatigue loading may also be possible by the application of WF-FC (e.g. due to the gain in annual energy production). Of course, these increased fatigue loads need to be considered for the design as well.

In this context the application of a "digital twin" of a wind farm may be discussed, see also section 3.5. Based on the measured external conditions and the SCADA data of the wind turbines, a parallel simulation of the fatigue loads of some or all wind turbines may be carried out. The WF-FC may be adopted according to optimized power production of the wind farm and the summed fatigue loads of the single wind turbines. The application of a digital twin might mitigate the uncertainties regarding the fatigue loads within a wind farm. However, a detailed discussion concerning requirements of a digital twin application seems rather complex and cannot be carried out within this project.

4.5.4. Type Certification vs. Project Certification

Type Certification considers a stand-alone turbine only, while WFC can be applied only for wind farms. However, it is desirable to consider as much of WFC as possible already in the Type Certification to limit the effort for each Project Certification afterwards. At least, a realistic load level needs to be established already for the Type Certification. For this, reasonable assumptions need to be made within the Type Certification. These assumptions may consider WF-FC-actions and parameters, depending on the site conditions (e.g. wind speed, turbulence intensities, wind rose) and on the turbine spacing.

For a Type Certification all load cases should be simulated and evaluated (fatigue and extreme load evaluation) also for the mode "operation without WF-FC". It must be taken into account that single wind turbine or a wind farm do not have the option to operate in WF-FC mode. For the situations "operation with WF-FC" the DLCs need to be simulated and evaluated (fatigue and extreme load evaluation) as discussed below.

For a Project Certification all extreme DLCs should be simulated and evaluated for both modes "operation without WF-FC" and "operation with WF-FC". However, dependent on the site-specific conditions and WF-FC features, it may be demonstrated, that these site-specific conditions and WF-FC features are covered for extreme DLCs by the Type Certificate conditions. For this, it might be assumed, that the wind turbine in the first row of a wind farm are affected by the undisturbed external conditions only, and not be influenced by wind farm effects. It seems necessary to simulate and evaluate the fatigue loads of each single Project Certification for the site-specific conditions and WF-FC features. It seems unrealistic to demonstrate that the site-specific conditions (including the wind farm layout) and WF-FC features are completely covered by the Type Certificate conditions.

4.5.5. Possible Simplifications

Dependent on the wind turbine development and the strategy of the WFC the following simplifications might be considered. It should be noted that any of these simplifications are only general possibilities and cannot be applied without further detailed justification.

The aim of such simplifications would be to limit the complexity of the WFC operation and additionally to limit the complexity and amount of required DLC simulations and evaluations.

4.5.5.1. WF-FC only for normal power production

For some DLCs being described in sections 4.5.1.1 to 4.5.1.11, simplifying assumptions are discussed. Dependent on the WF-FC strategy, it might be considered that the mode "operation with WF-FC" may not be active for certain controlled situations as:

- Start-up
- Normal shut down
- Idling
- Parked and fault condition
- Standstill
- Maintenance

According to that strategy, the mode "operation with WF-FC" would not apply to the DLCs

- DLC3.x
- DLC4.x
- DLC6.x
- DLC7.1
- DLC8.x.

4.5.5.2. WF-FC wind speed range

Dependent on the WF-FC strategy, the mode "operation with WF-FC" may not be active for a certain wind speed range, i.e. $V_{WF\text{-}FC\_in} < V < V_{WF\text{-}FC\_out}$. Consequently, the WF-FC-affected DLC need only be simulated for this wind speed range.

4.5.5.3. Sensitivity analysis

Additionally, a "sensitivity study" may be carried out by the designer of the wind turbine. The intention of such a sensitivity study may be to show that only a subset of each "remaining" DLC to be simulated is load relevant. This subset may be a combination of certain wind conditions with the mode "operation with WF-FC". As an example, it may be shown that for wake steering combined with DLC1.3, only the combinations of +5deg to + 15deg and -5deg to -15deg yaw offset at wind speeds between 12m/s and 18m/s are load dimensioning for DLC1.3. This can then cover this mode "operation with WF-FC" for DLC1.3 with yaw offsets e.g. from -20deg to +20deg at wind speeds e.g. between 4m/s and 25m/s.

Such a sensitivity study needs to be carried out at least for each wind turbine platform and / or WF-FC concept and modes and needs to be agreed beforehand in detail with the certification body.

4.5.6. Example Project for a generic wind farm including WF-FC "wake Steering"

Within this section a general procedure is sketched, describing how the control and protection system, the grid code compliance and the DLC definition for the load calculation could be carried out for a project certification. This is done for a generic and simple wind farm, in order to keep the example understandable.

Some simplifying assumptions are made:

- Only external wind conditions are considered for a flat terrain, no waves, no complex terrain.
- WF-FC has only one WF-FC feature "wake steering": all wind turbines of the first row (upstream row) do yaw offset demand of ±15deg for 1/3 of the time (probability = 0.33) in positive direction (+yaw), 1/3 of the time in negative direction (-yaw) and 1/3 of the time with no yaw offset demand (0yaw)
- WF-FC is inactive during start-up, normal shut-down, idling, parked and fault condition, standstill and maintenance
- WF-FC runs from V_{in} to V_{out}
- The wind farm controller controls '+yaw' and '-yaw' without any safe supervision. That means possible control failures may not be noticed and therefore need to be considered as load cases.
- GCC actions initiated by WFC have no effect on the DLC definitions

Please note, that these assumptions are made here on a rather arbitrary basis in order to simplify the example project. Any of these assumptions might not be valid for any real wind farm project. For a certification these simplifying assumptions have to be proved.

What to do for Control and Protection?

For this example, we assume that the FMEA and the functional safety considerations for the WF-FC functions result in the necessity of following failures to be considered for load simulations:

- DLC2.1: Yaw run away. WFC submits too large control signal for both '+yaw' and '-yaw', such that the first-row wind turbines switch off with status code "yaw offset demand high".
- DLC2.4: Uncontrolled operation in yaw offset demand. It is assumed that yaw offset demand is ±25deg instead of ±15deg. It is assumed to take 1 year, until the failure is noticed and corrected.

What to do for DLC definitions

- Extreme DLC
  - DLC1.1 for extrapolation
    - DLC1.1 considers the both modes "operation without WF-FC" and "operation with WF-FC" in combination. For any real wind farm it can be assumed that both modes will occur during the life time.
    - Two different approaches seem possible: A "full approach" and a "simplified but possibly conservative approach".
    - "Full approach": Define DLC and the probabilities of occurrence for each load situation, parameters to be varied against each other for DLC1.1 are:
      - All wind directions according to wind rose -> for different wind directions, different wind turbines are "front row" and thus WF-FC-active, and others are "downwind turbines" and thus WF-FC-passive and affected by the wakes from the front row wind turbines.
        - For the downwind wind turbines, the wind distribution and turbulence intensity must be calculated applying appropriate wake models. For the mode "operation with WF-FC" these wake models need to handle wake redirection by yaw offset demand.
      - all wind bins
      - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw (0yaw = mode "operation without WF-FC"); consider also normal yaw error of appr. ±8deg
      - This needs to be done for each single wind turbine or at least cluster of similar wind turbines to determine the most extreme loaded wind turbine.
      - Section 4.5.6.1 below lists an example setup for this DLC1.1 "full approach" for extrapolated extreme loads, which is nearly identical to the DLC1.2 for fatigue loads.
    - Simplified approach": A simplified but possibly conservative approach for the extrapolation of extreme loads may be followed instead:
      - Assume that WF-FC-active wind turbines in the front row are more severely affected by external wind conditions than WF-FC-passive downstream wind turbines, being affected by upstream wakes
      - Assume that WF-FC-active wind turbines in the front row are more severely affected by external wind conditions than WF-FC-active wind turbines in downstream rows.
      - Assume that the front row turbine feels no wind farm effect and can be treated as a stand-alone wind turbine
      - To confirm this, the wind conditions (mean wind speed, turbulence intensity) are needed to be compared between the external wind conditions and the wake conditions inside the wind farm.
      - Define DLC1.1 and the probabilities of occurrence for each load situation as stand-alone wind turbine, parameters to be varied against each other:

            - all wind bins (combine wind distributions of all sectors of wind rose to one single wind distribution)
            - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw (0yaw =mode operation without WF-FC); consider also normal yaw error of appr. ±8deg
        - Some thoughts on the extrapolation procedure can also be found in section 4.1.2.2.
        - Possibly, also alternative simulation approaches as surrogate models, being described in section 4.2.2, may be applied for extrapolation
- As a first DLC set, all extreme DLC from DLC1.3 on are defined for the mode "operation without WF-FC", "just as normal" ! Additionally, the extreme DLCs from DLC1.3 are defined for the mode "operation with WF-FC", as listed below.
- DLC1.3/DLC1.4/DLC1.5
    - Preliminary assumptions (see also section 4.5.1.2): Assume that WF-FC-active wind turbines in front row are more severe affected by extreme gusts than WF-FC-passive wind turbines downstream
    - Assume that front row turbine feels no wind farm effect, can be treated as stand-alone wind turbine
    - Select highest ETM, ECD, EWS from any of the sectors of the wind rose
    - parameters to be varied against each other for DLC1.3:
        - all wind bins
        - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw, consider also normal yaw error of appr. ±8deg
    - parameters to be varied against each other for DLC1.4:
        - all wind bins
        - ECD changing to plus and minus wind direction
        - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw
    - parameters to be varied against each other for DLC1.5:
        - all wind bins
        - EWS vertical positive gradient / EWS vertical negative gradient / EWS horizontal positive gradient / EWS horizontal negative gradient /
        - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw, consider also normal yaw error of appr. ±8deg
- DLC2.1/DLC2.2
    - Consider any "regular" fault mode outside WFC application.
    - Additionally, consider WFC fault modes according to FMEA as described above: Yaw run away; WFC submits a control signal which is too large for both '+yaw' and '-yaw', such that the first-row wind turbines switch off with status code "yaw offset demand high".
    - parameters to be varied against each other for DLC2.1/DLC2.2:
        - single fault mode
            - for any fault mode outside WFC application
            - for WFC fault mode: +yaw runaway and -yaw runaway
        - all wind bins

        - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw, consider also normal yaw error of appr. ±8deg
- DLC2.3
    - Assume that WF-FC-active wind turbines in front row are more severe affected by extreme gusts than WF-FC-passive wind turbines downstream
    - Assume that front row turbine feels no wind farm effect, can be treated as stand-alone wind turbine
    - Wind from north and west higher extreme wind conditions, select highest EOG
    - parameters to be varied against each other for DLC2.3:
        - all wind bins
        - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw, consider also normal yaw error of appr. ±8deg
- DLC2.4
    - Consider any "regular" fault mode outside WFC application.
    - Additionally, consider WFC fault modes according to FMEA as described above: Uncontrolled operation in yaw offset demand. It is assumed that yaw offset demand is ±25deg instead of ±15deg. It is assumed to take 1 year, until the failure is noticed and corrected.
    - parameters to be varied against each other for DLC2.4:
        - single fault mode outside WFC application
            - all wind bins
            - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw, consider also normal yaw error of appr. ±8deg
        - for WFC fault mode: ±25deg for 1 year
            - all wind bins
            - All WF-FC features: 0.33 +yaw 25deg / 0.33 -yaw -25deg/ 0.33 0yaw, consider also normal yaw error of appr. ±8deg
- DLC2.5
    - Consider any "regular" LVRT modes according to requirements by system operator, no effect by WFC application.
    - parameters to be varied against each other for DLC2.5:
        - all single LVRT modes
        - all wind bins
        - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw, consider also normal yaw error of appr. ±8deg
- DLC3.x
    - WF-FC inactive during start-up
    - DLC3.x only to be simulated without WF-FC
- DLC4.x
    - WF-FC inactive during normal shut-down
    - DLC4.x only to be simulated without WF-FC
- DLC5.1
    - parameters to be varied against each other for DLC5.1:
        - all emergency-stop modes (in case there are more than one mode)
        - all wind bins

        - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw, consider also normal yaw error of appr. ±8deg
    - DLC6.x
        - WF-FC inactive during idling
        - DLC6.x only to be simulated without WF-FC
    - DLC7.1
        - WF-FC inactive during parked and fault condition
        - DLC7.1 only to be simulated without WF-FC
    - DLC8.x
        - WF-FC inactive during standstill and maintenance
        - DLC8.x only to be simulated without WF-FC

- Fatigue DLC
    - The fatigue calculations include the definition of the single DLCs, their probability of occurrence according to the design lifetime and the evaluation.
    - The fatigue calculation needs to consider the modes "operation without WF-FC" and "operation with WF-FC". For any real wind farm, it can be assumed that both modes will occur during the lifetime.
    - DLC1.2
        - In general, the definition of DLC1.2 and the probabilities of occurrence for each load situation is very similar to DLC1.1 for the "Full approach": Define DLC and the probabilities of occurrence for each load situation, parameters to be varied against each other for DLC1.2 are:
            - All wind direction according to wind rose -> for different wind directions, different wind turbines are "front row" and thus WF-FC-active, and others are "downwind turbines" and thus WF-FC-passive and affected by the wakes from the front row wind turbines
                - For the downwind wind turbines, the wind distribution and turbulence intensity must be calculated by wake models. For the mode "operation with WF-FC" these wake models need to handle wake redirection by yaw offset demand.
            - all wind bins
            - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw; consider also normal yaw error of appr. ±8deg
            - As for DLC1.2 "Extrapolation", this needs to be done for each single wind turbine or at least cluster of similar wind turbines to determine the most extreme loaded wind turbine. However, for fatigue analysis, contributions from other fatigue DLCs as listed below, need to be considered as well.
            - Section 4.5.6.1 below lists an example setup for this DLC1.2 for fatigue loads, which is nearly identical to the DLC1.1 "full approach" for extrapolated extreme loads.
        - For the application of alternative modelling approaches as surrogate models see section 4.2.2.
    - DLC2.4

        - consider fatigue relevant fault modes and their duration without WF-FC, IEC 61400-1 section 7.4.3.4 footnote 7 gives some ideas
        - define the <u>additional WF-FC fault modes</u> and probable frequency/duration according to FMEA from C&P for those events which "do not cause an immediate shutdown and the subsequent loading can lead to significant fatigue damage" (IEC section).
        - parameters to be varied against each other for DLC2.4:
            - all single fault modes
            - all wind bins
            - All WF-FC features: 0.33 +yaw / 0.33 -yaw / 0.33 0yaw, consider also normal yaw error of appr. ±8deg
    - DLC3.1
        - Consider start up events without WF-FC, IEC 61400-1 section 7.4.4 footnote 9 gives some numbers
        - WF-FC inactive during start-up -> DLC3.1 "operation with WF-FC" drops out
    - DLC4.1
        - Consider normal shut down events without WF-FC, IEC 61400-1 section 7.4.4 footnote 10 gives some numbers
        - WF-FC inactive during normal shut-down -> DLC4.1 "operation with WF-FC" drops out
    - DLC6.4
        - Consider idling without WF-FC
        - WF-FC inactive during idling -> DLC6.4 "operation with WF-FC" drops out
    - The definition of all DLCs and their probability of occurrence according to the design lifetime needs to be done for each single wind turbine or at least a cluster of similar wind turbines to determine the most extremely loaded wind turbine. For each single wind turbine or at least cluster the fatigue loads are simulated and evaluated by an aeroelastic code like Bladed, HawC, Flex. This might end up in a very complex and time-consuming procedure.
        - As a support, simplifying surrogate models might be applied to determine the most loaded wind turbine, for details see also section 4.2.2.
        - Only for this determined "most loaded wind turbine" all DLCs are then calculated applying an aeroelastic code like Bladed, HawC, Flex to determine the fatigue loads of this most loaded wind turbine.

4.5.6.1. Setup of DLC1.1 / DLC1.2

Within this section an illustrative example setup for the definition of DLC1.1/DLC1.2 is described For DLC1.1 this follows the "full approach" for extrapolation. This "full approach" is rather extensive but shows as an illustrative example the procedure of DLC definitions by varying all relevant parameters. For any possible simplifications, e.g. by applying assumptions for the turbulence intensity and wake propagation or by using surrogate models, see also section 4.2.2.

For this specific example, some assumptions are made:

- The wind farm has a chess board orientation north-south / west-east direction, the Figure 8 marks two wind turbines for the descriptions below.

- The wind turbines start at V_{in} = 4m/s and runs until V_{out} = 30m/s, no WF-FC features below 4m/s
- WF-FC has only one feature: all wind turbines of the first row (upstream row) do yaw offset demand of 15deg with probability **0.33** in positive direction (+yaw), of -15deg **0.33** in negative direction (-yaw) and **0.33** with no yaw offset demand (0yaw), this includes the normal yaw error

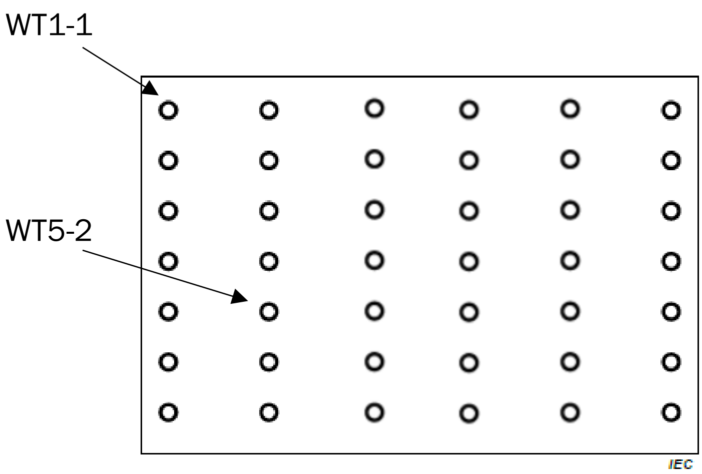

Figure 8 - Layout of example wind farm, copied and modified from IEC 61400-1 Figure E-1 [5]

- The wind rose consists of:
  - 12 sectors, each 30deg, with "probability of sector" in **green**
  - each sector has for each wind bin
    - individual "wind bin probabilities" in **red**
    - individual "turbulence intensities per wind bin" for each sector in **blue**

Table 23 – Arbitrary wind rose data for example wind farm

wind rose sector [deg from north]	0		30		60		...	330		sum of probabilities over all sectors
probability of sector	5%		10%		15%		...	5%		100%
wind bin [m/s]	wind bin probability in sector 0deg	turbulence intensity in wind bin for this sector 0deg	wind bin probability in sector 30deg	turbulence intensity in wind bin for this sector 30deg	wind bin probability in sector 60deg	turbulence intensity in wind bin for this sector 60deg	...	wind bin probability in sector 330deg	turbulence intensity in wind bin for this sector 330deg	
4 to 6	3%	0.18	4%	0.22	3%	0.24	...	2%	0.17	
6 to 8	4%	0.17	5%	0.20	5%	0.22	...	3%	0.16	
8 to 10	5%	0.16	6%	0.18	6%	0.20	...	4%	0.15	
...	...	...	...	...	...	...	...	...	...	
28 to 30	1%	0.11	2%	0.12	1%	0.12	...	2%	0.10	
sum of probabilities in each sector	100%		100%		100%			100%		

The value of each single parameter is of no concern and might not be realistic for any site. Table 23 lists these values just to track them in the following examples for WT1-1 and WT5-2.

For two typical wind turbine locations the DLC definition is carried out. These are wind turbines WT1-1 and WT5-2 according to Figure 8 - Layout of example wind farm, copied and modified from IEC 61400-1 Figure E-1 .

Example DLC1.1 / 1.2 definition for WT1-1:

- is "front row wind turbine" for all wind sectors from north and west, i.e. wind sectors 0deg, 30deg, 60deg, 210deg, 240deg, 270deg, 300deg, 330deg
- Is wake influenced "downwind turbine" for all other wind sectors from east and south, i.e. wind sectors 90deg, 120deg, 150deg, 180deg

- **sector 0 deg**, WT1-1 sees no wake but undisturbed external wind, probability = 0.05
    - wind bin 4 to 6m/s, probability 0.03
        - +yaw, probability 0.33
            - simulation: operation at 5m/s and TI=0.18 with +yaw, combined probability: 0.05 * 0.03 * 0.33 = 0.000495
        - -yaw, probability 0.33
            - simulation: operation at 5m/s and TI=0.18 with -yaw, combined probability: 0.05 * 0.03 * 0.33 = 0.000495
        - 0yaw, probability 0.33
            - simulation: operation at 5m/s and TI=0.18 with 0yaw, combined probability: 0.05 * 0.03 * 0.33 = 0.000495
    - wind bin 6 to 8m/s, probability 0.04
        - +yaw, probability 0.33
            - simulation: operation at 7m/s and TI=0.17 with +yaw, combined probability: 0.05 * 0.04 * 0.33 = 0.000666
        - -yaw, probability 0.33
            - simulation: operation at 7m/s and TI=0.17 with -yaw, combined probability: 0.05 * 0.04 * 0.33 = 0.000666
        - 0yaw, probability 0.33
            - simulation: operation at 7m/s and TI=0.17 with 0yaw, combined probability: 0.05 * 0.04 * 0.33 = 0.000666
    - wind bins 8 to 28m/s equivalent to previous case
    - wind bin 28 to 30m/s (also analogue, but shown here for illustration), probability 0.01
        - +yaw, probability 0.33
            - simulation: operation at 29m/s and TI=0.11 with +yaw, combined probability: 0.05 * 0.01 * 0.33 = 0.000165
        - -yaw, probability 0.33
            - simulation: operation at 29m/s and TI=0.11 with -yaw, combined probability: 0.05 * 0.01 * 0.33 = 0.000165
        - 0yaw, probability 0.33
            - simulation: operation at 29m/s and TI=0.11 with 0yaw, combined probability: 0.05 * 0.04 * 0.33 = 0.000165
- **sector 30 deg**, WT1-1 sees no wake but undisturbed external wind, probability = 0.1
    - wind bin 4 to 6m/s, probability 0.04
        - +yaw, probability 0.33

        - simulation: operation at 5m/s and TI=0.22 with +yaw, combined probability: 0.1 * 0.04 * 0.33 = 0.00132
      - -yaw, probability 0.33
        - simulation: operation at 5m/s and TI=0.22 with -yaw, combined probability: 0.1 * 0.04 * 0.33 = 0.00132
      - 0yaw, probability 0.33
        - simulation: operation at 5m/s and TI=0.22 with 0yaw, combined probability: 0.1 * 0.04 * 0.33 = 0.00132
    - wind bin 6 to 8m/s, probability 0.05
      - +yaw, probability 0.33
        - simulation: operation at 7m/s and TI=0.20 with +yaw, combined probability: 0.1 * 0.05 * 0.33 = 0.00165
      - -yaw, probability 0.33
        - simulation: operation at 7m/s and TI=0.20 with -yaw, combined probability: 0.1 * 0.05 * 0.33 = 0.00165
      - 0yaw, probability 0.33
        - simulation: operation at 7m/s and TI=0.20 with 0yaw, combined probability: 0.1 * 0.05 * 0.33 = 0.00165
    - wind bins 8 to 30m/s equivalent to previous case
- **sectors 60deg, 210deg, 240deg, 270deg, 300deg, 330deg** equivalent to previous case: WT1-1 sees no wake but undisturbed external wind
- **sector 90 deg**, WT1-1 is wake influenced "downwind turbine" by 5 upwind wind turbines in a row, the most eastern row (being the front row for wind sector 90 deg) does yaw offset demand; probability = 0.15
    - wind bin 4 to 6m/s and TI=0.24, probability 0.03; apply wake model to determine wake conditions for "wake@5m/s+TI=0.24" based on external 5m/s, TI=0.24 and upwind wind turbines with yaw offset demand
      - most eastern row has +yaw, probability 0.33
        - simulation: operation at "wake@5m/s+TI=0.24 with +yaw", combined probability: 0.15 * 0.03 * 0.33 = 0.001485
      - most eastern row has -yaw, probability 0.33
        - simulation: operation at "wake@5m/s+TI=0.24 with -yaw", combined probability: 0.15 * 0.03 * 0.33 = 0.001485
      - most eastern row has 0yaw, probability 0.33
        - simulation: operation at "wake@5m/s+TI=0.24 with 0yaw", combined probability: 0.15 * 0.03 * 0.33 = 0.001485
    - wind bin 6 to 8m/s and TI=0.22, probability 0.07; apply wake model to determine wake conditions for "wake@7m/s+TI=0.22" based on external 7m/s, TI=0.22 and upwind wind turbines with yaw offset demand
      - most eastern row has +yaw, probability 0.33
        - simulation: operation at "wake@7m/s+TI=0.22" with +yaw, combined probability: 0.15 * 0.07 * 0.33 = 0.003465
      - most eastern row has -yaw, probability 0.33
        - simulation: operation at "wake@7m/s+TI=0.22" with -yaw, combined probability: 0.15 * 0.07 * 0.33 = 0.003465
      - most eastern row has 0yaw, probability 0.33

   - ➢ simulation: operation at "wake@7m/s+TI=0.22" with 0yaw, combined probability: 0.15 * 0.07 * 0.33 = 0.003465
 - o wind bins 8 to 30m/s analog
- **Sectors 120 deg to 180deg analog:** WT1-1 is wake influenced "downwind turbine" by multiple wakes in in different configurations for each sector; always the front row to the wind does yaw offset demand
  - o the applied wake model needs to be adopted to the different configurations for each sector and then for each wind bin and with the yaw offset demands +yaw, -yaw and 0yaw for the front row

For each single wind turbine, the sum of all combined probabilities over all sectors, all wind bins and all misalignments green*red*magenta needs to be close to 1 (the wind bins below v_{in}=4m/s and above v_{out}=30m/s are not considered).

Example DLC1.1 / 1.2 definition for WT5-2:

- is wake influenced "downwind turbine" for all wind sectors
  - o is wake influenced by a single wake for wind sectors from west, i.e. wind sectors 240deg, 270deg, 300deg
  - o is wake influenced by multiple wakes for all wind sectors from north, east and south, i.e. wind sectors 0deg, 30deg, 60deg, 90deg, 120deg, 150deg, 180deg
  - o wind sectors 210deg and 330deg are something in between "single wake" and "multiple wakes"

- **sector 0 deg**, WT5-2 is wake influenced "downwind turbine" by four upwind wind turbines in row, the most northern row (being the front row for wind sector 0 deg) does yaw offset demand; probability = 0.05
  - o wind bin 4 to 6m/s and TI=0.18, probability 0.03; apply wake model to determine wake conditions for "wake@5m/s+TI=0.18" based on external 5m/s, TI=0.18 and upwind wind turbines with yaw offset demand
    - ▪ most northern row has +yaw, probability 0.33
      - ➢ simulation: operation at "wake@5m/s+TI=0.18 with +yaw", combined probability: 0.05 * 0.03 * 0.33 = 0.000495
    - ▪ most northern row has -yaw, probability 0.33
      - ➢ simulation: operation at "wake@5m/s+TI=0.18 with -yaw", combined probability: 0.05 * 0.03 * 0.33 = 0.000495
    - ▪ most northern row has 0yaw, probability 0.33
      - ➢ simulation: operation at "wake@5m/s+TI=0.18 with 0yaw", combined probability: 0.05 * 0.03 * 0.33 = 0.000495
  - o wind bin 6 to 8m/s and TI=0.17, probability 0.04; apply wake model to determine wake conditions for "wake@7m/s+TI=0.17" based on external 7m/s, TI=0.17 and upwind wind turbines with yaw offset demand
    - ▪ most northern row has +yaw, probability 0.33
      - ➢ simulation: operation at "wake@7m/s+TI=0.17" with +yaw, combined probability: 0.05 * 0.04 * 0.33 = 0.00066
    - ▪ most northern row has -yaw, probability 0.33

  - ➢ simulation: operation at "wake@7m/s+TI=0.17" with -yaw, combined probability: 0.05 * 0.04 * 0.33 = 0.00066
- most northern row has 0yaw, probability 0.33
  - ➢ simulation: operation at "wake@7m/s+TI=0.17" with 0yaw, combined probability: 0.05 * 0.04 * 0.33 = 0.00066
- wind bins 8 to 30m/s equivalent to previous case

- **Sectors 30 deg to 330deg** equivalent to previous case**:** WT5-2 is wake influenced "downwind turbine" by multiple wakes in in different configurations for each sector; always the front row to the wind does yaw offset demand – only for wind sectors 240deg, 270deg, 300deg WT5-2 is wake influenced by a single wake
  - the applied wake model needs to be adopted to the different configurations for each sector and then for each wind bin and with the yaw offset demands +yaw, -yaw and 0yaw for the front row

For each wind turbine a considerable number of single DLCs / simulations are generated:
- 12 sectors, each having
  - 13 wind bins, each having
    - 3 WF-FC modes, each to be simulated with
      - ➢ appr. 6 turbulent seeds for fatigue evaluation
      - ➢ significantly more turbulent seeds for extrapolation
- for wake influenced "downwind turbines", a wake model needs to calculate the wake conditions first

4.6. Proposals for certification requirements

4.6.1. Proposals for WFC software validation

Section 4.3 lists a number of requirements for the validation of software to be applied in the context of WFC simulation. These requirements define the level which DNV would claim as a prerequisite in certification context. Nonetheless, the specific wind energy standards today do not list requirements for software validation yet. Regarding simulation model software validation for WF-GC see Section 1.3.2.3.

4.6.2. Proposals for Design basis / DLC definition

The certification schemes as listed sections 1.2.2 and 1.2.4 include the certification module / phase "Design Basis". One part of the "Design Basis" is the definition of the DLCs. For the definition of the single DLCs under the consideration of WF-FC, the text of sections 4.4 and 4.5 including Table 22 reflects already the relevant text to be incorporated into future standards. For that, the DLC description text from section 4.5 may be reformulated and / or condensed. It should be noted, that the above discussed DLCs consider only the case "with presence of WF-FC". The "regular" DLCs according to IEC 61400-1:2019 [5] (Table 2) and (Table B.1) or DNVGL-ST-0437 [14] (Table 4-3) and (Table 4-4) for the case "without the presence of WF-FC" need to be considered as well.

However, for the reduction of DLCs to be simulated and evaluated, the following Guidance Notes are suggested, to be incorporated into future standards.

Guidance note:
The simulation of certain DLCs may be omitted, according to the strategy of the WF-FC. This might be case, if WF-FC is inactive in certain situations as:

- Start-up
- Normal shut down
- Idling
- Parked and fault condition
- Standstill
- Maintenance
- The wind speed is outside a pre-defined wind speed range where is WF-FC is active

The inactive mode of the WF-FC shall be clearly defined. This could be carried out in order to reduce the number of load simulations to the relevant ones.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

Guidance note:
The designer of a specific wind turbine may demonstrate by a sensitivity study, that within one specific DLC, only certain combinations of WF-FC features and external conditions of this DLC are load dimensioning. This could be carried out in order to reduce the number of load simulations to the relevant ones. These combinations would then cover a defined wider range of combinations of that WF-FC feature and external conditions of this specific DLC.
Example: For wake steering at DLC1.3, only the combinations of +5deg to + 15deg and -5deg to -15deg yaw offset at wind speeds between 12m/s and 18m/s are load dimensioning for DLC1.3. This covers this WF-FC feature for DLC1.3 with yaw offsets from -20deg to +20deg at wind speeds between 4m/s and 25m/s.
This limitation of simulations applies only for the determination of ultimate loads.
One sensitivity study covers only wind turbine variants of the same platform.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

4.6.3. Proposals for Design Evaluation / Load Simulation

The certification schemes as listed sections 1.2.2 and 1.2.4 include the certification module / phase "Design Evaluation". One part of the "Design Evaluation" is the simulation and evaluation of the design loads of the wind turbine, based on the Design Basis as described above in section 4.6.2. For this, all DLC being defined under consideration of WF-FC need to be simulated and evaluated for all regular analyses, as standard extreme loads (including extrapolation), fatigue loads and serviceability state analysis (including blade deflection). It should be noted, that the above discussed DLCs consider only the case "with presence of WF-FC". The "regular" DLCs according to IEC 61400-1:2019 [5] (Table 2) and (Table B.1) or DNVGL-ST-0437 [14] (Table 4-3) and (Table 4-4) for the case "without the presence of WF-FC" need to be considered as well.
The load simulation and evaluation tools being applied need to fulfil requirements according to IEC 61400-1 or DNVGL-ST-0437. This includes successful validation of the tools, see also section 4.3.

5. GRID CODE COMPLIANCE (GCC)

5.1. General

State of the art of GCC is documented in various international standards, national rules, governmental orders and in the EU regulation 2016/631 [1]. Those documentations are widely called grid codes and they are usually setting requirements to be fulfilled by wind farms at the connection point to the grid of public distribution and transmission of electrical energy. Fulfilling those requirements is called compliance with grid codes, or in short: Grid Code Compliance (GCC).

Requirement set in grid codes are mostly functionalities implemented in the wind turbine or the central equipment of the wind farm intended to perform controlling of electrical characteristics in the meaning of IEC 61400-21-1:2019 [13]. Functionalities like this are called GCC features. State of the art GCC features are described in Section 5.2 (a kind of baseline GCC to be implemented within WF-GC) putting the focus on those GCC features being relevant for WFC elaborating where GCC is relevant for WFC features.

The amount of GCC features required at an individual wind power plant grid connection point and the values to be reached are differing. They differ per country, per connection voltage, per total installed capacity (wind farm total power) and per local instruction or local rules of the relevant system operator in charge. Some of those features or at least some of the values to be reached are contradictory between different countries throughout Europe as further described in Section 5.3.

Many of those GCC features are related to voltage control or direct control of reactive power exchange with the grid. Their impact on TotalControl is described in Section 5.4.

Mostly important for TotalControl is the limitation of controllability by GCC features in order not to destroy grid code compliance when implementing WFC into wind power plants. Corresponding data exchange is hence of highest importance to enable wind power plants with control features as suggested within TotalControl to be grid code compliant, nevertheless. The question which GCC features are relevant for WFC features as defined in TotalControl is also described in Section 5.5. Relevant interfaces between WT, WFC and wind farm grid connection point and how to handle them during testing, simulation and assurance is described in the same Section.

Suggestions regarding how to assure implementation of grid code compliance in the TotalControl ideas in general, in the WT type design and in the wind farm's grid connection are described in Section 5.7. This includes testing procedures which are also differing from country to country (covered in Section 5.3) as well as suggestions how to cope with the lack of standardization on EU level regarding this (covered in Section 5.7.2). One possible way to reduce costly testing and to cover site specific differences is simulation of GCC features. How these simulation models should be validated against test results is covered in Section 0, potential alternative approaches in Section 0. The Section 5.7 also describes who should evaluate test results, simulation results and assessment results in general including suggestions for corresponding acceptance criteria.

Some of the GCC features are also referred to as ancillary services. This is especially the case for those GCC features for which it is expected that they are valuable for system operators and might hence be paid when activated or when performing the desired result. In general, each of the GCC features could also be called an ancillary service. They are therefore covered in the below Sections and as their payment is not part of the scope here, the wording "ancillary service" is not used further.

5.2. Relevant GCC functionalities (GCC features)

GCC features are listed in the Annex of [88] which is a summary of GCC feature descriptions in various grid codes as listed in the grid code listing [89].

As not all of those GCC features are relevant within this report, only those which deem to be relevant are listed below. Numbering refers to the list in the standard [88].

Grid code requirements might be restrictive or not, depending on the grid code to be applied (depending on the site and its POC) and depending on its total capacity (see G3 below) which is classified in the European grid code RfG [1] as Type A, B, C and D with corresponding national power levels.

An overview on the impact the below described GCC Features will have on the subject this report is dealing with can be seen from Table 24 in Section 5.2.6.

5.2.1. General GCC features

G1 Grid code identification

Grid code compliance can only be granted when referring to a specific grid code (i.e., a publicly available document defining requirements, tests, or other specifications to be applied when connecting a WT or wind farm to any electric power system e.g., as listed in [89]).

The point of connection POC is the point at which a WF connects to an electric power system. Grid code requirements usually apply at POC, unless otherwise stated.
Issues related to short circuit power (S_k) are normally regarded as project specific parameters.

G3 MW size classification

Some grid codes are specifying a certain MW threshold above which the grid code, or parts of its requirements, are to be applied (e.g., Type A, B C and D in NC RfG [1] called the significance in (9) of its definitions).

G4 System voltage level

Some grid codes are specifying a certain voltage threshold (or range) from which the grid code is applicable.

5.2.2. Rating and design related GCC features

R1 U/f/P/t-figure

A voltage-frequency-power-time figure relating to the WT design. Corresponding figures (or corresponding tables or pure descriptions) are specifying the operating area for simultaneous values of voltage, frequency, output power and time.

R5 Reactive power rating for both, WT and WF design
The steady-state reactive power capability shall be specified in a PQ-chart. The PQ-chart shall be valid for the full active power operating area.
If the intended requirement is not solely clear from the PQ-chart only, the PQ-chart shall be associated with a text thoroughly explaining the conditions as voltage, power factor and any technical limitations as stability, technical minimum operation, excitation etc.
Part of the steady-state requirements are required to be dynamical (fast). In the PQ-chart such shall be stated, too.
The reactive power capability versus the grid operation voltage in the POC-point including the effects of voltage control shall be specified in a single UQ-chart.
If the intended requirement is not solely clear from the UQ-chart, the UQ-chart shall be associated with a text thoroughly explaining the requirement.

5.2.3. Dynamic GCC features

D3B Active power control – Maximum start-up ramp rate
This ramp rate defines the maximum increase of MW/min (or per 10 min) during start-up.

D3C Active power control – Maximum shut-down ramp rate
This ramp rate defines the maximum decrease of MW/min (or per 10 min) during shut-down (provided occurrence of suitable wind conditions).

D3D1 Active power control – Maximum normal ramp-up rate
This ramp rate defines the minimum ramp-up rate to be required during normal operation for remotely controlled WFs.

D3D2 Active power control – Maximum normal ramp-down rate
This ramp rate defines the maximum ramp-down rate to be required during normal operation for remotely controlled facilities, modules or plants, provided suitable wind or solar intensity or any other renewable source conditions.

D3E Active power limitation control mode
This describes any special active power control mode. If this control mode is applied, functionality and parameters and any interdependence to other required control requirements shall be clearly specified. The method of calculation of actual production shall be well defined (e.g. floating average, 1-minute, 10-minute average and so on).

D3F Active power balance control mode
If this control mode is applied, functionality and parameters and any interdependence to other required control requirements shall be clearly specified.
This mode is assumed to be identical to remote control of the WF according to some schedule or the WF being part of a frequency secondary control arrangement.

The method of calculation of actual production shall be well defined (e.g. floating average, 1-minute, 10-minute average and so on).

D3G Active power gradient control mode

If this control mode is applied, functionality and parameters and any interdependence to other required control requirements shall be clearly specified. The method of calculation of actual production shall be well defined (e.g. floating average, 1-minute, 10-minute average and so on).

D3H Active power delta control mode

Active power delta control mode: This is a special active power control mode. If this control mode is applied, functionality and parameters and any interdependence to other required control requirements shall be clearly specified.

The method of calculation of actual production shall be well defined (e.g. floating average, 1-minute, 10-minute average and so on).

D3I Other active power limitation modes

Any other method other than the above describe power control modes should be described accordingly.

D4A Minimum run-back ramp rate (active power) description

Run-back is a special pre-armed automatic system protection scheme (SPS) used to protect against loss of thermal transfer capability or transient angle instability. This type of functionality is sometimes called a 'remedial action scheme' (RAS), i.e., it must be pre-installed and being fully automatic the functionality shall be guaranteed at any time. In such cases a remote signal will order the plant to run back the active power with a certain minimum ramp down rate to a predetermined power level, e.g., 50 %, and stay there until the run-back signal is cleared.

D4B Parameter for D4A

If required, this parameter specifies the minimum ramp down rate of active power in p.u./s based upon rated power per WT.

D4C Maximum run-back starting point (active power)

This parameter is the maximum initial active power before a run-back is ordered. This parameter will normally be the rated power of the WT/WF, i.e. 100 %.

D4D Minimum run-back stopping point (active power)

This parameter is the lowest possible run-back level which can be pre-programmed. This parameter will normally lie in the order of 50-20 % based upon rated power of the WT/WF. This parameter should not necessarily be very low to assist the power system in a proper way.

D4E Minimum operation level (active power)

Due consideration needs to be given to WT's technical minimum production at any time, i.e., independent of the wind speed at any time (high wind speed situations).

D5 Frequency response, also called frequency sensitive mode (FSM)

Depending on system frequency changes active power of WTs will be changed actively by control

D5M Limited frequency response during over frequency situations (LFSM-O)
As soon as system frequency is rising above a threshold (parameter) of a corresponding dead band around 50 Hz (or 60 Hz), the active power shall be reduced depending on the measured system frequency in a droop (parameter). Corresponding ramp rates or settling times are defined in some grid codes. Mostly only the droop is relevant.

D5N Same as D5M but limited to under frequency (LFSM-U)
As soon as system frequency is falling below a threshold (parameter) of a corresponding dead band around 50 Hz (or 60 Hz), the active power shall be increased depending on the measured system frequency in a droop (parameter). Corresponding ramp rates or settling times are defined in some grid codes. Mostly only the droop is relevant. This is usually not required for wind farms but can be offered as ancillary service (see Section 5.6.1)

D6 Delta P for LFSM-O droop
Specify the range the power set-point shall be able to be curtailed to. E. g., 100 to 50 % of the rated output of the WF. Attention shall be given to limitations due to the technical minimum production in high wind speeds.

D7 Inertia response (synthetic inertia, inertia emulation)
During a low inertia phase in the grid, SO may require WT to provide artificial inertia for a short period of time. Typically, the functionality of this GCC feature is slowing down the WT rotor and supporting the grid with additional active power for a short time. This is called "artificial inertia" because it is emulating the physical behaviour of a synchronous machine with a large flywheel by changing the rotor speed via the frequency converter control for a limited time.

D8 controls utilizing the reactive power capability of the wind farm: D9, D10 or D11

D9 power factor control mode
Reactive power of each WT is coordinated by the WF-GC in order to achieve the desired **power factor** as requested via remote control by the SO to be set at the wind farms PoC.

D10 reactive power control mode
Reactive power of each WT is coordinated by the WF-GC in order to achieve the desired **reactive power value** as requested via remote control by the SO to be set at the wind farms PoC.

D11 voltage control mode
Reactive power of each WT is coordinated by the WF-GC in order to achieve the desired **voltage value** as requested via remote control by the SO to be set at the wind farms PoC.

D12 FRT (fault ride-through capability i.e., OVRT and UVRT)
D12D Re-closures
D12I FRT – post fault oscillatory behaviour (active power)

D14 Dynamic electric behaviour during voltage dips or swells initiated by FRT events
D14B reactive current injection
D14C…F reactive current injection dead time, rise time, settling time, post-fault support time

D14G active current injection
D15 OVRT

D16 System and relay protection e.g., f, voltage and current protection

5.2.4. OTHER GCC FEATURES

Int1 communication and control interface requirements Int2...12
Int2...12 Status at PoC: Maximum available power, currently available power, lost production, reactive power production, voltage, transformer tap position, main transformer fault indication, cuircuit-breaker position indicatior, current measured at PoC, status of compensation equipment

P Wind farm status information
P1 stopped due to: high or low wind, maintenance, forced outage, out of operation, with limited capacity, internal network topology information, alarms, frequency response mode signal, frequency response mode status indication
P2 metereological information: wind speed, direction, ambient temperature, atmospheric pressure, existence of simulation models

5.2.5. POTENTIAL FUTURE GCC FEATURES OF WTS

B Black-start capability. The ability to start the grid after a black-out

AHF Active harmonic filtering. The ability of e.g., the WT's frequency converter to generate harmonic currents in such a way to supperpose existing harmonic currents and to eliminate parts of the existing or even eliminating all harmonic voltages at a the PoC

5.2.6. SUMMARY ON RELEVANT GCC FEATURES AND THEIR IMPACT HERE

As grid code requirements are different depending on various site-specific issues, general recommendations what requirements have to be applied are difficult to give. The column "scope of requirements" in below Table 24 gives an overview, on which issues the scope of requirements is depending on.

System operators require minimum times a WT can be operated at different voltage and at different system frequency f. Such is leading to potential failure operation which is demanding for thermal and isolation design of the WT.

Table 24 – Overview on Impact of GCC Features

GCC Feature	Defining the scope of requirements	WT design	WF design	Limitation of active power dynamic control	Potential paid ancillary service	Reducing active power below maximum possible at given wind speed via WF-GC	Controlling the reactive power of the WT	must be located in the WT	Fault operation per Figure 13	Signal exchange	Set-points to be set	Wind farm status information
G1	x											
G3	x											
G4	x											
R1		x										
R5		x	x									
D3				x	x	X						
D4				x	x	X						
D5				X		X			x			
D6				X								
D7		x		x	x	x			x			
D8					x		x					
D12				x						x	x	
D14				x			x			x	X	
D15				x			x			x	X	
D16			x								X	
Int		x	x									X
P		x	x									x
B		x	x		x						x	
AHF		x			x					x	x	

5.3. Contradictory GCC requirements within the EU

In principle NC RfG [1] is intended to avoid contradictory requirements throughout the EU regarding grid code compliance. However, many parts are leaving it open to national SO's to define details (so-called non-exhaustively defined requirements).

In this section the question shall be answered if there are contradictory requirements throughout the European Union regarding grid code compliance. At the time being, not all countries (i.e., EU member states) have defined their details. The question cannot be answered by now completely, as corresponding countries did not yet issue documentation of their national implementations (i.e. requirements which are not exhaustively defined in NC RfG are neither completely defined by some countries) [90], even if corresponding maps indicate that they did. Those countries are (as listed in [90]):

- Bosnia and Herzegovina
- Bulgaria
- Cyprus
- Czech Republic
- Estonia
- Iceland
- Latvia
- Luxembourg
- Macedonia
- Montenegro
- Netherlands
- Norway
- Portugal
- Serbia
- Slovakia
- Slovenia
- Switzerland

For the time being the known contradictory GCC requirements are mainly referring to the following aspects.

1. Testing requirements differ and testing needs to be repeated for different countries.
2. While Germany has a very specific testing procedure [36] Spain has such, too, being different and cannot be harmonized [28] fully, the same for Italy [91]. Regarding some issues e.g., proof of capability to operate at other frequencies than 50 Hz, some require testing (Poland, Romania) and other accept such without testing real frequency changes with full power.
3. The requirement to provide active current during UVRT situations is required in UK but the opposite (requiring reactive current during UVRT).
4. Various settings in the WF-GC will be different for each different grid code to be applied.

5.4. Impact of reactive power- and voltage-control strategies on WFC

5.4.1. General

Optimization of reactive power dispatch within large wind farms is described in D2.4 [15]. While losses in the wind farm (e.g., 1%) can be reduced by e.g., 6% as detailed in [15] it must be taken care of the priorities as outlined in Figure 13. Even during normal operation, the system operator (SO) usually has the right to control the power factor or the reactive power at the Grid Connection i.e., the point of connection (PoC).

Taking into account the outcome of D2.4 [15], the optimal way of reducing electrical losses within the wind farm while the SO is requesting lower power factor than one or higher reactive power than zero will need to include the optimisation principles from D2.4 [15] into the WFC. Priority is clear:

1. The requirements (regarding power factor or reactive power) from the SO have to be fulfilled
2. It is up to the optimisation principles in the WFC, which of the WT within the wind farm will deliver (or consume) the corresponding reactive power

5.4.2. VOLTAGE CONTROL WITHIN THE WIND FARM AND OUTSIDE OF IT

Voltage control is a functionality to constantly adapt the voltage at a given electrical point (e.g., PoC or WT or transformer terminals) by dynamically controlling the reactive current of all or of specific WTs within the wind farm.
Technically voltage control is performed by changing the reactive current proportion generated in the main frequency converter of the WT. Only in very rare wind farm examples a corresponding reactive current is generated in additional FACTS (Flexible AC Transmission Systems) or even by HVDC terminals. Physically the additional reactive current flowing in any electric cable will add a corresponding voltage drop along the cable. Depending on the type of cable, the length and the actual electrical power flowing through the cable such additional reactive current in the cable will let the voltage rise at the one or the other end of this specific power cable.
Voltage control is a typical functionality used by system operators (mainly by TSO) to coordinate power flow, to reduce transmission losses and to control voltage for staying inside design insulation levels of the corresponding transmission lines. Hence, TSO typically request a corresponding voltage support from wind farms at their PoC (or at the corresponding connection point between distribution and transmission system, which usually lies outside the wind farm). This request is either submitted by set-point or by contractual agreement in line with the connection agreement between system and wind farm operator. In case of an online provided set-point command the reference point for such voltage control setting is the PoC of the wind farm. Dispatching such set-point command to the individual WTs within the wind farm is a typical task of the WF-GC already being state of the art in e.g., Germany (by FGW TG8 [27]).
Additionally, it might be a functionality within the wind farm to control WT terminal voltages.
It needs to be said, that electrical protection settings (inside and outside the wind farm and in the substation) need to be aligned with such voltage control settings. Typically this is assessed within project certification per Sections 1.2.5, 1.3.2.4 and 5.7.7. Verification of such is described in Section 1.3.2.5 based on testing per Section 6.4.3.
Potential system stability risks due to voltage control are further described in Section 3.6 especially in 3.6.1.

5.4.3. FALL-BACK SOLUTIONS

The idea of fall-back solutions is to be able to keep the WFC running as WF-GC (seeTable 1) and adhering to GCC, while some of the sensors and maybe some of the electrical value detecting devices or control systems (not only related to yaw and pitch control in the WF-FC (see Table 1) but also related to electrical value detection (current, voltage, power factor) are out of order. Future work is expected in this respect (forthcoming deliverable D4.6) especially regarding corresponding simulations with the Total Control Reference Wind (TC-RWP) electrical grid model proposed in D4.2. Sensors used are described in deliverable D4.2.

The task to evaluate such fall-back solutions regarding grid code compliance ensuring the voltage control and reactive power capability will be part of individual certification cases. Implementation in specific design will anyway differ from manufacturer to manufacturer or even depending on the wind farm design, adapted to the conditions of a specific site.

5.5. Impact of GCC on mechanical loads and vice versa

Within this section only those mechanical loads are covered which are directly impacted by torque and counter torque within the drive train of a WT. In general, only active power is contributing to mechanical load levels.
Starting with the impact GCC has on mechanical loads a short introduction on typical drive train concepts is given.
State of the art WTs are not directly coupled to the grid but are having a power-electric frequency converter, especially those in compliance with typical grid code requirements. The influence of this frequency converter is of major importance for the evaluation of GCC impacts on the load and nowadays a typical way of decoupling the driving torque originating from wind from that torque used for generating electricity withing the rotating electric machine used in the WT.
Within this scope here, old style WT types without main frequency converters can be neglected because they are only operated at electric power systems without substantial grid code requirements.
WT types covered by this section are either using full-power frequency converters (i.e., all power fed into the grid is converted), or they are of the doubly fed type. In both cases reactive power is controlled independently from active power. Controlling reactive power independently from active power does also mean, that impact on mechanical loads within the drive train can be controlled by the main frequency converter directly.
Any grid code requirement (described as GCC features in Section 5.2) is controlled by either the main frequency converter software or the W**T**-CS as described in Figure 1. WT-GC and W**F**-CS are usually higher-level control and only transferring the commands to the frequency converter control in the end (the main frequency converter control is the sub-ordinate control).
Impact from the relevant GCC features on the loads is coming from those grid code requirements which are changing the active power. As those GCC features are mandatory given by the system operator and usually linked to emergency situations in the electric power system, they anyway cannot become over-ruled by any action from the WF-FC. This is also described in Section 5.6.4. Impacts are usually controlled ramp rates of active power change. An overview is given in Table 24.
A typical impact of GCC on loads is the UVRT-requirements. During well-defined voltage dips occurring in electric power system under fault conditions (short circuits in the electric power system outside the wind farm) each WT within the wind farm will experience a strong speed increase during the voltage drop and another strong counter torque in the drive train when voltage is coming back suddenly (after fault clearance). The impact on the loads in such UVRT-events is type tested by corresponding field tests (see Section 6.4.2.1) but usually not assessed by the certification Body as structural integrity is not a focus within grid code compliance certification. For load assessment usually the fatigue impact is important which could be evaluated by taking into account the frequency of such events over time. Unfortunately, system operators are not collecting such statistics as their aim is to monitor longer grid outages in order to avoid legal cases due to longer outage events. Hence numbers and kinds of faults not required to be stored by electrical energy quality standards (e.g., [92]) are not collected by TSO nor DNO. To have statistics would be important for adequate consideration in fatigue load calculation.

The impact on electrical values (including active power) can be simulated by using those simulation models validated in line with the GCC Equipment Certification (see Section 1.3.2.2) and loads by using the deliverable D1.5 : Electro-mechanical model of reference wind power plant [93].

So far this sub-section discussed the impacts of GCC on loads. The impacts of mechanical loads on the GCC features are mainly those introduced by WFC to reduce loads. If such measures, initiated by the WF-FC, are resulting in active power reduction this is impacting many GCC features.

5.6. Control limitation & data exchange to cover GCC

In order to ensure grid code compliance also during WFC operation in a wind farm, some of the control principles of WF-FC need to be limited for those short periods in time where corresponding grid events, coming from the electric power system outside the wind farm are taking place.
Such events can be:

- Deviations from the nominal system frequency value of f=50 Hz further elaborated in below Section 5.6.1
- During normal operation the system operator in charge for the electric power system, the wind farm is connected to, shall be allowed to require the setting of specific power factors, reactive power values, voltage control set-points or any other P-Q-characteristics. See 5.6.2
- Also, during normal operation very steep power changes required by WF-FC might disturb the electric power system outside the wind farm. See 5.6.2
- Short-circuit events followed by line protection. These are those faults leading to the well-defined under- or overvoltage events which are tested per Section 6.4.2.1 (UVRT or Fault Ride-Through testing). They are further elaborated in below Section 5.6.3

In general, this can be also be described as priorities in control and protection requirements in relation to grid code requirements, see also D4.7 CL-Windcon [40] and D2.1 FarmConners [7], e.g. 3.3.1 and 3.3.2 and further below in Section 5.6.4

In the deliverable D2.3 within total control [8] further details on control are described. It needs to be noted, that WF-GC is called WPP within that deliverable. Also, ancillary services are mentioned in that deliverable D2.3. The difference between GCC features per above Section 5.2 and ancillary services in Section 6 of D2.3 are only existing regarding payment. While many GCC features are mandatorily required by SO's (depending on grid code) ancillary services are usually paid services but also covered here as GCC features. Section 5 in D2.3 is also covering valuable information on setpoint optimization with dynamic wake meandering approach. Section 7 of D2.3 is dealing with multidimensional set point control, which also is of importance regarding the topic of this Section.

Applying virtual synchronous machine approach in controlling the main frequency converter is another future topic which is not directly related to WFC but having major impact on grid code compliance is further investigated in the TotalControl deliverable D3.2 [94] including some good simulations in this respect.

Data exchange for grid code compliance is typically performed by the WF-GC. Figure 1 and Figure 13 might be helpful for this.

5.6.1. Highest Priority for Frequency Power Response (LFSM-O)

System operators are responsible for operating the electric power system outside the wind farm in a safe way. They need to ensure constant supply with electrical energy, but keeping the system frequency constantly in a quite narrow tolerance window has highest priority. For such, they expect wind farms to support this by reducing the active power at over frequencies (GCC feature LFSM-O) while increasing active power during under-frequency (LFSM-U) is usually not required from wind farms. The steepness, response characteristics, hysteresis- and other characteristics are defined very detailed in grid codes and shall not be changed by any control, e.g., by the WF-FC.
The origin of such frequency deviations are unbalances between generation and load, followed by the triggering of the GCC feature D5M per Section 5.2.3. Figure 9 gives typical reasons for that in an overview.

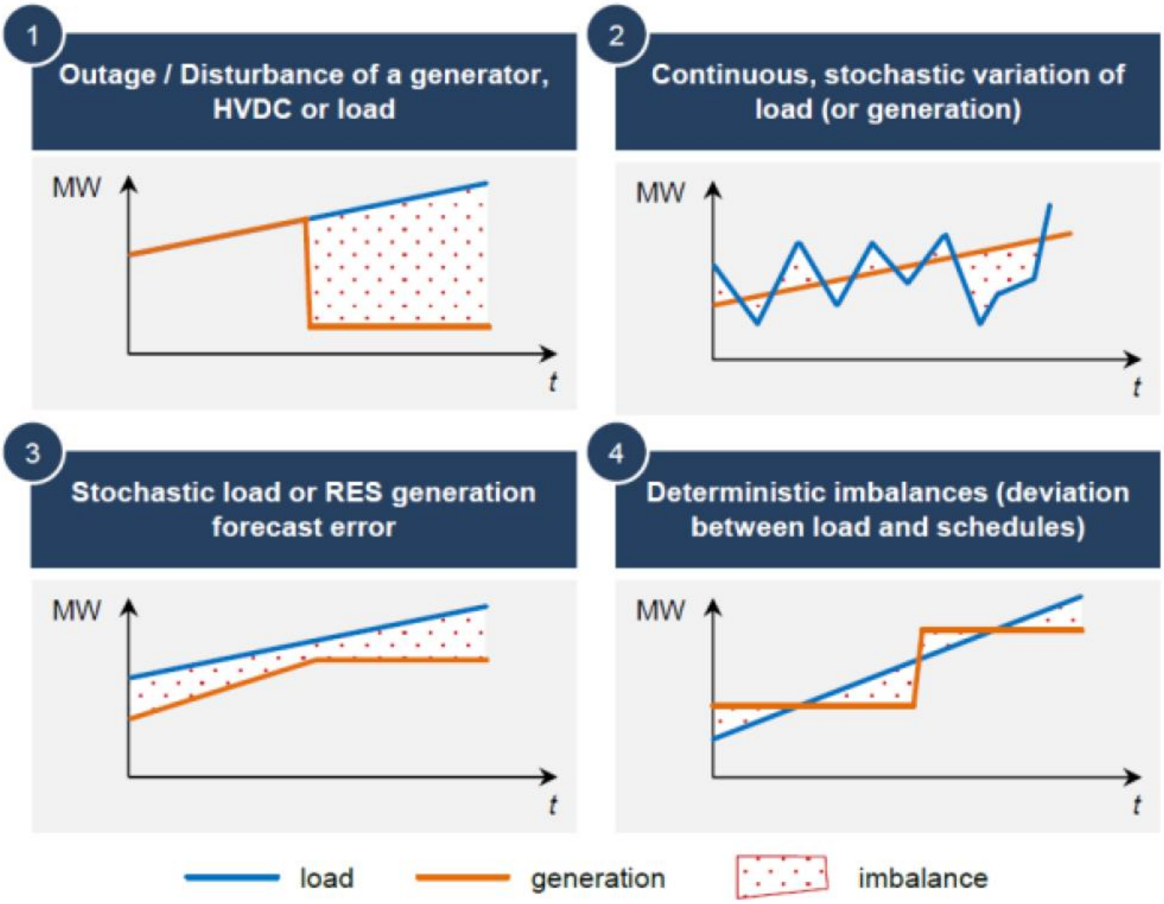

Figure 9 – Typical reasons of unbalanced load versus generation leading to frequency deviation in electric power systems [2]

In the case of wind farms this frequency response is limited to over frequency (LFSM-O). This GCC feature is described in Section 5.2.3 as D5M. During such faults any other control of active power (e.g., originating from WF-FC) except those controls related to D5M or to the generation of active power shall be prohibited for the duration of a relevant system frequency deviation (usually 50Hz ± 200 mHz).
This subject is also detailed in [5] of deliverable D4.1 [2], but mainly for under frequency issues which are optional ancillary services as described further below. In this deliverable also typical frequency response requirements are given, taking the Irish grid as an example (Figure 3-12 in D4.1

[2]). In this deliverable the traditional wording of primary, secondary, and tertiary control is used, which in other countries (depending on grid code) is not applicable to wind farms. All these three control categories are referring to using the so called operating reserve for supporting the system frequency to stay as close as possible to 50 Hz and to even control past unbalances in such a way, that old style watches, using the system frequency as a time reference, will not show a wrong time, even after frequency deviations (tertiary control (TOR2)).

Virtual inertia (GCC feature D7 in Section 5.2.3) is further detailed in the TotalControl deliverable D4.1 [2]. Virtual inertia is a control approach for controlling the WT in a way to temporarily reduce speed by injecting additional active power to the grid (and by taking it back after some seconds by increasing the speed again). Such can also be used for improving the amount of active power which could be used in frequency response in under-frequency situations (LFSM-U), which usually is not required for wind farms but generally is needed by SO's. An example can be seen in below Figure 10 (taken from [2]). This is also an example for an ancilliary service which could be sold to the SO (GCC feature D5N).

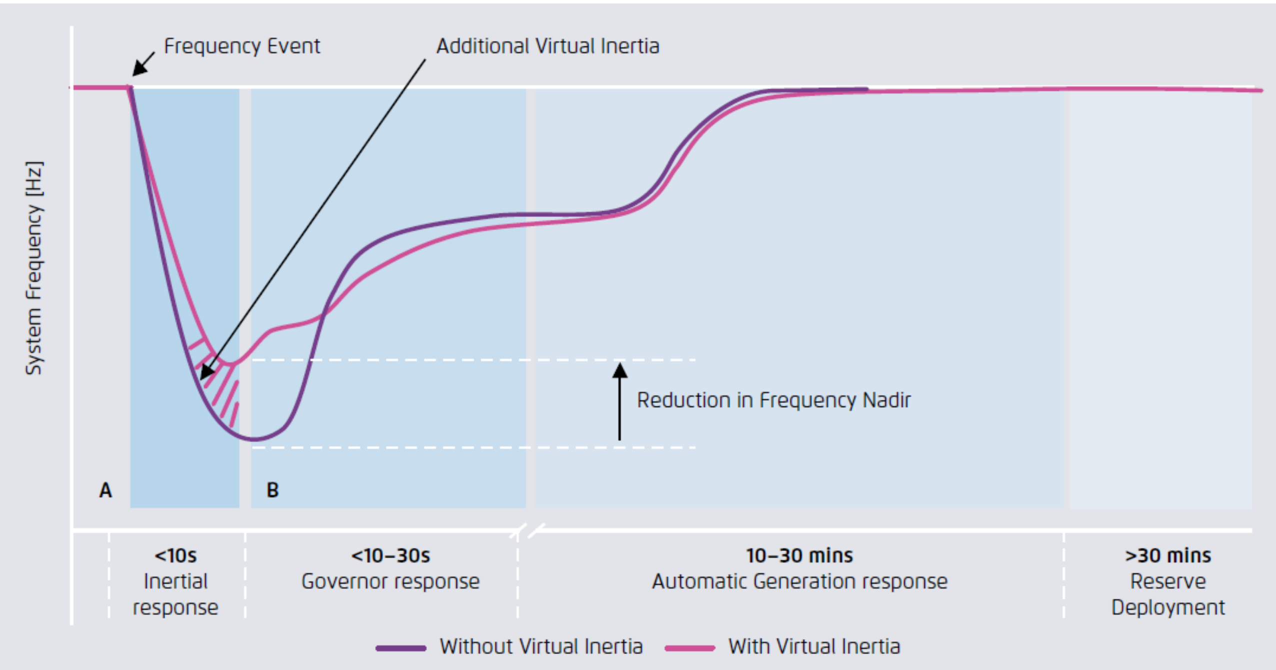

Figure 10 – virtual inertia response used for frequency response at under-frequency (LFSM-U), a voluntary anciliary service available from wind farms [2]

5.6.2. DATA EXCHANGE & PRIORITIES BETWEEN TURBINES & SUBSTATION

Controlling active and reactive power is a GCC requirement to be fulfilled at the PoC. It has priority in those cases where GCC features of the group D3 apply (see Section 5.2.3). Those are different ramping requirements and ramping limitations of active power during normal operation. They are applicable in weak grids in which changing the active power may lead to protection triggering in the electric power system outside the wind farm. Due to that the system operator in charge is allowed to require limiting active power change rates in the one or the other way. No other control,

e.g., WF-FC shall be allowed to change the active power in a contradictory way compared to those ramp rates or other limitations of active power required by grid code.
Similarly, this also applies to controlling reactive power by the system operator. The relevant GCC features per Section 5.2.3 are D8 through D11.

Regarding data exchange in this respect the WF-GC is responsible for properly operating and distributing the data.

Relevant data is coming from the following sources and are to be transferred to the following control systems:

- System operator (or dispatch centre) outside the wind farm is sending commands regarding GCC during normal operation. These commands are input to the WF-GC and must be transferred to the individual WT-CSs for implementing the corresponding measures, such as reactive power supply set-points.
- Measurements such as power factor, voltage, and power from the PoC (usually from the substation) must be compared to corresponding set-points, forming closed loop controls.

5.6.3. Data exchange & Priorities within each WT

Since the availability and transmission of the system frequency measurement signal is time-critical, it is measured locally at the WT and values are transferred within the WT to those control systems implementing LFSM-O. Any transfer from PoC is too time consuming to deliver good results, hence keeping this locally within the WT is good and common practice. As detailed in above Section 5.6.1 LFSM-O must have highest priority.

The same is true for voltage measurements regarding UVRT capability. Any activity by the WF-FC must be halted during UVRT-events and any power reduction initiated by the WF-FC must be ramped back in a way which has to be tested per Section 6.4.2.1. It is not allowed, that any WF-FC activity might be deteriorating or disabling the UVRT-capability of the WT to ride through faults and provide the requested current and voltage behaviour during the fault and thereafter.

5.6.4. Overall control scheme to cover Power System priorities

Per definition (see Section 1.1) we have the overall WFC which is covering three sub controls: WF-GC, WF-FC and O&M requirements, see Figure 1 in Section 3, description in Section 3.6 and below Figure 13. The WF-FC is further described in the deliverable D4.2 [95].

An example of today's state of the art WF-GC is given in Figure 11 (source: FarmConners report D2.1 [7]). It is mainly referring to Section 2.13 of [96] where the WF-GC is called PGS controller, in Figure 11. WF-GC is called WPP controller (which is another name for the same thing: wind power plant control) State of the art of WF-GC is also covering details on how to prepare corresponding simulation models of WF-GC as described in [32].

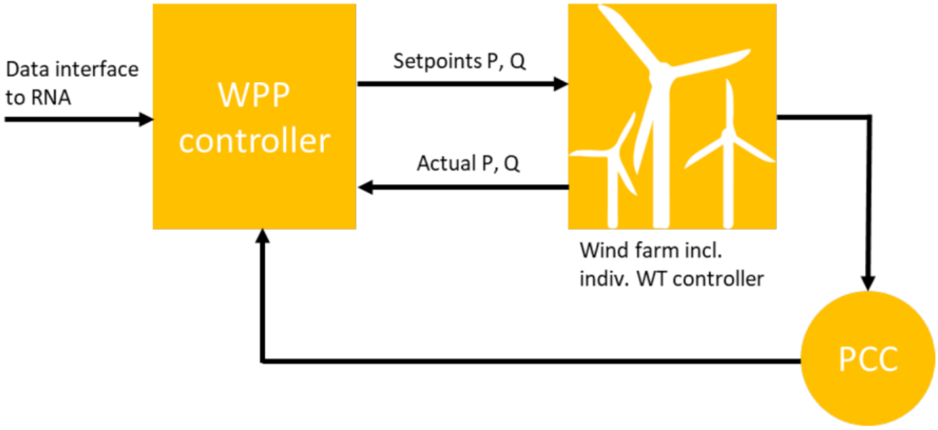

Figure 11 – State of the art WF-GC (source: FarmConners report D2.1 [7])

In some cases, WF-GC needs to be applied to different parts of wind farms (wind farm A, wind farm B etc.) resulting in a "master" WF-GC and several "slave" WF-GC, see Figure 12 (source: FarmConners report D2.1 [7]). This is a typical case when existing wind farms are extended by additional WTs later on. Similar cases exist within one single wind farm, when different WT types are having different WF-GC types installed and those different WF-GC types need to interact between each other. In those cases "Wind farm A" and "Wind farm B" in below Figure 12 can be understood as sub parts of one wind farm representing a group of WT types A and a different group in the same wind farm with WT types B (each type having its own WF-GC type A and type B).

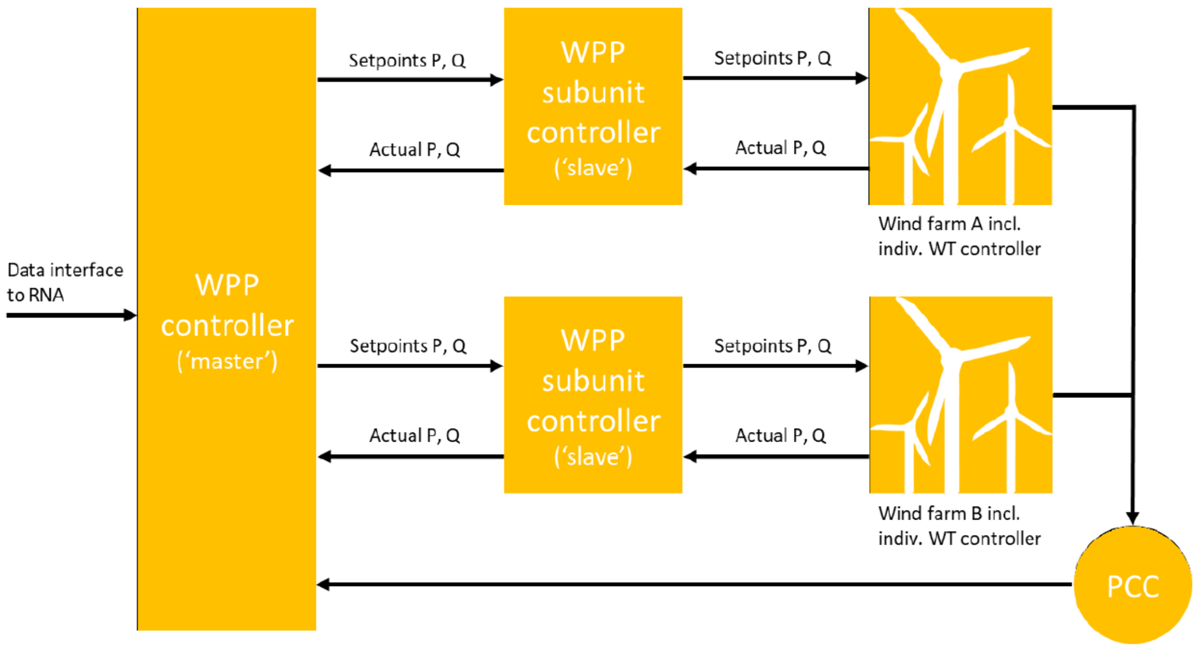

Figure 12 – WF-GC in "master" and "slave" arrangement (source: FarmConners report D2.1 [7])

For implementing WF-GC into the complete WFC, co-operation with WF-FC is necessary. In Figure 27 of [7] such co-operation is drafted. However, priority control regarding grid code compliance is missing in this figure. In section 5.2.2 of [7] priorities have been discussed regarding individual subjects of control and it is suggested to evaluate each of those subjects regarding priority (parallel approach), i.e. subjects like re-connection strategies, ramp-rates for active power and system frequency, f.

In a so-called parallel approach in Section 5.2.1 of [7] the WF-FC is activated or deactivated, depending on priority. This approach is not taking into account the optimisation possibilities as described in D2.4 [15] and mentioned already in above Section 5.4.1 within this deliverable.

To solve these deficiencies the approach in Figure 13 was developed. The priorities shown are better for reducing overall losses in the wind farm from reactive power currents. It can be done by means of one of the signal paths shown in Figure 13
Coming from the Electric power SO control or dispatch centre the signal requesting the power factor, or the reactive power value will pass through the substation at the grid connection to the WFC. The WFC is not yet defined as hardware and is it also not clear where it will be placed physically in the wind farm. It could be the substation, one of the WT towers or somewhere else. Within the drawing the WFC is represented as a box, showing the general software functionality of the WFC to perform a kind of case selection. The case selection will be "normal operation" if the request from the SO is not related to a fault in the electric power system outside the wind farm. Being regarded as normal operation the signal path in the drawing (Figure 13) can:

- Either go through the WF-FC and ending directly at the WT-CS of each WT.
- Or go through the WF-GC and ending at the input port of the WT regarding reactive power control of each WT within the wind farm.

In both cases priority must be given to fulfilling the requirement from the SO while optimizing is allowed as described in above Section 5.4.1. and 5.4.2.

Priority means that in cases where the electric power grid is endangered to fail, governmental rules usually give highest priority to those measures helping to beware the electric power grid from running into black-out situation. In below Figure 13 an alternative approach compared to [7] is described. This approach requires a switch-over between two states within the WFC:

1. Normal operation with no grid failure means operation of WF-FC and WF-GC
2. Grid fault operation means switch-over to WF-GC only and to de-activate WF-FC during fault duration

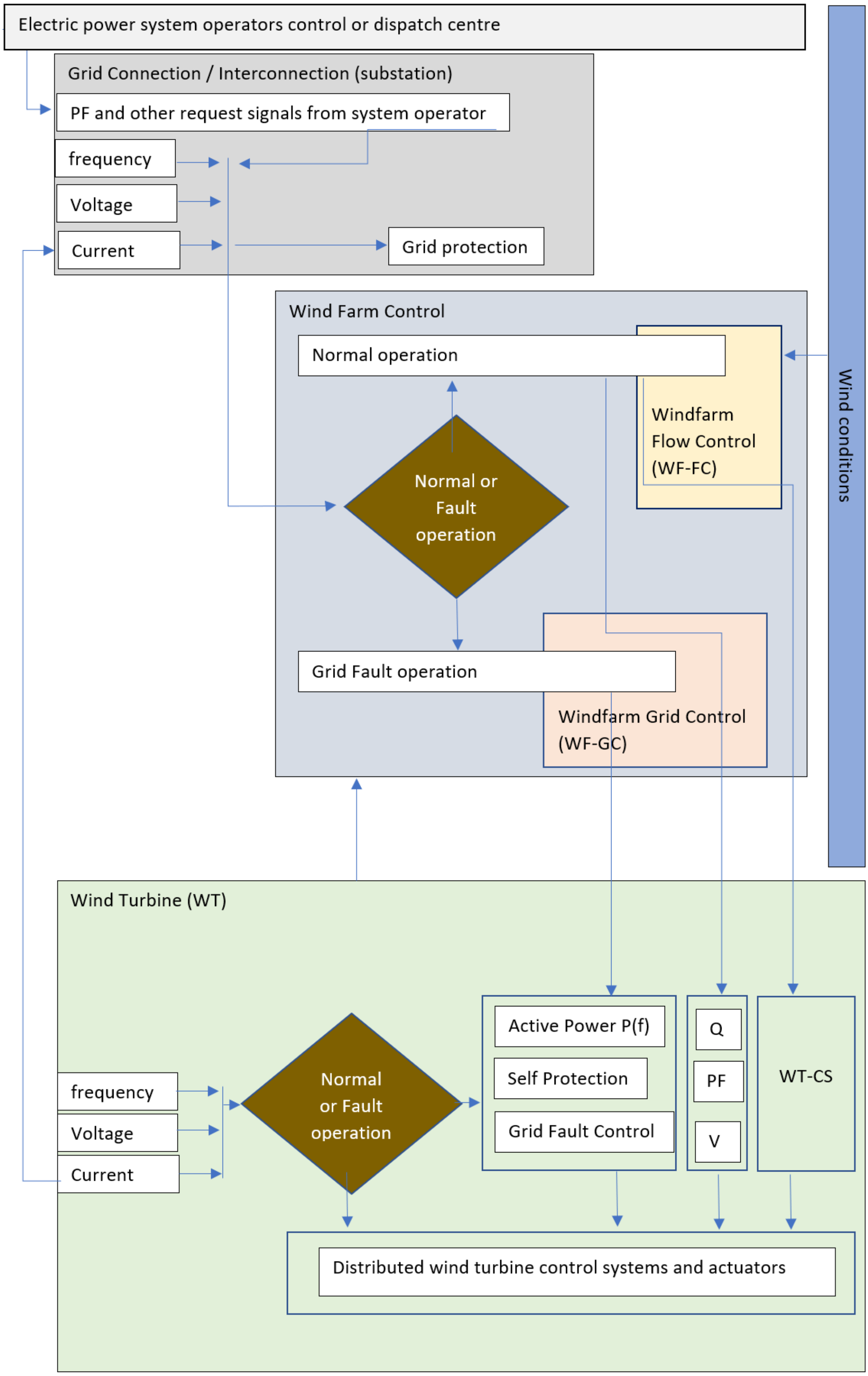

Figure 13 – Priority co-ordination regarding wind farm control (WFC)

Apart from those priorities drafted in Figure 13 there are technical reasons for locating some of the GCC feature functionalities in the WT. They can be part of the WFC, but the hardware of this part of control needs to be located in the WT. This is due to delays when signals have to travel through several cables, hubs and control, which in some cases heavily reduces the dynamic control capabilities where reaction times in the range of 1 to 100 ms are required. Those GCC features are the following.

1. FRT can only be implemented within the WT
2. LFSM-O (D5M in Section 5.6.1) shall be implemented within the WT

5.7. Proposal for certification requirements

For grid code compliance certification any requirement is depending on the grid code to be applied. Nevertheless, some typical requirements can be given here. However, in the end all is depending on the grid code applied in each individual certification case regarding GCC.
Regarding certification requirements coming from NC RfG [1] has to be said, that regarding certification always national requirement, especially certification requirements are on top of it (so-called non-exhaustive requirements).
In general, the following grid code requirements need to be considered additionally when implementing measures into wind farms and WTs as described within this Project TotalControl, i.e., application of WFC.

1. Those requirements listed in Section 5.2.6 as far as they are required in the grid code to be applied at the PoC of the Wind Farm to be certified or in the grid codes relevant for the market the WT type shall be sold to
2. All other changes introduced to the WT or Wind Farm under certification which are having impact on the conformity with the relevant grid code compared to WTs or wind farms without such changes.
3. Existing GCC certification can be used as far as the above will be taken into consideration when implementing the new measures.

5.7.1. PRODUCT CERTIFICATION VS. SITE-SPECIFIC CERTIFICATION FOR GCC

The general principle of EqC and PC will not be changed, it will just be explained once more below. Possible certification levels can be split in two kinds of certificates:

1. Equipment Certification of well-defined WT types i.e., product certification (WT level)
2. Project Certification of wind farm project i.e., site-specific certification (wind farm level)

While each wind farm consisting of several WTs each of them can be described by the same EqC (if all WTs are of the same type), several wind farms can never be described by the same PC as they are site-specifically differing from each other.
SOs wanting to know the electrical behaviour of the wind farm connected to their PoC will need a PC for such. Certification Bodies wanting to issue a PC will need the EqC of each type of WT used within the wind farm to be certified.

Manufacturers of WTs will need to have an EqC for each type they deliver, covering all grid codes of the countries they will deliver to.
Wind farm operators, planners and EPC contractors will need to purchase only those types of WTs for their wind farms which have an EqC for the grid code to be applied at the future PoC of their wind farm. They will be asked by the SO to provide a PC if required in the country in question.

5.7.2. WT Design Assessment

The impact of WFC on all relevant GCC features (as far as required by the grid code) shall be described by the designer of the WFC and verified by the manufacturer of the WT who implemented the WFC in his WT design. Which GCC features might be relevant is listed in Table 24. This list of impacts shall be provided to the certifier for assessment regarding grid code compliance.
For several GCC features the value of available power from the wind is needed for calculating the required set-points. When the WFC is actively reducing the active power in some cases, this needs to be considdered in the calculation principles of the corresponding control. This calculation principle needs to be adapted when WFC is implemented. A detailed description by the WFC designer, verified by the manufacturer of the WT regarding this adaption is needed and will be assessed by the certifier. The description shall contain the corresponding calculation formula, the way of its implementation in the software, the software shall be named and corresponding release numbers of the software version to be certified shall be provided. The description shall contain the location where the corresponding hardware is installed (e.g., towers nacells, substation) and the way and the location of the measurements shall be given. A test programm for corresponding validation shall be provided.

5.7.3. Test & Measurement

Details for testing are covered in Section 6 in general, those for GCC in Section 6.4. Below some general issues are described.

5.7.3.1. WT level

PQ-chart and UQ-charts shall be measured again, if any of the functionalities of WF-FC or other additional functionalities within this report are changing the GCC Feature R5 per Section 5.2.2. The new measured PQ- and UQ-chart shall be used in the grid code compliance assessment. Typical WFC activities with impact on active and reactive power shall be initiated during measurements to show worst case impact and principle of functioning.
UVRT-testing shall be repeated with the maximum yaw angle misalignment the WFC can set to a single WT.
The proper functioning and the plausibility of the results regarding calculating the available power with active WFC shall be shown by measurement.

5.7.3.2. Wind farm level

IEC 61400-21-2 [97] defines the procedures for measurement and fault recording for the verification of power plant electrical simulation models in relation to undervoltage and overvoltage ride through events. These measurement procedures are valid for wind farms, including WF-GC (they call it "power plant controller") and other connected equipment, necessary for the operation of the wind farm. The measurement procedures in [97] are valid for any size of wind farm connected to the point of connection (POC) at one connection point. The procedures for assessing and verifying the compliance with grid connection requirements are valid for wind farms in power systems with fixed frequency and a sufficient short-circuit power. Out of the scope of this standard [97] are: Multi park control, i.e. cluster management of several wind farms or several connection points.

5.7.4. Simulation with & Validation of simulation models

5.7.4.1. Fault Ride-Through behaviour

The behaviour during Under-Voltage Ride-Through conditions (UVRT) might be changed when WFC is active. As described in Section 5.6.4 a priorisation scheme is needed. A description shall be provided by the designer of the WFC verified by the WT manufacturer and provided to the certifier for assessment. The description shall show:

- What influence of WFC on FRT-behaviour of the WT can be expected in worst case (e.g., maximum direct active power decrease by WFC, maximum indirect active power decrease by intentional yaw misalignment, will reactive power be changed by WFC?)
- Will active power (in worst case) be further decreased during the UVRT?
- Will the WFC detect an UVRT? If yes: how will it react regarding active power control?
- General control concept of the WFC

5.7.4.2. Reactive power behaviour during normal operation

PQ-chart and UQ-charts shall be simulated again, if any of the functionalities of WF-FC or other additional functionalities within this report are changing the GCC Feature R5 per Section 5.2.2. The new simulated PQ- and UQ-chart shall be used in the grid code compliance assessment.

5.7.5. Other proof of evidence

5.7.5.1. Thermal and electric insulation design

It needs to be assessed if any of the functionalities of WF-FC are leading to additional thermal loads or if it is adding electrical stress on insulations. If such is the case, it has to be proven, that the GCC feature R1 and the corresponding design as described in Section 5.2.2 is not changed. If U/f/p/t-figures are changed, this has to be taken into consideration during the corresponding grid code compliance assessment. Corresponding proof of evidence shall be provided as design descriptions and manufacturer declarations.

5.7.6. Equipment Certificates (EqC) & other product certificates

Proving conformity with grid code requirements according to NC RfG [1] can be performed by an authorized certifier who issues a corresponding Equipment Certificate (EqC). The certification

process for Germany [27] and Spain [28] requests starting with the verification phase per Section 5.7.6.2 as all is defined very well in these certification procedures while other international Equipment Certification has to start with the Definition Phase described in the following Section 5.7.6.1 in order to define the scope applied in each certification performed.
For Grid Code Compliance the following phases apply in general, based on [29], other certification procedures as listed in Table 2 and Table 3 may differ slightly.

5.7.6.1. Definition phase

Prior to starting any evaluation by testing, assessment, or other means, defining the scope is essential. Such scope definition is called definition phase [29] and is similar to the design basis phase in structural integrity certification as described in Section 1.2.2.

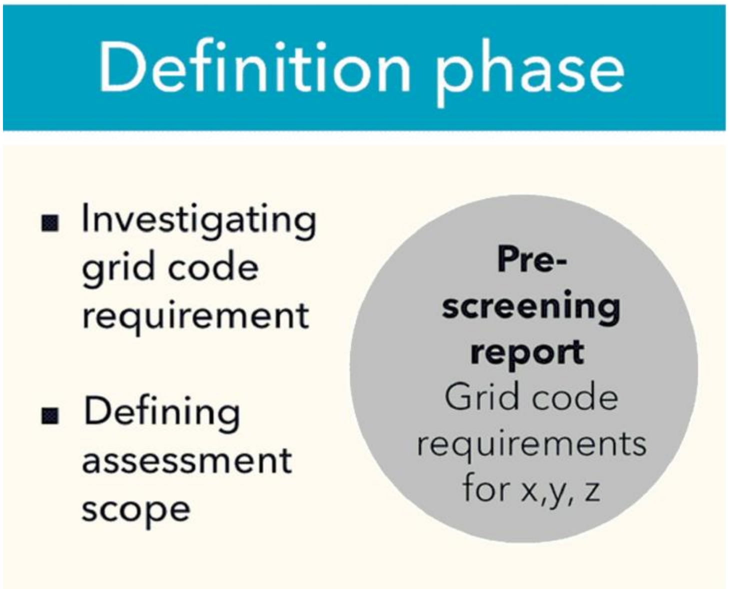

Figure 14 - Scope of definition phase

While the investigation and pre-screening is optional, defining the scope is mandatory for starting any certification.

5.7.6.2. Verification phase

Verification requires testing. Prior to the tests and measurements, a corresponding test plan per Section 6.4.1 is recommended. Tests will be performed by a test lab accredited for such according to ISO 17025. Evaluating the measurement results and validating the simulation models accuracy will be performed by the authorized certifier per NC RfG [1].

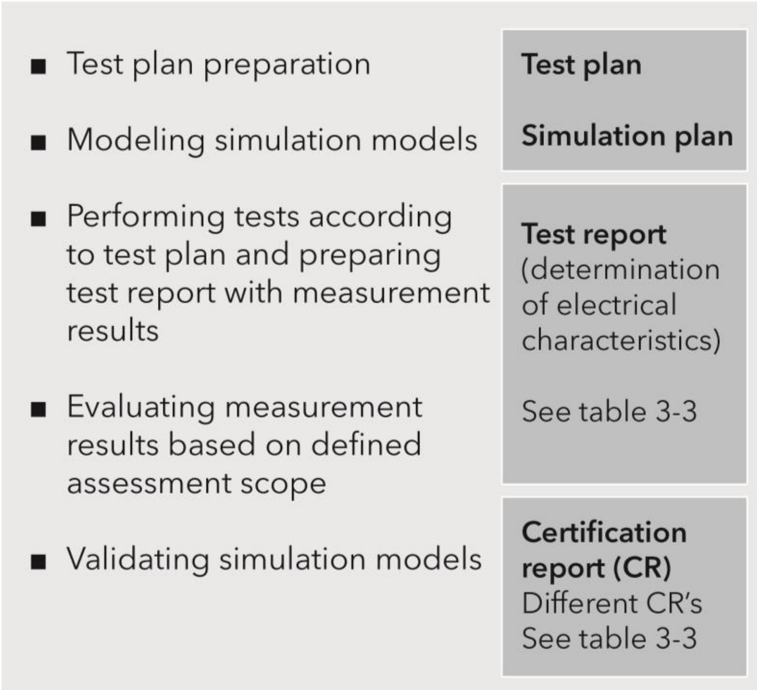

Figure 15 – Scope of validation phase, table references refer to [29]

5.7.6.3. CERTIFICATION PHASE

Following the verification phase the Certification will be performed by the authorized certifier per NC RfG [1].

Figure 16 – Scope of certification phase, table references refer to [29].

5.7.7. PROJECT CERTIFICATE REGARDING GCC

A project certificate (PC for GCC) is issued for a wind farm at a specific site having a specific grid connection point (PoC) with specific values and requirements.
To obtain a project certificate, all types of WTs installed in the wind farm shall have a valid type certificate per Section 5.7.6.
The project certificate states compliance of the wind farm according to the applicable grid code requirements. Depending on the corresponding grid code(s) or other requirements it will be assessed for the specific site given. Dynamic and static simulations shall prove compliance with requirements regarding all items as far as required by the grid code.
The following information will be shown on the project certificate:

- details about the type certificates of the WTs within the wind farm
- component certificates involved (if applicable)
- corresponding references, descriptions, requirements and / or grid code(s) will be listed on the certificate as well as other acknowledged standards and guidelines if applied
- Conditions under which the project certificate is valid will be stated in the related reports
- Project certificates are valid up to 10 years if sufficient regular inspections are performed on yearly intervals. After that a re-assessment of design changes shall be considered. The scope of re-assessments depends on the changes
- If no regular inspections have been performed the project certificate is valid 3 years. After that a re-assessment of design, implementation and settings should be performed.

5.7.8. COMPONENT CERTIFICATE REGARDING GCC

The component certificate for grid code compliance is described in Section 1.3.1.4 in detail. Further details about components and potential certification as a priori validation of each single component can be found in the reference [7].

WF-GC can be certified regarding its compliance with grid codes. As an example, in Germany the WF-GC is called PGS-control and can receive a corresponding component certificate [27] if the WF-GC is not part of the product certificate of the WT type. One application for such component certificates is the case where different types of WF-GC are used in the wind farm or different WT types are used within one wind farm.

6. Testing

The following sections 6.1 to 6.3 deal with required tests for Type Certification (structural integrity) according to certification schemes IECRE OD-501 [17] and DNV-SE-0441 [21]. These tests deal with *measurements of loads* and *power performance* as well as *safety and function tests / Test of Turbine Behaviour*.

WFC is designed for the application in wind farms. Onshore and offshore wind farms are covered by Project Certification according to certification schemes [23] and [24], while Type Certification according to certification schemes [17] and [21] considers a stand-alone wind turbine. It is not possible to include all effects of WFC in Type Certification – the downstream effects in a wind farm cannot be covered by measurements of a stand-alone wind turbine. However, it is desirable to consider as many certification aspects of WFC as possible already in the relevant certification modules / phases of the Type Certificate, so that the effects on the turbine are known as early as possible. Additionally, all issues which are already covered by the Type Certificate leave less work for each single Project Certificate and enable a straightforward process.

On the other hand, WFC might be developed after a Type Certificate has been issued. A wind farm might be equipped with a "WFC-upgraded" wind turbine. In this case, a Type Certificate not including WFC may be applied for the Project Certification applying WFC. Any remaining assessment of WFC (Design Basis, Design Evaluation) and all related Type Tests which appear outstanding from Type Certification need to be carried out during Project Certification in that case. If the WF-FC strategy of the Project Certificate differs significantly from the one tested in the Type Certification, then the Type Certification load measurements for the WF-FC-active wind turbines should need consideration also in the Project Certification.

Section 6.4 addresses tests required for certification of grid code compliance as per different certification schemes listed in Table 2 and Table 3 e.g., [29]. Most of those tests are to be performed at a single WT in the field as part of a product testing campaign with one of the first specimen of the production of a new type of a WT. Testing as part of project certification is not covering the heavy test equipment for UVRT-Testing and hence less effort is needed for GCC measurements on project level.

6.1. Load measurement and Load validation

The intention of load measurements and load validation within Type Testing is to validate the design loads of a wind turbine for a Type Certificate or a Project Certificate. The focus is on the validation of the simulation model of the specific turbine type and the simulated load assumptions in combination with the applied simulation tools. Measurements for a Type Certificate focus mainly on the validation of fatigue loads, but also on extreme loads to a limited extend (based on DLC1.2 and some transitional DLCs).

Apparently, the process proposed by current certification schemes for Type Certification requires measurements on a stand-alone wind turbine. The measurements performed shall be representative for the loads each wind turbine in a wind farm is expected to see. This is especially the case because any wind turbine in a wind farm is operating on the same "greedy" control operation mode, independently to the control of the other wind turbines.

Depending on the techniques of WFC applied to a wind farm a centralized logic will operate the single wind turbine to the benefit of the whole wind farm. The control behaviour of the single wind turbine is not depending anymore purely on individual external conditions the wind turbine experiences. To some extent it depends on how the centralized logic analyses and optimises the interaction of all wind turbines under all external conditions given. Thus, it is impossible to operate a stand-alone wind turbine in full "WFC mode" to perform load measurements for full WFC validation as if it was placed in a project specific wind farm environment.

Project Certification schemes do not require site-specific load measurements similar to those for Type Certification.

Instead, it is assumed that the necessary validation of WFC for the project setup has sufficiently been performed in a generic way in context to the validation of the wind farm simulation tools including wind farm and wake models used, see section 4.3.
This means that also the load influence of WF-FC on the WF-FC-passive turbines (mostly the downwind turbines) has been measured and validated, i.e. that wake propagation within the wind farm has been considered properly.

The following sections provide proposals for certification requirements regarding Type Testing.

6.1.1. Proposal for certification requirements

The certification schemes as listed in sections 1.2.2 and 1.2.4 include the certification module / phase "Type Testing". Load measurements under the influence of WFC should be carried out in accordance with latest version of IEC 61400-13 [12].

For any general details on requirements for load measurements and validation of the simulation model and the design loads, see e.g. DNVGL-ST-0437 [14] section 5.4.

6.1.1.1. Load Measurements for Type Certification considering WF-FC

To include WF-FC actions into a Type Certificate, load measurements under the influence of WF-FC need to be carried out. The load measurements are then applied for validation of the simulated model that was applied to calculate the design loads. For Type Certification (stand-alone wind turbine) the load effects of the WF-FC-active wind turbine should be investigated. WF-FC-active wind turbines are the wind turbines carrying out WF-FC-controller actions. In a wind farm this would be commonly the first row (upstream row) of wind turbines.

Power production load cases (MLC/DLC1.1) should be measured and analysed for both fatigue and relevant extreme loads, applying different turbulence intensity levels (see also 3.2.2.3 (6)).

Assumptions have to be made on how the wind turbine would behave in a setup representative for WF-FC, i.e. as if it was operated within a whole wind farm (see also 3.2.2.3 (2)). Naturally, measurements on a stand-alone wind turbine can only be performed representing a WF-FC-active wind turbine in first row position.

For the WF-FC technique "wake steering" assumptions should be made, e.g., on a distribution of yaw offset demand angles (see Figure 3) depending on wind speed (see also 3.2.2.3 (2)). For a representative selection of these yaw offset demand angles measurements shall be performed. For WF-FC technique "axial induction control" or other control modes with reduced rated power it might be possible to argue that those are covered by the control mode operating at nominal power. For WF-FC technique "wake mixing" assumptions on the operation as WF-FC active turbine can be made to include respective fatigue load cases as well (see also 3.2.2.3 (2)).

After completion of the measurements, a load validation need to be carried out. For the load calculation, the same simulation model applied for achieving the load assumption certified within the certification module / phase Design Evaluation should be applied, especially considering the WF-FC. If necessary, the model should be adopted to site conditions (e.g. tower & foundation design). With this model, measured load cases need to be simulated, considering the wind conditions – and if applicable wave conditions – as documented in the measurements. In the simulation, both fatigue and relevant extreme loads should be investigated. Special attention should be paid to WF-FC actions. It should be investigated whether the applied load simulation model and tools are capable of simulating loads under WF-FC actions correctly.

Guidance note

At least the Blade Element Method is known to have difficulties in modelling loads correctly under large yaw errors.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

6.1.1.2. LOAD MEASUREMENTS FOR PROJECT CERTIFICATION CONSIDERING WF-FC:

If it is deemed that validation of simulation tool and models considering the propagation of wakes through the wind farm and the effects on WF-FC passive turbines has been performed to a sufficient extent according to section 4.3, no further load measurements for validation are required. If it is concluded that further validation work is required in the context of Project Certification, one possible approach to follow is provided according to section 8.13 in [24].

For Project Certification (the realized wind farm) mainly the load effects of the WF-FC-passive wind turbine should be investigated. WF-FC-passive wind turbines are the wind turbines which do not carry out WF-FC-controller actions but are influenced by them. In a wind farm these would be commonly the downstream rows of wind turbines. If the WF-FC strategy of the Project Certificate differs significantly from the one tested in the Type Certification, then the Type Certification load measurements for the WF-FC-active wind turbines should be repeated in the Project Certification.

6.2. Power performance

6.2.1. PROPOSAL FOR CERTIFICATION REQUIREMENTS

Power performance under the influence of WFC should be carried out in accordance with latest version of IEC 61400-12-1 [98].

6.2.1.1. Power performance of wind turbines

According to certification scheme DNV-SE-0441 [21] the measurement of the power performance of a wind turbine is optional, while the power performance measurement according to certification scheme IECRE OD-501 [17] is mandatory.

WFC as a technology to operate a wind farm in an optimized way cannot be represented by and fully tested on a single wind turbine type. The impact of a specific WFC technique on the power performance of a first-row turbine could be measured, but for Type Certification it is rather recommended to retain the measurement of power performance to that of the 'greedy' control mode.

Impacts on the power performance of a downstream turbine could be measured in a setup of at least two turbines. Such measurements do not appear reasonable in the context of wind turbine Type Certification as this would be highly depending on the setup and siting.

For any general details on requirements for power curve measurements, see e.g. DNVGL-ST-0437 [14], section 5.3.

6.2.1.2. Power performance of wind farms

According to certification schemes DNV-SE-0190 [24] and IECRE OD-502 [19] the measurement of the power plant performance is optional. Measurements can be performed on a specific site and project. Thus, the impact of the selected WFC techniques on the power performance of individual wind turbines can be analysed as well as the overall performance of the whole power plant.
WFC responds to an extended envelope of external conditions. As a consequence, the measured power curve for a wind power plant operated under WFC will not only be a function of wind speed. It will also depend on the parameter wind direction and eventually other external conditions (turbulence intensity, requirement from grid connection, ...).

Thus, no changes in certification requirements for power performance measurement of wind farms are suggested here.

6.3. Safety and Function Tests / Test of Turbine Behaviour

6.3.1. General

During Type Certification WTs undergo testing "to verify that, under testing, the wind turbine displays the behaviour predicted in the design" (IECRE OD-501 [17] section 7.4.3). These tests are labelled *Safety and function tests* in IECRE OD-501 [17] and *Test of wind turbine behaviour* in DNV-SE-0441 [21].

As explained above we recommend designing and certifying WFC measures in two steps. Step 1 being integration of WFC measures in WT design and certification whereas Step 2 is the implementation of WFC measures in wind farm design and certification. See "Two step approach" section 3.1 Table 19.

Following this two-step-approach WFC measures should be incorporated in the *Safety and Function Tests / Test of Turbine Behaviour*.

6.3.2. PROPOSAL FOR CERTIFICATION REQUIREMENTS

Technical requirements to *Safety and Function Tests / Test of Turbine Behaviour* are part of **DNV-ST-0438** [13] and **IECRE OD-501-5** [19]. Suggestions for additions of WFC measures to these standards are given above in section 3.2.2.3, see item (5) f) as well as section 3.2.3.3.

In this regard we do not suggest any changes to the certification schemes **IECRE OD-501** [17] and **DNV-SE-0441** [21].

6.4. Grid Code Compliance

Test and measurement shall always be performed per test plan, see Section 6.4.1. Testing per Section 6.4.2 is mandatory for any WT and any WFC, unless the grid code in question does not require fault ride-through capabilities. For most site-specific demonstrations as e.g. for project certification or declaration of conformity per [27], the measurements per Section 6.4.2.2 and 6.4.3 apply.

6.4.1. GCC TEST PLAN

Generally, for grid code compliance typical national product testing specifications do exist and shall be used where applicable, see [36], [28] and [91] the European specification as drafted in [99] and IEC has another testing specification [13] which mainly is aligned with the German one**.** An overview is shown in Table 25. However, testing for GCC should be designed based on standards but tailored to the need regarding the relevant markets (which grid codes to be applied). For a test plan on fault ride-through helping hints in Section 3.2.2 of [29] can be used.

In those cases where a product certificate for GCC is existing already without WFC, GCC testing will need to be repeated with worst case scenarios as described in Section 5.7 or to be repeated completely while WFC is active.

For the certification of a WFC as component certificate Section 5.7.8 applies.

For of a wind farm site-specific project certification for GCC specific testing as indicated in the corresponding product certificate of the WT types used (Equipment Certificate, Unit Certificate or Type Certificate for GCC) shall be followed or further detailed based on the grid code to be applied at the PoC. Existing Grid Code Compliance component certificates for the WFC can be used.

Table 25 – State of the art GCC testing standards

Country	Title	Reference
Germany	Technical Guidelines for power-generating units, modules as well as storage and for their components Part 3 (TR3)	[36]
Spain	Technical conformity supervision standard per EU Regulation 2016/631 for power-generating modules (NTS 2.1)	[28]
Italy	Technical Guideline, Annex 18	[91]
EU	Draft of EN 50549-10, Requirements for generating plants to be connected in parallel with distribution networks – Part 10: Tests demonstrating compliance of units	[99]
World	IEC 61400-21-1:2019 Wind energy generation systems - Measurement and assessment of electrical characteristics – Wind turbines	[13]

6.4.2. Product-Specific GCC-testing

6.4.2.1. Fault Ride-through testing

FRT testing shall be repeated with the maximum possible yaw offset demand which can be set by the WFC in combination with the WT in question, assuming that FRT testing has already been performed without the measures of TotalControl being implemented in the WT. Also different operation conditions as identified in relation to Section 2.2.3.1 shall be covered by tests with running WFC. Alternatively, simulations can be performed instead of performing FRT testing, showing that yaw offset demand does not lead to unacceptable loads. This can be performed by using state of the art load calculation tools. Additionally, it shall be shown that grid code requirements of FRT are fulfilled even with such yaw offset demand. Those simulations shall be performed with a simulation model validated against test results per Spanish NTS 2.1 [28] or per German FGW TG8 [27] combined with TG4 [35].
If no FRT testing has been performed before all the testing shall be performed having the WFC running, controlling the WT also during the FRT testing in order to verify the priorities per above Sections 5.6.1, 0 and 0. Alternative simulations are not acceptable in this case. Typical additional test cases shall be developed during the test plan preparation according to Section 6.4.1. At minimum the following case shall be tested with at least 2 representative voltage dips:
During an activity of the WF-FC reducing the active power of the WT under test the voltage dips shall be performed with the test equipment. The case shall show that FRT-capability is fulfilling all requirements of the grid code, even while the active power of the WT has been reduced by the WF-FC to the maximum possible extent. Typical GCC features for this are listed in Section 5.2.3 as D12 through D14G.

6.4.2.2. Controllability and Power Quality measurements

PQ-chart and UQ-charts shall be measured again, if any of the functionalities of WF-FC or other additional functionalities within this report are changing the GCC Feature R5 per Section 5.2.2. The new measured PQ- and UQ-chart shall be used in the grid code compliance assessment. Typical

WFC activities with impact on active and reactive power shall be initiated during measurements to show worst case impact and principle of functioning.
The following tests apply additionally:

1. It shall be verified by testing and measurement, if the ramp rates of active power, corresponding response times, settling times, rise times and reaction times as defined per IEC 61400-21-1 [13] are still fulfilling the corresponding grid codes while WFC is active and all measures per TotalControl are activated. In the same way shall be tested and measured the ramp-down time and the recovery time.
2. It shall be verified by measurement and testing, if the signal "available active power" is showing the correct value even during active power reductions initiated by the WF-FC. The test program suggested by the manufacturer as described in Section 5.7.2 shall be performed after it has been successfully assessed by the certifier.

6.4.3. SITE-SPECIFIC GCC-TESTING

Following to field commissioning of the wind farm (or together with it) it shall be shown that the as-built status of the wind farm is fully covered by the project certificate, plausibility tests show similar behaviour and all conditions listed in the project certificate are fulfilled (some of them will be testing requirements and parameter settings, which can be checked together with performing site-specific measurements). This site-specific testing is mandatory prior to conformity declaration in Germany as detailed in Section 1.3.2.5.

1. It shall be verified if LFSM-O per Section 5.6.1 is working properly while WF-FC is active. This shall be done by injecting a simulated frequency signal instead of the measurement signal or by adding an off-set signal on top of the measurement signal of the system frequency f.
2. It shall be verified by measurement and testing, if the signal "available active power" is showing the correct value even during active power reductions initiated by the WF-FC.

7. CONCLUSIONS

The task of the present TotalControl deliverable D4.7 was to analyse existing service specifications and standards for their application on the certification of wind farm control (WFC) and to identify existing gaps in the procedure for this new technology.
For this task the main topics were the control and protection system of the wind turbine, the way how to calculate loads and the compliance of a wind turbine and farm regarding existing grid codes. In case gaps were discovered the report proposes additional requirements to supplement existing standards.
The work is summarized and consequential conclusions are given in the following:

Control and Protection System

Qualitative risk analysis, FMECA
An FMECA (Failure Mode, Effects and Criticality Analysis) was performed per IEC 60812. This FMECA focuses on the WFC features. It is done as a high level FMECA on main component/system level.
One main outcome from the FMECA is the identification of risks from WFC listing potential risks for a wind farm project. Another main outcome is the conclusion, that risks to WTs and wind farms introduced by WFC features can be handled well by counter measures, applied in state-of-the-art WT and wind farm design. Furthermore, existing systems are well prepared for the monitoring and processing of operational data supplemented by WFC.

WT control system
WFC makes use of the wind turbine (WT) control system, the wind farm communication system and the wind farm control system. For both the WT control system and the wind farm control system recommendations are given how standards can be further developed to incorporate WFC measures.
It is suggested to incorporate WFC capabilities into the WT design already during Type Certification in order to ensures the readiness of WT design for WFC (make it "WFC-fit"). For this, this deliverable suggests amendments of technical standards for WT design as well as related certification schemes. These should require definitions of WFC related turbine actions, load cases, possible failures, testing and requirements on the Control and Protection system.
The control and protection system shall ensure that the WT is protected against any failures in control procedures introduced by WFC. This includes that the individual WT shall be able to return to its own control functions in case of any sensor or communication failures from outside the WT.
For wind farm communication in general no further requirements are suggested.
It is suggested to incorporate requirements on WFC into related certification schemes. These should require definitions on WFC actions, assets affected, possible failures, failure detection, commissioning procedures, testing and requirments on the Control system.

Design Loads

Wake models
The present report discusses available wake models for their suitability to calculate loads for wind turbines applying WFC. It is concluded that Frandsen's wake model provided by IEC61400-1 Ed.3 is insufficient. For WFC the dynamic wake meandering (DWM) model according to IEC61400-1 Ed. 4 should be the minimum requirement to capture the main effects of wake propagation through the wind farm, as well as the associated loads on the wind turbines. Furthermore, fatigue and ultimate loads can be analysed in a more consistent way for the wind turbines in the wind farm.
Though, DWM according to IEC61400-1 Ed.4 does not describe wake effects under large yaw misalignment sufficiently. A further limitation is seen in the fact that the DWM model is only assuming neutral atmospheric stratification. Although certification does not yet consider any aspects of atmospheric stability, not even in Project Certification, this is expected for the future. As a matter of fact, no reasonable approach to consider atmospheric stability was yet proposed by research which could be incorporated into certification.

Load calculation methodologies
Under WFC, a large variety of load situations might occur. They are created by the possible combinations of different control approaches and states the wind turbine may experience, regarding yaw, pitch angle, power and wake conditions. As a consequence, much higher efforts for load simulation are necessary to cover all these cases, compared to the efforts required when applying standard wind farm design with Frandsen's simple wake model.
A feasibible solution is seen in the application of less time-consuming simulation using surrogate models. This report discusses different tools currently under development. The solutions provided are promising, but further development and proper validation is required. The integration of such tools into common practices would be a significant evolutionary step in wind turbine and wind farm design which naturally impacts certification.

Presently, no integrated load simulation tool exists, including all relevant models for large yaw errors and wake propagation is available which reliably calculates fatigue and ultimate wind turbine loads for any location in a wind farm. Consequently, several case specific solutions with different tools need to be chosen to achieve representative load sets for WFC. In some cases, this might mean a compromise, where a specific simulation tool is considered the best under the non-perfect solutions available. Besides upcoming surrogate models for wind farm load calculation, the standard tools applying the blade element method (BEM) might be a good choice for the analysis of wind turbines in the first row of a wind farm. If the tool allows analysis of DWM, it might even be applied for a second-row turbine in the wake of another one.
To consider more complex cases with wake phenomena under large yaw misalignment or turbines in multi-wake position, CFD or even LES tools might be an option.

Validation
As a prerequisite to the application of any new wake models and wind farm simulation tools, an appropriate validation is required for certification. This report proposes a validation process requiring a comparison to measurements. In those cases where measurements are unavailable for validation, code-against-code validation may serve as a replacement. For selected cases new codes may be compared to either standard BEM tools or against code of higher fidelity (CFD/LES).

Less efforts on the validation of a surrogate tool is required, in case the tool is only applied in a relative approach to determine the most loaded turbine.

Design load cases

The IEC61400-1 Ed.4 load case table was analysed for application of WFC. It is noted that the design load case catalogue only considers wake effects in a generic way. The present report tries to close this gap. For the WF-FC example cases "wake steering", which is expected to be the most relevant to apply, a methodology for design load case definition is proposed.
WFC may increase the efforts for load calculation to a large extent. All standard DLCs have to be calculated with and without WFC, as WFC may be inactive during relevant periods of lifetime. This applies also for the extrapolation and fatigue load cases DLC1.1/DLC1.2. Though, this report proposes some assumptions for simplification that might reduce the number of load cases required. Furthermore, sensitivity studies may be performed to show that certain subsets of a load case are of no relevance and may be omitted for further consideration.

Depending on the operating strategy many possible combinations may occur. The report provides guideline which design load cases should be considered for fatigue respectively extreme load analysis. Knowing that wind farm operation is not possible for a single wind turbine, orientation is given which load cases should be analysed already for Type Certification, while other wind farm related load cases and specific site conditions are proposed to be first checked during Project Certification. The opportunities in the optimisation of a wind farm, provided by WFC are accompanied by an extended complexity of the system, requiring a more thorough verification. In this context, Type Certification provides the initial basis for the verification for a wind farm controlled project. However, it must be expected that efforts on the analysis of the site-specific conditions and specific WFC design will need to be performed during Project Certification.

The sketched efforts necessary to thoroughly analyse a wind farm seem to disenchant the opportunities of WFC to some extent. The tasks for tool development and validation as well as running the design load cases may appear numerous. Anyway, it can be expected that the first wind farms will feature rather simple techniques of WFC. Wind turbine industry is expected to develop the first WFC projects in incremental steps. Starting with more simple approaches, it will gather experience in simulation, in onsite tests and as well in the certification of the projects.

Grid Code Compliance

By introducing WFC with its various functionalities the active power of single WTs and also of the full wind farm is changed compared to state of the art technology. Also the yaw angle of single WTs will be changed by applying WFC compared to yaw angles aligned fully with the wind. Regarding compliance with grid code requirements this has an effect which cannot be neglected. Corresponding conclusions are given below.

Calculation of available power

For several GCC features the value of available power from the wind is needed for calculating the required set-points. When WFC is actively reducing the active power in some cases, this needs to be considdered in the calculation principles in the corresponding control. This calculation principle needs to be adapted when WFC is implemented.

Priority implementation
Grid code requirements are top priority as usually the grid access is only granted while all grid code requirements are fulfilled. In order to ensure this even with WFC being active, this means a priority management shall be active and working properly regarding the relevant GCC features as listed in Table 24. This is explained further in Section 5.6.

Grid code compliance assessment
Depending on grid code and scope different GCC features apply. Relevant GCC features need to be re-assessed regarding the impact WFC will have on them in each individual case. Details are given in Section 5.7.2.

Validation
Simulation models for simulating the electrical behaviour of wind farms regarding grid code compliance at the PoC of a specific site usually are part of product certificates. Typical product certificates for grid code compliance are described in Sections 5.7.6 and 1.3.2. As the electrical behaviour during UVRT may change due to the impact of WFC, simulation model validation based on measurement results shall be repeated with WFC. Details are given in Section 5.7.4.

WT field testing
UVRT testing shall be performed with maximum yaw angle misalignment the WFC can set. WFC activities during UVRT shall be tested. Relevant parts of power quality measurements. Details see Section 6.4.2

Prospects

The basic processes to perform certification of wind farms applying WFC are already implemented in existing service specifications, see [21] and [24] – they are similar to the certification of wind farms without WFC. Thus, certification of wind farms applying WFC can be performed already today with guidance regarding WFC specific details provided by this report. This allows both, Type and Project Certification of wind turbines and wind farms regarding their structural integrity or grid code compliance.
The results of TotalControl task D4.7 are intended to contribute to the further launch of WFC to the market. DNV aims to contribute to further development of the WFC topic in international wind energy standards as well as to provide own service specifications and standards.
One mayor challenge identified is that load calculation models and tools required for WFC need to be validated sufficiently for certification purposes. If this cannot be achieved in the required time frame, DNV provides a shortcut to achieve a site-specific design assessment (SSDA) for an actual project: Instead of performing substantial validation activities in advance, onsite load and performance measurements can be performed in the delivered project applying DNV’s service specification for Project Certification DNV-SE-0190.
First wind farms to apply WFC may be existing wind farms retrofitted with new control features. Furthermore, WT OEM’s may try to sell new wind farms with new WFC features. In both cases, the first WFC features to be applied are expected to consist of ‘wake steering’ in open loop control. For both cases, the present report provides the path for certification.

Operators of wind farms, especially of older ones, will aim to improve the performance of their assets with WFC. This is recommended to be performed in co-operation with the OEM of the wind farm's turbines, because it enables the beneficial access to original design documentation including loads, control and protection system and allows best harvest of reserves in the design and straightforward integration of new control features.

WFC is providing large potential for optimisation of a wind farm in terms of loads and power performance as well as operation. The development is just starting up, scratching at the edges of what is possible. Currently the 'low hanging fruits' are seen in the WFC feature 'wake steering' eventually combined with 'induction control'. But with increasing possibilities for more detailed simulation of the flow through the wind farm, more complex control scenarios may be realized where even higher performance gains are expected.

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