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Deliverable *3.2*
VVT and Certification Plan

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Versioning and contribution history

Version	Description	Contributions
0.1	General outline of Deliverable 3.2	Karin Eustorgi (Fraunhofer IWES), Gesa Quistorf (Fraunhofer IWES)

Reviewer

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List of Abbreviations

LCoE	Levelized Cost of Energy
VVT	Verification, Validation, Testing
DFMA	Design Failure Mode Analysis
HALT	Highly Accelerated Life Test
FPQ	First Piece Qualification
RoCoF	Rate of Change of Frequency
EMT	Electro Magnetic Transients
HiL-Testing	Hardware-in-the-Loop Testing
DyNaLab	Dynamic Nacelle Testing Laboratory (at IWES)
DUT	Device under Test
PCC	Point of Common Coupling
CV	Component Validation
IV	Integration Validation
SV	System Validation
PT	Prototype Validation

Executive Summary

Within WP3, IWES and GE, with the advisory of DNV, TNO and Ingeteam, established a process for risk assessment and risk mitigation through validation. This process has then been executed by IWES and GE for the most critical components of the new turbine. As a result, the partners of WP3 recommend reasonable validation activities that make the turbine reliable while contributing to lower LCoE.

IWES proposes and develops, in close cooperation with GE, a component-based approach to parts of the certification process that will be conducted in parallel to the development of the turbine, making the process modular, more flexible and faster while contributing to lower LCoE.

1. Introduction

1.1. Objectives of Deliverable 3.2

The objective of this deliverable is to present the overall roadmap for validation and certification of the newly developed turbine. This document describes the process of defining the validation activities suggested by the team of WP3. Furthermore, a focus of this document is on a new and innovative approach for certification in parallel to the development process of the turbine that has potential to gain an appreciable amount of costs and time, lowering therefor the LCoE. All these activities will make validation and certification more modular, suitable for future variants of the turbine and assure validation and certification at the earliest stage possible, thereby decreasing the risk of the new development.

Due to reasons of confidentiality, the roadmap itself cannot be presented in this public deliverable, at this stage of the turbine development. Details regarding the planned activities for validation and certification as well as the failure modes addressed by them are very sensitive information and are therefore not part of this document.

1.2. Content of Deliverable 3.2

Chapter 2 describes the process of defining recommended validation activities.
Chapter 3 describes different possibilities for grid compliance testing, focussing on a highly innovative solution.

2. Risk Mitigation through Validation

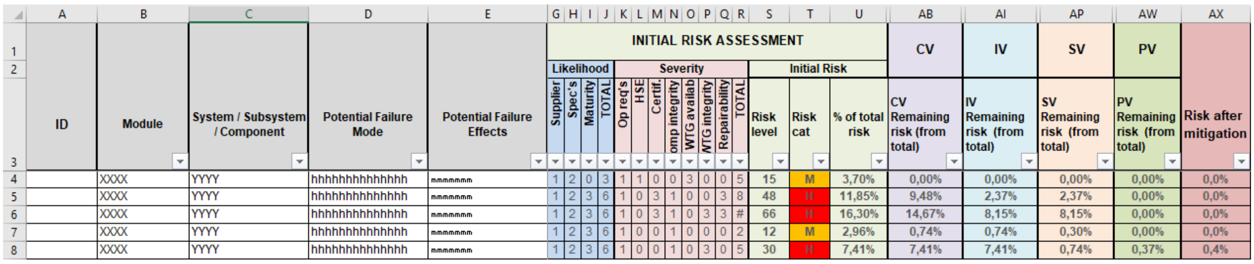
The partners involved in WP3 had selected 10 components and subsystems to be analysed for validation and certification within ReaLCoE. The methodology for this process is described in the Deliverable 3.1. There the procedure for risk assessment workshops is specified and the requirement verification matrix is defined.

Within Task 3.2 “Set-up of a verification, validation, testing (VVT) and certification plan” this previously defined process has been executed for the most critical of the 10 selected components. They have been selected for their highest need for validation and most effort for certification. For organisational reasons, the execution of this analysis for the rest of the 10 components is shifted to Task 3.3 “Definition, supervision and execution of components tests” as part of the development of the test specifications.

As explained in the introduction, it is not possible to present the results of this process in this public deliverable as it involves very sensitive information that at this moment is subject to confidentiality. The following sections explain in detail the process of defining the recommended validation tasks and the advantages of this approach.

2.1. Description of Process for Risk Mitigation

As described in Deliverable 3.1 the table for the “requirement verification matrix”, shown in Figure 1, serves as the basis for the risk assessment workshops. Its content and how it serves as a very powerful tool in the process, is described in the following.

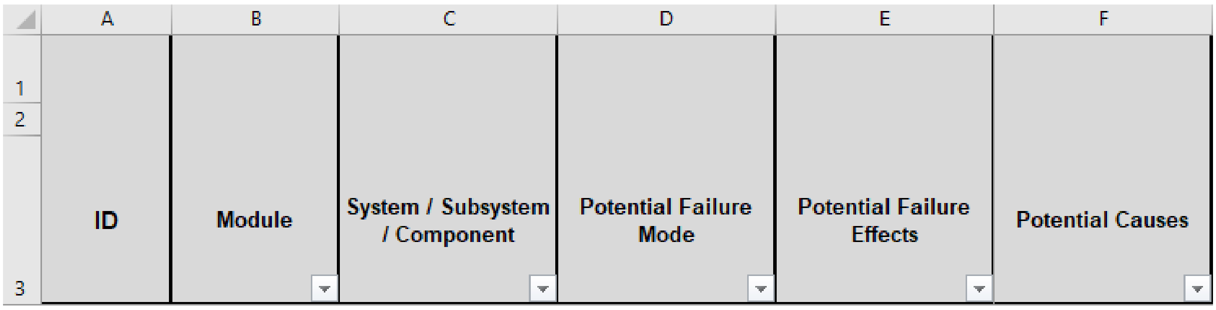


	A	B	C	D	E	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	AB	AI	AP	AW	AX
1	ID	Module	System / Subsystem / Component	Potential Failure Mode	Potential Failure Effects	INITIAL RISK ASSESSMENT															CV	IV	SV	PV	Risk after mitigation
2						Likelihood				Severity								Initial Risk							
3						Supplier	Spec's	Maturity	TOTAL	Op req's	HSE	Certif.	omp integrity	WTG availab	WTG integrity	Repairability	TOTAL	Risk level	Risk cat	% of total risk	CV Remaining risk (from total)	IV Remaining risk (from total)	SV Remaining risk (from total)	PV Remaining risk (from total)	
4		XXXX	YYYY	hhhhhhhhhhhhhh	mmmmmmm	1	2	0	3	1	1	0	0	3	0	0	5	15	M	3,70%	0,00%	0,00%	0,00%	0,00%	0,0%
5		XXXX	YYYY	hhhhhhhhhhhhhh	mmmmmmm	1	2	3	6	1	0	3	1	0	0	3	8	48	H	11,85%	9,48%	2,37%	2,37%	0,00%	0,0%
6		XXXX	YYYY	hhhhhhhhhhhhhh	mmmmmmm	1	2	3	6	1	0	3	1	0	3	3	#	66	H	16,30%	14,67%	8,15%	8,15%	0,00%	0,0%
7		XXXX	YYYY	hhhhhhhhhhhhhh	mmmmmmm	1	2	3	6	1	0	0	1	0	0	0	2	12	M	2,96%	0,74%	0,74%	0,30%	0,00%	0,0%
8		XXXX	YYYY	hhhhhhhhhhhhhh	mmmmmmm	1	2	3	6	1	0	0	1	0	3	0	5	30	H	7,41%	7,41%	7,41%	0,74%	0,37%	0,4%

Figure 1: Requirement verification matrix (entries partially made unrecognizable)

2.1.1. Failure Mode Analysis

The investigation for every component or subsystem starts with a failure mode analysis using the very left section of the requirement verification matrix, see Figure 2. Afterwards a risk assessment is carried out and necessary validation activities for risk mitigation are defined.
As an input to this process, the results of the design failure mode analysis (DFMA) are required and the thereby identified most critical failure modes are imported into the requirement matrix (column D). They are assigned to systems, subsystems, components or interfaces (column C). The corresponding module and the GE-internal ID are listed (column A, B). Potential failure effects and causes are specified (column E, F) for a quick understanding of the failure mode.



	A	B	C	D	E	F
1	ID	Module	System / Subsystem / Component	Potential Failure Mode	Potential Failure Effects	Potential Causes
2						
3						

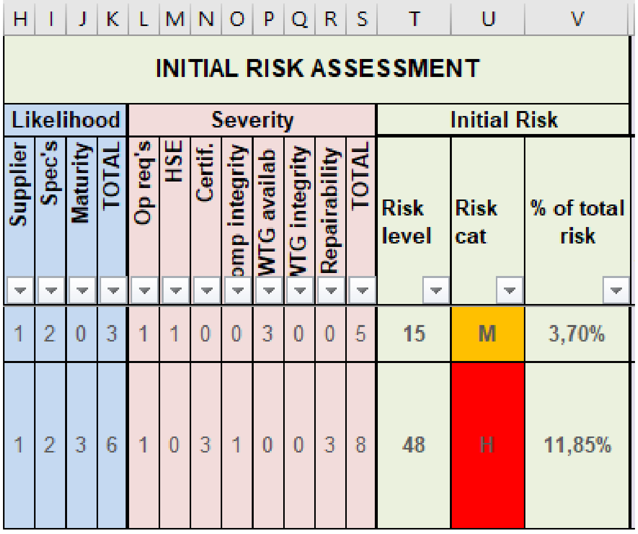
Figure 2: Columns for failure mode analysis

2.1.2. Initial Risk Assessment

The initial risk for each failure mode is defined by rating likelihood and severity in the requirement matrix, see Figure 3. The rating of the likelihood that a failure occurs is based on the three categories collaboration with supplier, experience with specifications and product maturity. The rating is summarized in Table 1 based on the following questions:
Does an established business relation with the supplier already exist (0) or not yet (1)? Are the specifications known from past projects (0) or are they new (2)? Is the potential failure affecting a mature product or a new development?

The rating of the severity of a failure is summarized in Table 2 and based on the assumption of which aspects of the turbine would be affected. The level of the weighting reflects the scope of the impact of a failure.

In the requirement verification matrix, the initial risk for each failure mode is recorded (columns T - V). For this purpose, the risk level, defined as likelihood x severity, is determined (column T) and the associated risk category is specified (column U), as it is defined in Table 3. The values in this table are based on long-time experience of the turbine manufacturer. In a next step, the share of the failure on the total default risk in % is calculated (column V). The sum of the initial risks in column V is defined to be 100%. The aim of the validation activities is to mitigate this risk for each failure mode to occur to 0%.



H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
INITIAL RISK ASSESSMENT														
Likelihood				**Severity**								**Initial Risk**		
Supplier	**Spec's**	**Maturity**	**TOTAL**	**Op req's**	**HSE**	**Certif.**	**omp integrity**	**WTG availab**	**VTG integrity**	**Repairability**	**TOTAL**	**Risk level**	**Risk cat**	**% of total risk**
1	2	0	3	1	1	0	0	3	0	0	5	15	M	3,70%
1	2	3	6	1	0	3	1	0	0	3	8	48	H	11,85%

Figure 3: Initial risk assessment with example entries

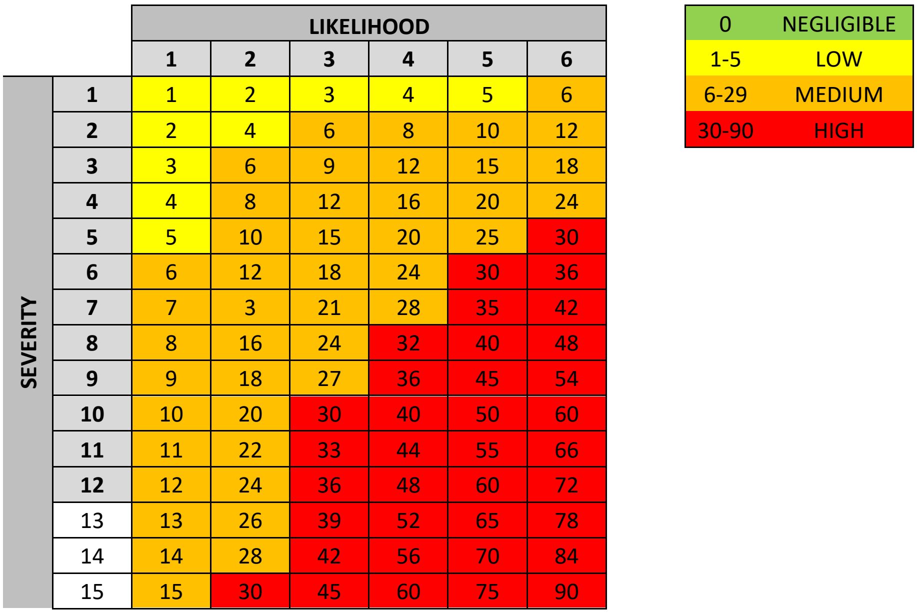
Table 1: Aspects and rating of likelihood

LIKELIHOOD		
Description	**Weight**	**Rating**
Maturity	3	0=mature product/specification - 3=unmature
Specifications	2	0=known specification - 2=new specification
Supplier	1	0=known supplier - 1=new supplier

Table 2: Aspects and rating of severity

SEVERITY		
Effects on	**Weight**	**Rating**
Key performance & operational requirements	1	0=no affectation - 1=affectation
HSE	1	0=no affectation - 1=affectation
Certification	3	0=no affectation - 3=affectation
Component integrity	1	0=no affectation - 1=affectation
Turbine availability	3	0=no affectation - 3=affectation
Turbine integrity	3	0=no affectation - 3=affectation
Repairability	3	0=no affectation - 3=affectation

Table 3: Risk categories depending on risk level, based on long-time experience of the turbine manufacturer



		LIKELIHOOD					
		1	**2**	**3**	**4**	**5**	**6**
SEVERITY	**1**	1	2	3	4	5	6
	2	2	4	6	8	10	12
	3	3	6	9	12	15	18
	4	4	8	12	16	20	24
	5	5	10	15	20	25	30
	6	6	12	18	24	30	36
	7	7	3	21	28	35	42
	8	8	16	24	32	40	48
	9	9	18	27	36	45	54
	10	10	20	30	40	50	60
	11	11	22	33	44	55	66
	12	12	24	36	48	60	72
	13	13	26	39	52	65	78
	14	14	28	42	56	70	84
	15	15	30	45	60	75	90

0	NEGLIGIBLE
1-5	LOW
6-29	MEDIUM
30-90	HIGH

2.1.3. Risk Mitigation

To mitigate this risk, suitable validation measures are defined in the next step. As already described in D 3.1, the validation process is divided in the following four phases that can be executed in parallel:

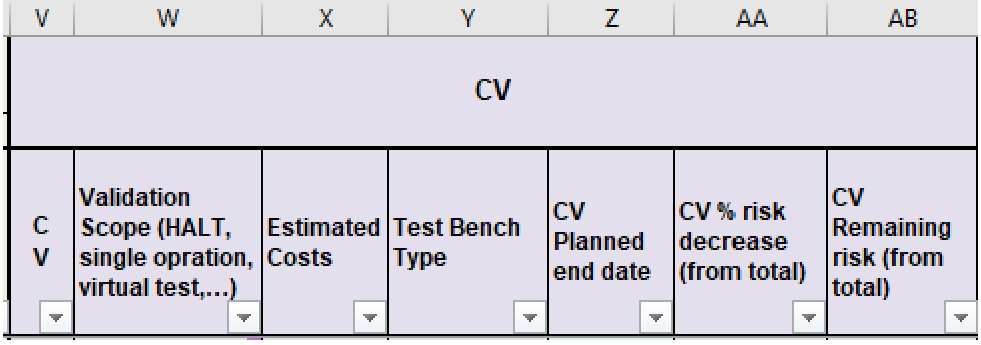
Component validation: These tests are happening at supplier's facilities or laboratories with single mechanical or electrical components, such as gearboxes, drives, generator elements (magnets, coils, pole shoes), etc. The tests at this phase are not only first qualification of pieces, but also functional and HALT.

Integration validation: These tests happen at the GE manufacturing facilities. They consist of checking the manufacturability of the parts, making sure everything is fitting with each other. Additionally, some functional tests can happen, such as heat runs for the generator, cooling performance, etc.

System validation: These tests are happening at different laboratories with specific systems of the WT. These are blades test bench, pitch bearing and main bearing test benches, grid test bench, etc.

Prototype validation: Test happening on a field WT. These includes the type certificate testing (power curve, loads, safety and function) and performance (pitch, yaw, cooling systems, control strategies, etc.).

For each failure mode it is decided in which validation phases which risk mitigation activities are recommended. And each of these activities is defined in more detail, see Figure 4 for the corresponding columns of the requirement matrix.

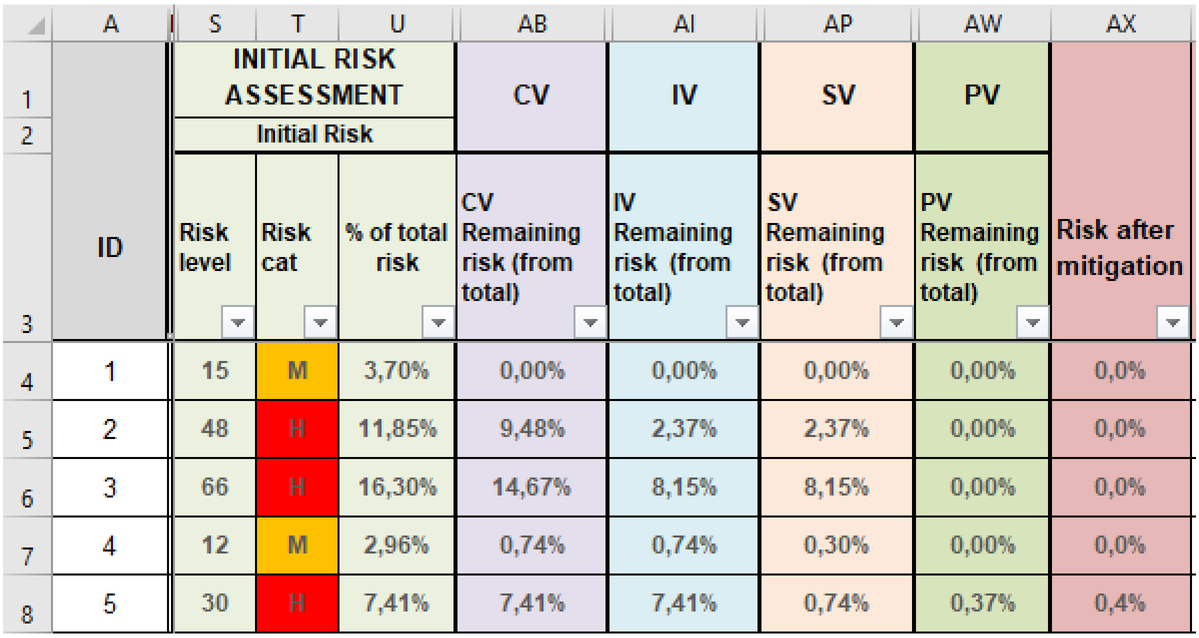


V	W	X	Y	Z	AA	AB
CV						
C V	Validation Scope (HALT, single opration, virtual test,...)	Estimated Costs	Test Bench Type	CV Planned end date	CV % risk decrease (from total)	CV Remaining risk (from total)

Figure 4: Definition of validation task within the component validation phase

The type of the validation activity needs to be defined in column W (for CV phase), i.e. FPQ, HALT, function test, operational tests or virtual tests. The estimated costs for each validation step are noted as well as possible test bench types and the planned end dates for the activity (column X – Z for CV phase). This information is used for the decision making, whether a listed activity will really be implemented and included into the validation roadmap or if the risk will be mitigated later at a different validation phase. Finally, it is specified, how much the activity within the validation phase decreases the original risk of the failure mode (column AA for CV phase) and the remaining risk after the validation phase is calculated (column AB for CV phase). This process is then repeated for IV, SV and PV.

Figure 5 shows five examples for the risk mitigation throughout all four phases. The risk for the failure mode with ID 1 can be fully mitigated with validation on component level, while most of the failure modes need to be addressed in all 4 phases, sometimes even with a remaining risk after validation, in this example that’s the case for ID 5.



	A	S	T	U	AB	AI	AP	AW	AX
1	ID	INITIAL RISK ASSESSMENT			CV	IV	SV	PV	Risk after mitigation
2		Initial Risk							
3		Risk level	Risk cat	% of total risk	CV Remaining risk (from total)	IV Remaining risk (from total)	SV Remaining risk (from total)	PV Remaining risk (from total)	
4	1	15	M	3,70%	0,00%	0,00%	0,00%	0,00%	0,0%
5	2	48	H	11,85%	9,48%	2,37%	2,37%	0,00%	0,0%
6	3	66	H	16,30%	14,67%	8,15%	8,15%	0,00%	0,0%
7	4	12	M	2,96%	0,74%	0,74%	0,30%	0,00%	0,0%
8	5	30	H	7,41%	7,41%	7,41%	0,74%	0,37%	0,4%

Figure 5: Risk mitigation over the 4 validation phases and remaining risk after mitigation shown for 5 exemplary failure modes (ID 1-5)

The content of the requirement matrix is a very valuable tool for the development of the test specification within Task 3.3 as it analyses the main failure modes and its weighting to be addressed in the tests. This is likewise helpful when dealing with variants of the turbine in the future as the matrix only need to be adapted to the new requirements.

With the completed requirement verification matrix, we present GE the recommendations from ReaLCoE for validation including costs and a rough timeline. For most components, several possibilities exist for validation. For example, many failure modes can be addressed during integration validation as well as with prototype validation. A trade-off between having the test results at an earlier stage in parallel to the development process with the costs of these tests is needed. With the content of the requirement verification matrix, possible variants can be visualized to support decision making, highlighting the advantages of validation in parallel to the development of the turbine. An example is shown in Figure 6.
The requirement verification matrix gives a well-founded bases for decision making that leads to an optimized validation process, making the turbine reliable while lowering LCoE.

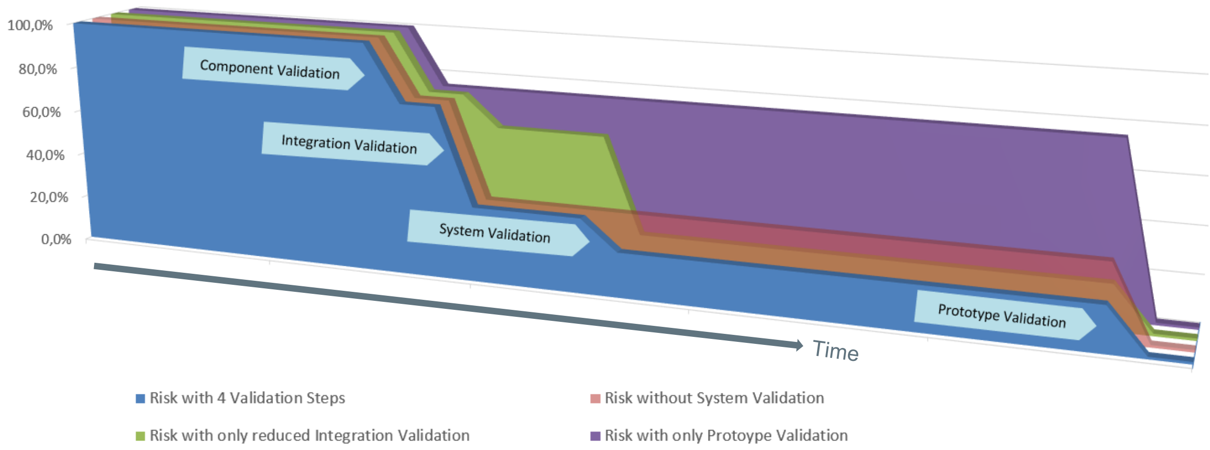


Figure 6: Exemplary visualization of risk mitigation over time for different validation possibilities

3. Innovative Approaches for Grid Compliance Testing of the Turbine

Within WP3 the partner identified the certification of the electrical characteristics regarding grid compliance testing as a cost expensive and time-consuming bottleneck that is generally only done at the prototype in field at the very end of the development process for a new turbine. Furthermore, the tests in the field are not reproducible and testing at the end of product development is contrary to the development process according to the V-Model. For this reason, nacelle test benches and subsystem test benches for testing the electrical drive train were developed to perform the field tests in laboratory environments. The reproducibility of the field tests on these test benches according to standards such as IEC 61400-21-1 and FGW TR3 have been demonstrated in research projects (CertBench, Hil-GridCoP). Due to the power increase of new wind turbines, the current nacelle test benches are reaching their power and torque limits. Furthermore, wind turbine manufacturers need to release a valid electrical model of the turbine to their customers as early as possible in the turbine development process. The background is that these models are required for the electrical planning of (offshore) wind parks and (offshore) grids by park planners and grid operators. Another challenge is the large number of country-specific grid codes and new requirements on the electrical properties of the turbine, which cannot be tested in the field with conventional field tests and test equipment. A very promising solution for the challenges regarding grid compliance testing is the component-based unit certification, described in Section 3.1.

3.1. Component based Unit Certification

3.1.1. Motivation

The general purpose of grid integration testing is the evaluation of the turbine performance and the generation of measurement data for model validation. In the near future, new challenges will be the need for validated models available already during the development phase of the turbine and advanced grid integration requirements (e.g. Rate of Change of Frequency (RoCoF), grid forming control, phase jumps). At the same time, the performance limits of the existing nacelle test benches are exceeded by the performance of the new turbine generations.

3.1.2. Concept

An answer to these challenges is a component-based validation process developed by Gesa Quistorf at Fraunhofer IWES, according to the general 3-leg V-model, see Figure 7. The model validation is performed in accordance with the turbine development according to the V-Model and contains detailed EMT-models on component level. These EMT-models are validated on component test benches and can then be combined to a comprehensive EMT-model of the turbine, based on validated sub-models. With this detailed model, the turbine manufacturer can validate a generic RMS model or vendor specific models of the turbine in a model-to-model validation. The aggregation of the model to wind farm model can also be carried out. At the component level, functionalities, capabilities and, to a large extent, the performance of the turbine can thus be checked at an early stage in the development process. Furthermore, the parameterization of the control system and the converter can be carried out on the test benches. In order to verify the overall performance of the turbine, the scope of testing in the field is reduced to a worst-case test.

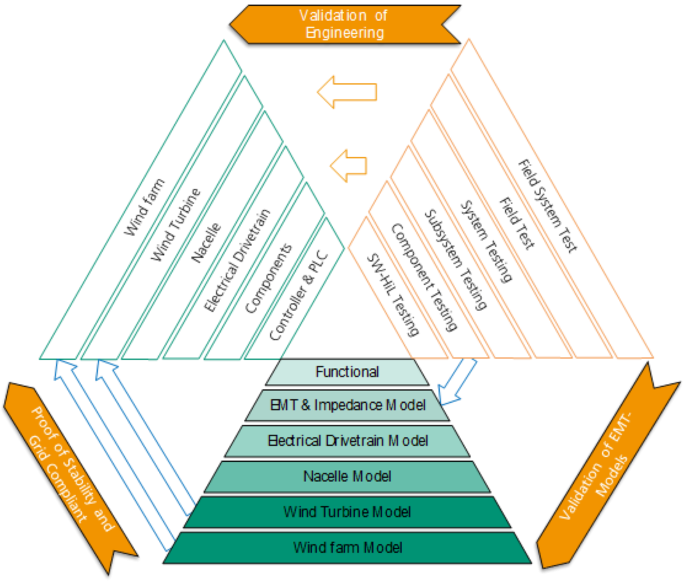


Figure 7: Proposed component-based validation process for grid integration according to the 3 legs V-model

3.1.3. Grid compliance Testing on Test Benches

While the development of the turbine is based on the V-model and the design of the turbine is checked by functional tests of components on test benches or by HiL-procedures for software or controller development, the validation of the electrical characteristics is only measured on the whole wind turbine in field. Figure 8 shows the implementation of the grid compliance testing on test benches according to the V-Model of a wind turbine (red dash line).

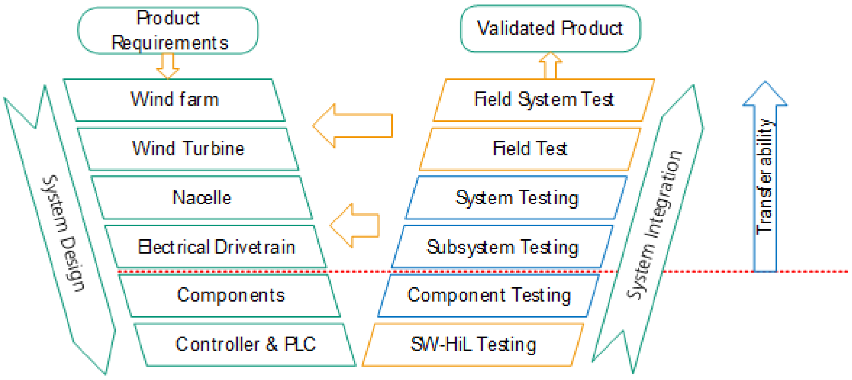


Figure 8: Implementation of grid compliance testing on test benches according to the V-model

Testing of the electrical characteristics on system test benches (nacelle test bench) and subsystem test benches (testing of the electrical drive train, generator converter system) is proven by research projects and industrial measurements campaigns. Within these projects, field tests of the same wind turbines were replicated on test benches to prove that the transfer of the test bench results is possible. Within the projects, tests according to IEC 61400-21-1 and FGW TR 3 were reproduced and test benches and test methods were developed. The description of the test methods, evaluation processes and documentations procedures are described in IEC 61400-21-4 and FGW TR 3. The basic idea of the component-based unit measurement is described in IEC 61400-21-4. In Germany a working group has been set up within the FGW to work on the overall process of component-based unit certification. A detailed elaboration of the process and the verification by wind turbine manufacturer is still open and the topic represents a research topic within the next years.

The following approach represents a first step towards the elaboration and verification of the component-based unit measurement and certification.

A converter test bench is to be used for this purpose. The converter system of the turbine consisting of two conversion lines is connected to a generator emulator and to a grid emulator. The principal setup at the Dynamic Nacelle testing Laboratory (DyNaLab) is shown in Figure 9.

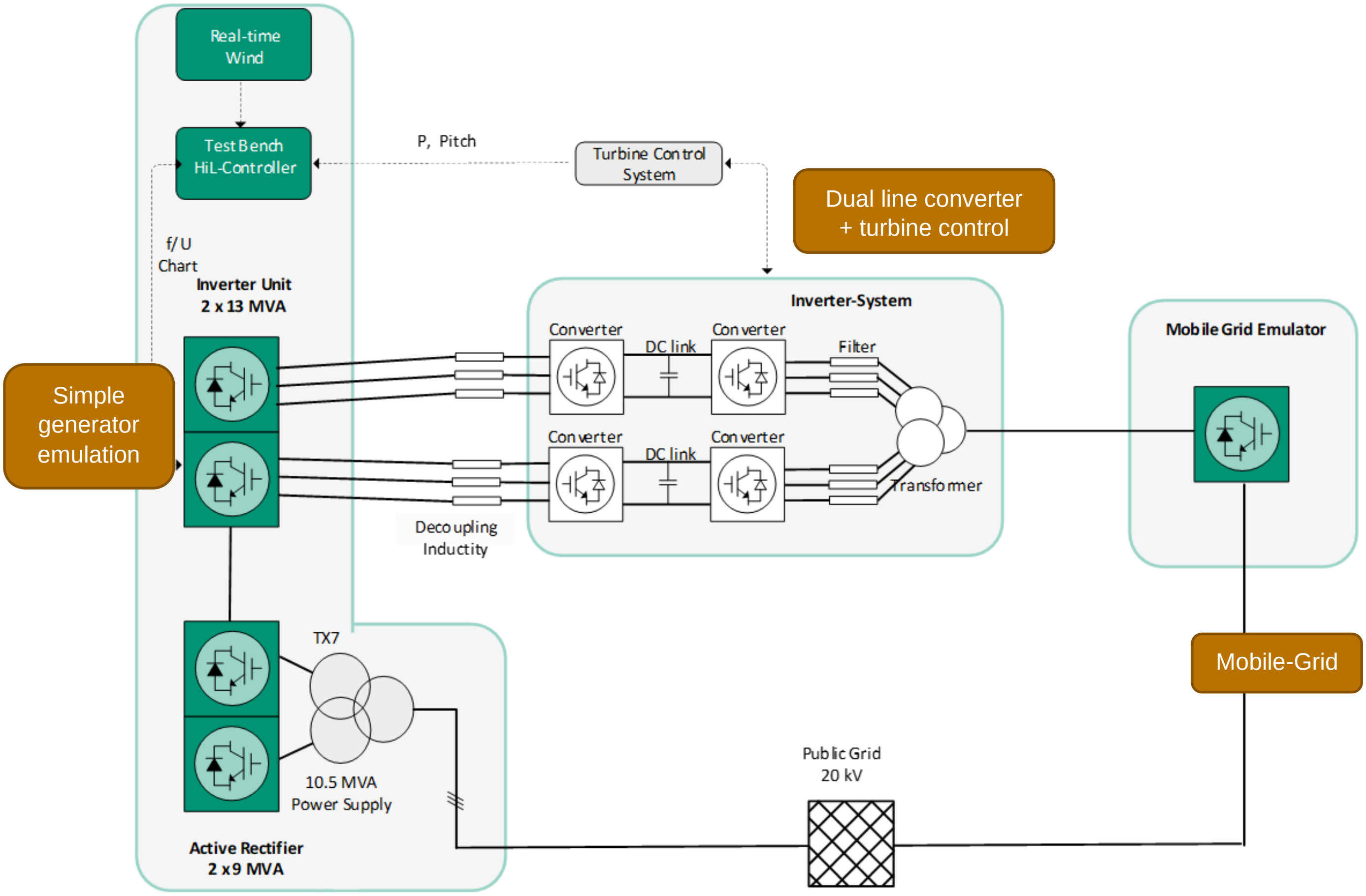


Figure 9: Possible test set-up on a test bench

The converter unit represents the generator emulator and is controlled by the test bench HiL-controller. The wind turbine converter is set up with the original turbine controller on the test bench. In order to emulate the 66 kV voltage level, the mobile grid emulator Mobile-Grid-CoP (“Mobile test bench for Grid Compliance Testing, in german: Prüfung”) of Fraunhofer IWES is used. The generator model and Fraunhofer IWES's own aero-elastic turbine model (MoWiT) are parameterized and verified for the wind turbine to be tested.
The turbine converter will be commissioned on the test bench and the parameterization of the controller variables for the corresponding grid codes will be verified and optimized. When the optimization phase is completed, the tests for the verification of the electrical characteristics are tested and measured on the test bench for the different grid codes. The measurement can be performed by an accredited measurement institute and a certifier will be invited to

accompany the measurement campaign, so that the test performance on the test bench is communicated and shown transparently.

After completion of the test campaign on the test bench, the DUT and the mobile grid emulator are set up on a prototype in the field. The test set-up in field is shown in Figure 10. The mobile grid emulator will be connected between the prototype in field and the grid connection point of the wind turbine. The same grid scenarios for one grid code are emulated with the mobile grid emulator in field. The results of the test bench tests and the field tests are compared to validate the component based approach. Ideally, once the first tests with the generator emulator are validated and certified at the field wind turbine, future configurations of the power conversion set-up (i.e. second converter suppliers, software updates, additional countries certification, etc.) could be validated and certified only with the generator emulator.

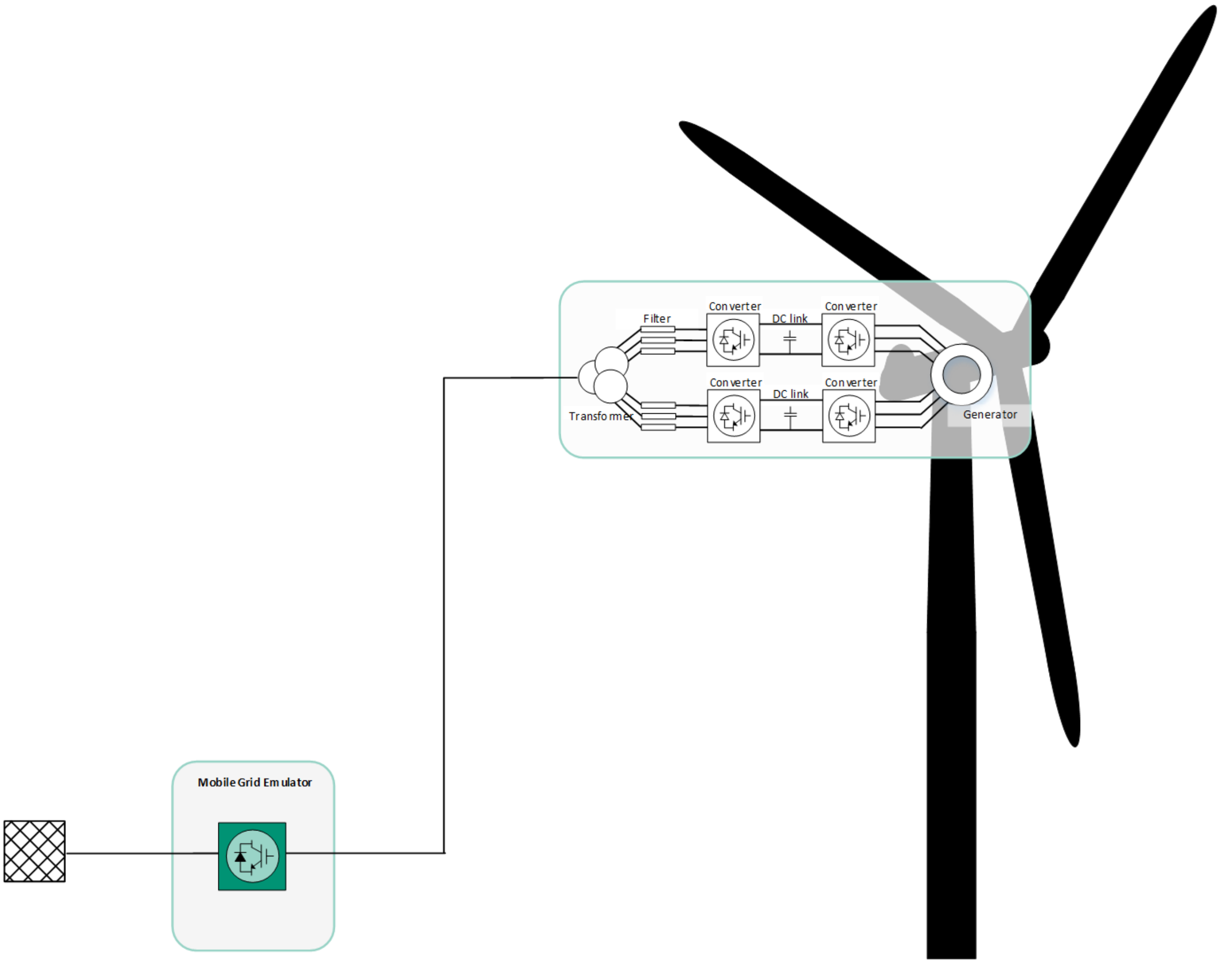


Figure 10: Field tests with Mobile-Grid

3.2. On-site Testing with Mobil-Grid-CoP

Testing on the wind turbine prototype in the field with the mobile grid emulator and without prior test bench testing represents a second possible validation strategy of the electrical characteristics. For this purpose, the Mobil-Grid-CoP will be connected between the Point of Common Coupling (PCC) and the DUT at test side, as previously described in Figure 10. A switch is intended for the possibility of a direct coupling of the DUT at the PCC without any modification of the Mobil-Grid-CoP. The commissioning and parameterization of the inverter as well as the official tests for certification according to the grid codes to be tested are carried out completely in field.

4. Conclusion and Outlook

Within WP3 we have implemented a process for risk assessment and risk mitigation that leads to optimal validation and certification. The comprehensive requirement verification matrix gives an optimal basis to decide about validation activities and to make a profound trade-off between costs and benefits and therefor making the turbine reliable while lowering LCoE.

We are developing an innovative solution for certification in parallel to the turbine development: the component bases approach for grid integration testing. This will make the certification process modular, more flexible and faster while lowering LCoE.

References

The IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE System) (2018). IECRE OD-501 OPERATIONAL DOCUMENT. Edition 2.0

IEC 61400-21-1:2020-08, Windenergy generation systems - Part 21-1: Measurement and assessment of electrical characteristics - Wind turbines (IEC 61400-21-1:2019)

FGW e.V. Fördergesellschaft Windenergie und andere Erneuerbare Energien. Technische Richtlinien für Erzeugungseinheiten und -anlagen. Bestimmung der elektrischen Eigenschaften von Erzeugungseinheiten und -anlagen am Mittel-, Hoch- und Höchstspannungsnetz, Revision 25 Stand 29.04.2019.

F. Hans, G. Curioni, T. Jersch, G. Quistorf, M. Ruben, A. Müller, C. Wessels, C. Fenselau, I. Prima, J. Lehmann: "Towards Full Electrical Certification of Wind Turbines on Test Benches - Experiences Gained From The HiL-GridCoP Project." *21th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants (WIW 2022)*. Vol. 2022. IET, 2022. in press.