



PROJECT NUMBER: IEC TS 61400-21-4 ED1	
DATE OF CIRCULATION: 2022-05-27	CLOSING DATE FOR COMMENTS: 2022-08-19
SUPERSEDES DOCUMENTS: 88/685/NP, 88/702/RVN	

IEC TC 88 : WIND ENERGY GENERATION SYSTEMS	
SECRETARIAT: Denmark	SECRETARY: Mrs Christine Weibøl Bertelsen
OF INTEREST TO THE FOLLOWING COMMITTEES:	
FUNCTIONS CONCERNED: <input type="checkbox"/> EMC <input type="checkbox"/> ENVIRONMENT <input type="checkbox"/> QUALITY ASSURANCE <input type="checkbox"/> SAFETY	

This document is still under study and subject to change. It should not be used for reference purposes.
Recipients of this document are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

TITLE: Wind energy generation systems – Part 21-4: Measurement and assessment of electrical characteristics – Wind turbine components and subsystems
--

NOTE FROM TC/SC OFFICERS: In order to assist WG 21 when sorting and compiling the given comments on the CD document, it is of great importance that all comments given in the comments form refer to both clause and line numbers in the CD document
--

IECNORM.COM . Click to view the full PDF of IEC TS 61400 WG 21-4:2022

Information from the project leader to the chapter 9.5 and Annex H (marked with optional) : The subchapter 9.5 and Annex H is a new test procedure on grid forming capabilities of WT subsystems, as there is p.t no fixed requirements on the grid forming control aspects the chapter 9.5 defines the test requirements on the grid forming capabilities, based on the former defined test procedures in this TS. Annex H, provides an informative overview, how the test results can be analysed, mainly based on an existing VDE/ FNN guideline.

As the WG could not agree if these parts should be included in this TS or as a separate TR. The WG would like to have feedback from the NC on the following questions:

- 1) Shall the grid forming capability tests be included in this TS or should this be developed as separate TR in a later stage?

IECNORM.COM : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

CONTENTS

FOREWORD.....	6
INTRODUCTION.....	8
1 Scope.....	12
2 Normative references	14
3 Terms and definitions	15
4 Symbols and abbreviations	26
5 Overview of tests.....	29
6 Definitions of minimum DUT, components and subsystems.....	31
6.1 General.....	31
6.2 Description of components and subsystems.....	31
7 Test bench systems.....	33
7.1 General for test Benches	33
7.2 Nacelle test bench type (1a) and (1b)	33
7.2.1 Nacelle test benches with mHiL controller (1a)	34
7.2.2 Nacelle Test Benches in Speed / Power mode (1b).....	35
7.3 Electrical generation test bench (2a) and (2b).....	37
7.3.1 Electrical generation test bench with mHiL mode (2a).....	37
7.3.2 Electrical generation test bench (2b).....	38
7.4 Component test benches	39
7.4.1 Converter test bench (3a).....	39
7.4.2 Auxiliary test bench (3b).....	39
7.4.3 Controller test bench (3c).....	40
7.5 Test bench equipment.....	43
7.5.1 mHiL system.....	43
7.5.2 Prime mover for test benches	48
7.5.3 UVRT/OVRT HW equipment for test benches	48
7.5.4 Measurement systems for test benches	50
8 Measurement and test of electrical characteristics as defined in 61400-21-1	52
8.1 Power Quality aspects.....	52
8.1.1 Flicker during continuous operation	52
8.1.2 Flicker and voltage change during switching operations.....	52
8.1.3 Harmonics	52
8.2 Steady state operation	55
8.2.1 Maximum power	55
8.2.2 Reactive power characteristic ($Q = 0$)	56
8.2.3 Reactive power capability	57
8.2.4 Voltage dependency of PQ diagram.....	57
8.2.5 Unbalance factor	58
8.3 Control performance	59
8.3.1 Active power control	59
8.3.2 Active power ramp rate limitation	61
8.3.3 Frequency control.....	63
8.3.4 Synthetic inertia.....	65
8.3.5 Reactive power control	68

8.4	Voltage fault ride through.....	69
8.4.2	FRT - Performance testing according to Strategy 1	70
8.4.3	Functionality and Capability testing according to Strategy 2.....	77
8.5	Disconnection from the grid	83
8.5.1	Grid protection.....	83
8.5.2	RoCoF protection	84
8.5.3	Reconnection time	86
9	Additional measurement and test of electrical characteristics under controllable test conditions	87
9.1	Power quality aspects	87
9.1.1	Flicker Control	87
9.1.2	Flicker and voltage change during switching operations	90
9.1.3	Active filter / sink for harmonics	91
9.1.4	Frequency depended Impedance measurement	94
9.2	Steady state operation	99
9.2.1	Voltage capability	99
9.2.2	Frequency capability	100
9.2.3	Current Unbalance Factor in an unbalanced system	101
9.3	Control performance	102
9.3.1	Grid Impedance variations	102
9.3.2	Island operation.....	104
9.4	Dynamic performance	106
9.4.1	RoCoF – real df/dt – capability.....	106
9.4.2	Phase jump	106
9.5	Grid forming operation (Optional).....	109
9.5.1	Description	109
9.5.2	Power Hardware in the loop (PHiL) implementation	111
Annex A	(informative) Report template.....	113
A.1	The final detailed report template will be provided together with the CDV	113
Annex B	(informative) Subsystems	115
B.1	Guideline test flow - functional, capability and performance test	115
B.2	Overview of components, subsystems and control functions	116
Annex C	(informative) Replacement of components	119
C.1	Introduction.....	119
C.2	Definition of components.....	119
C.3	Workflow replacement of component.....	120
C.4	Test & measurement procedure	123
Annex D	(informative) Transferability examples	127
D.1	Power Quality aspects	127
D.2	Steady state operation	128
D.3	Control performance	129
D.4	Dynamic performance	130
Annex E	(informative) Harmonic assessment	135
Annex F	(informative) Examples of FRT functionalities and capabilities	145
Annex G	(informative) Variants of HiL.....	149
Annex H	(informative) Grid forming control (Optional)	151

H.1 Validation of grid forming control using reference curves 151
H.2 Example of tolerance band calculation 152
Bibliography 154

IECNORM.COM : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS

Part 21- 4: Measurement and assessment of electrical characteristics –
Wind turbine components and subsystems

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

Technical specification IEC TS 61400-21-4 has been prepared by IEC technical committee 88: Wind energy generation systems.

The text of this Technical Specification is based on the following documents:

FDIS	Report on voting
XX/XX/FDIS	XX/XX/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

The National Committees are requested to note that for this document the stability date is 20XX..

THIS TEXT IS INCLUDED FOR THE INFORMATION OF THE NATIONAL COMMITTEES AND WILL BE DELETED AT THE PUBLICATION STAGE.

IECNORM.COM : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

INTRODUCTION

Grid Code Compliance is a crucial element for Wind Power Plant (WPP) connection to the electrical power system. This compliance process is specified by grid codes, standards and guidelines on international as well as national level. From a Wind Power Plant point of view the single wind turbine (WT) is one element (unit) and consists of several subsystems and components, which supports with its given capabilities to grid compliance aspects. The capabilities of the WPP and WT's are to be verified and validated by defined performance and measurements tests as defined in the IEC 61400-21 series.

The IEC 61400-21 series - Measurement and assessment of electrical characteristics consist of the following standards, technical specifications and technical reports:

- IEC 61400-21-1 – Measurement and assessment of electrical characteristics - Wind turbine
- IEC 61400-21-2 – Measurement and assessment of electrical characteristics - Wind power plants
- IEC TR 61400-21-3 – Measurement and assessment of electrical characteristics - Harmonic models
- IEC TS 61400-21-4 - Measurement and assessment of electrical characteristics - Wind turbine components and subsystems

Figure 1 gives an overview of the TC 88 standards, in relation to grid connection requirements.

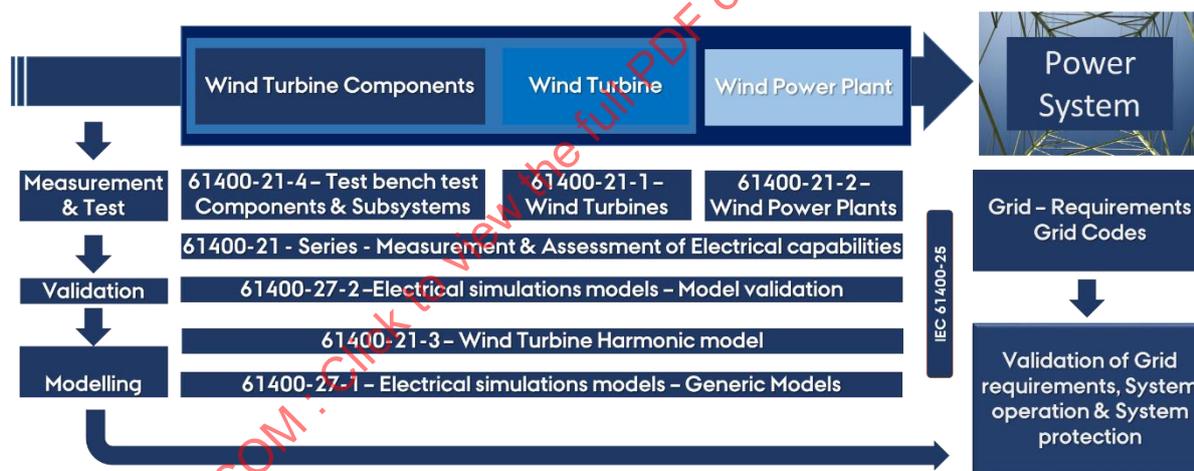


Figure 1 - Overview of TC 88 – Standards related to grid connection

This part IEC TS 61400-21-4 of the IEC 61400-21 series, specifies the test procedures and defines a uniform methodology that standardizes measurement, testing and assessment procedures of electrical characteristics of WT components and subsystems as basis for the verification of the electrical capabilities of WTs and WT families. The results of these component and subsystems test can be used to replace site specific tests as defined in IEC 61400-21-1.

The test & measurement procedures in this technical specification are based on the defined methods and requirements from the IEC 61400-21-1 and defines the same parameters in relation to the validation of the electrical capabilities.

31 It defines furthermore additional tests, which are only possible in a controlled test bench
32 environment, such as:

- 33 • Voltage capability test
- 34 • Voltage dependent reactive power capability tests
- 35 • Frequency capability test, RoCoF and phase jump tests
- 36 • Harmonic evaluations under ideal conditions
- 37 • Grid impedance variations

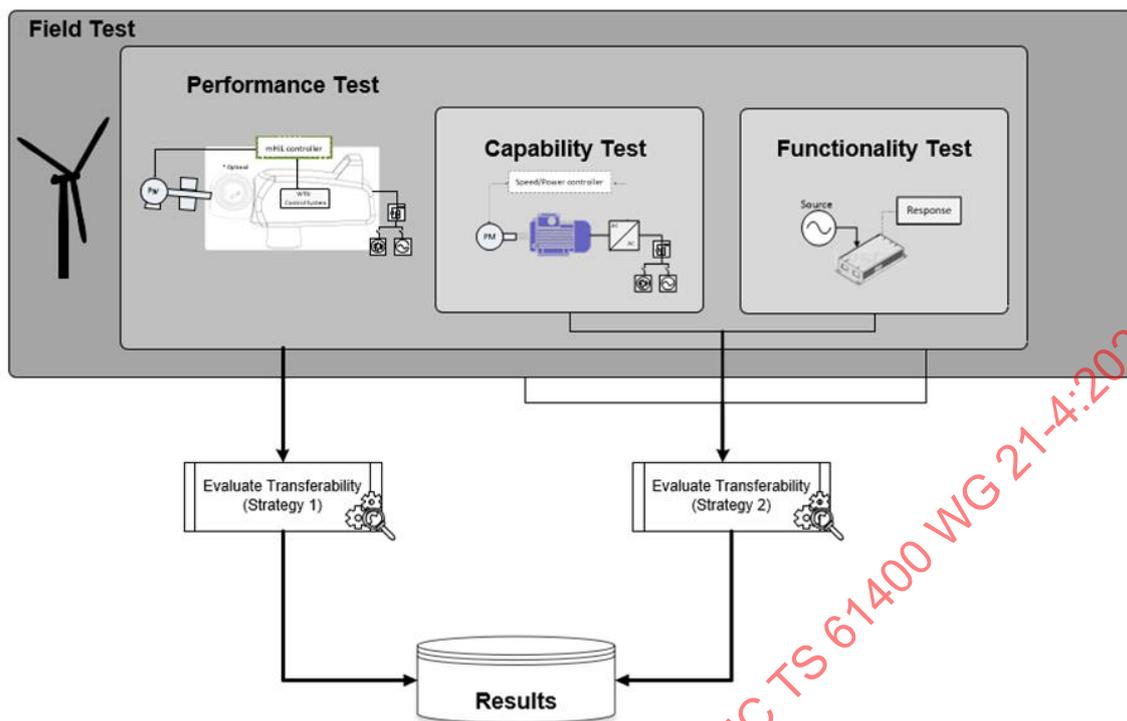
38 The procedures as defined in this technical specification provides the basis for detailed
39 simulation model validations and detailed validation of the electrical characteristics of
40 components and subsystems.

41 This technical specification defines:

- 42 • The minimum test setups in relation to the test & measurements of the electrical
43 capabilities in relation to Grid compliance requirements.
- 44 • The systems requirements for the test bench to perform these measurements.
- 45 • The procedures and related risks for the transferability of test bench components &
46 subsystems test results to Wind turbines and Wind turbines families.
- 47 • The documentation and validation requirements for the wind turbine components and
48 subsystems.

49 The technical specification is a supplement to the IEC 61400-21-1 and IEC 61400-21-2, and
50 does not replace all parts of these standards as there are some functions and performance
51 parameters, which only can be validated on the final product and at the project specific site.

52 The defined test and measurement procedures can be performed as a combination of
53 functional-, capability-, and performance tests. This TS will be further developed with the
54 increased experience of the defined test procedures as well as the development of test systems,
55 validation procedures and simulation models.



56

57 **Figure 2 - Overview of functional-, capability-, and performance tests, and their relation**
 58 **to the field tests.**

59

60 The combination of the different functional-, capability-, and performance tests on subsystem and
 61 component level can afterwards, be used to verify the overall performance of the Wind turbine. A
 62 detailed test overview and overview of the minimum subsystems, necessary for the verification and
 63 assessment of the electrical characteristics are defined in Annex B.

64 In cases where only minor changes in the subsystems requesting a refresh of certain tests and
 65 measurements, or if it has been validated and agreed that the test results are not affected by the different
 66 test level, a lower system test level than stated would be acceptable.

67 The structure of this technical specification is as follows:

68 Chapter 5: Gives an overview of the required tests, measurements procedures and
 69 documentation procedures.

70 Chapter 6: Defines the minimum setup and the interfaces of the DUT, used for the validation of
 71 the different parameters and functions.

72 Chapter 7: Defines the minimum system requirements and characteristics for the test bench
 73 systems to perform these tests of the requested minimum DUT. Furthermore, the overall
 74 requirements for the measurement systems. The detailed requirements are defined in the
 75 specific chapters.

76 Chapter 8: Defines the IEC 61400-21-1 specific test in relation to power quality, steady state
 77 operation, dynamic response and control performance, as well as the documentation
 78 requirements and a risk evaluation for the transferability of the test results towards the WT.

79 Chapter 9: Defines the optional additional tests, which are only possible in a controlled
 80 testbench setup as described in this TS in relation to power quality, steady state operation,

81 dynamic response and control performance, as well as the documentation requirements and a
82 evaluation for the transferability of the test results towards the WT.

83 Annex A: Defines a report template.

84 Annex B: Provides a detailed overview of the WT components and subsystems, and their
85 influence on the different tests. According to the modular structure defined in the IEC 61400-
86 27-1.

87 Annex C: Defines the test and validation procedure for the replacement of components.

88 Annex D: Shows measurement, validation examples and comparisons for the validity of the
89 transferability of test results.

90 Annex E: Defines exemplary the harmonic assessment methods.

91 Annex F : Examples of FRT functionality & capability tests.

92 Annex G: Overview of Hardware in the loop (HiL)systems.

93 Annex H: Guideline for grid forming control capability tests.

94

IECNORM.COM : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

95

96

WIND ENERGY GENERATION SYSTEMS

97

98

Part 21- 4: Measurement and assessment of electrical characteristics – Wind turbine components and subsystems

99

100

101

102 **1 Scope**

103 This Technical Specification IEC 61400-21-4 - Measurement and assessment of electrical
104 characteristics - Wind Turbine components & subsystems - specifies a uniform methodology,
105 defining measurement, testing and assessment procedures of electrical characteristics of Wind
106 Turbine components & subsystems, as basis for the verification of the electrical capabilities of
107 Wind Turbines and Wind Turbine families.

108 The technical specification includes the following aspects:

- 109 – Definitions of test bench, subsystems & interface descriptions
- 110 – Definitions of system requirements for the test bench to perform these measurements (grid
111 strengths, Sk", THD,...)
- 112 – Measurement procedures for quantifying the electrical characteristics;
- 113 – Test & measurements procedures of electrical characteristics of components &
114 subsystems in relation to grid compliance requirements.
- 115 – Procedures for the transferability of the component & subsystem test results, measured at
116 the test bench, to WT product families
- 117 – Documentation requirements & validation procedures of components, subsystems and
118 Wind turbines

119 The results of the measurements and assessments of the Wind Turbine components &
120 subsystems will be used as input for the verification of electrical capabilities as described in the
121 IEC61400-21-1 and for the validation & verification of the electrical simulation models for Wind
122 Power Plants (WPP) as described in the IEC 61400-27.

123 **Out of Scope of this technical specification are:**

- 124 - Design requirements of test bench systems
- 125 - Model development of WT subsystems and WT as e.g. described in IEC 61400-27
- 126 - Power Plant controls function test (e.g. FSM, Voltage Control) as described in IEC 61400-
127 21-2
- 128 - Specific component design test and validation of the Wind turbine equipment (switch- gears,
129 cables, transformer, generator etc., which are covered by other IEC standards
- 130 - Mechanical, structural loads & lifetime test
- 131 - Noise & acoustical measurements
- 132 - Certification procedures & Grid compliance at Wind Power Plant level
- 133 - Communication system functional and performance tests as defined in e.g. the IEC 61400-
134 25 series

135

136

137

138

139 NOTE

140 For the purposes of this document, the following terms for system voltage apply, based on IEC 60038

141 Low voltage (LV) refers to $100 \text{ V} < U_n \leq 1 \text{ kV}$;142 Medium voltage (MV) refers to $1 \text{ kV} < U_n \leq 35 \text{ kV}$;143 High voltage (HV) refers to $35 \text{ kV} < U_n \leq 230 \text{ kV}$;144 Extra high voltage (EHV) refers to $U_n > 230 \text{ kV}$

145

146

IECNORM.COM : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

147 2 Normative references

148 The following documents are referred to in the text in such a way that some or all of their content
149 constitutes requirements of this document. For dated references, only the edition cited applies.
150 For undated references, the latest edition of the referenced document (including any
151 amendments) applies.

152 IEC TR 61000-3-6, *Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of*
153 *emission limits for the connection of distorting installations to MV, HV and EHV power systems*

154 IEC 61000-4-7:2002, *Electromagnetic compatibility (EMC) – Part 4-7: Testing and*
155 *measurement techniques – General guide on harmonics and interharmonics measurements and*
156 *instrumentation, for power supply systems and equipment connected thereto*
157 IEC 61000-4-7:2002/AMD1:2008

158 IEC 62008, *Performance characteristics and calibration methods for digital data acquisition*
159 *systems and relevant software*

160 IEC 61400-1, *Wind energy generation systems – Part 1: Design requirements*

161 IEC 61400-21-1: 2019, *Wind energy generation systems – Part 21-1: Measurement and*
162 *assessment of electrical characteristics – Wind turbines*

163 IEC 61400-21-2 *Wind energy generation systems – Part 21-2: Measurement and assessment*
164 *of electrical characteristics – Wind power plants, CDV 2021*

165 IEC TR 61400-21-3, *Wind energy generation systems – Part 21-3: Wind turbine harmonic model*
166 *and its application*

167 IEC 60050-614:2016, *International Electrotechnical Vocabulary – Part 614: Generation,*
168 *transmission and distribution of electricity – Operation*

169 IEC 61400-27-1, *Wind energy generation systems - Part 27-1: Electrical simulation models -*
170 *Generic models*

171 IEC 61400-27-2, *Wind energy generation systems - Part 27-2: Electrical simulation models -*
172 *Model validation*

173 IEC 61400-25-1, *Wind energy generation systems - Part 25-1: Communications for monitoring*
174 *and control of wind power plants - Overall description of principles and models*

175 IEC 60255-181: *Measuring relays and protection equipment – Part 181: Functional*
176 *requirements for frequency protection*

177 IEC 60255-151:2009, *Measuring relays and protection equipment – Part 151: Functional*
178 *requirements for over/under current protection*

179

180

181 3 Terms and definitions

182 For the purposes of this document, the following terms and definitions apply.

183 ISO and IEC maintain terminological databases for use in standardization at the following
184 addresses:

- 185 • IEC Electropedia: available at <http://www.electropedia.org/>
- 186 • ISO Online browsing platform: available at <http://www.iso.org/obp>

187

188 3.1

189 **Actuator emulation**

190 Part of the real time HiL controller which simulates the signals and dynamics of missing WT
191 sensors and actuators.

192 3.1

193 **Auxiliary equipment**

194 equipment that is necessary for setting up all functions and assessing the correct
195 performance (operation) of the DUT (device under test) during the test.

196 [SOURCE: IEC 61000-4-19, modified: EUT replaced with DUT]

197 3.2

198 **capability**

199 describes the steady state and dynamic behaviour according of the component or system in
200 relation to the defined parameters.

201 Note 1 to entry: (e.g. reactive power capability describes the specified steady state capability of the reactive power
202 production or consumption)

203 Note 2 to entry: e.g. FRT tests showing the specified steady state but also dynamic capability

204 3.3

205 **capability test**

206 used to assess whether a component or system is able to meet the specifications or
207 requirements against defined parameters as defined in this standard.

208 3.4

209 **Closed loop control**

210 a type of automatic control in which control actions are based on feedback signals from the
211 controlled equipment or system.

212 [SOURCE: IEC 62270, ed. 2.0 (2013), modified]

213

214 3.5

215 **compliance test**

216 procedure to verify if a characteristic or a property complies with the stated requirements

217 [SOURCE: IEC 60050, 192-09-02]

218

219 3.6

220 **component**

221 A component is defined as the smallest unit where all necessary functions are available in the
222 unit and which cannot be divided into smaller parts without losing the primary function.

223 NOTE: Examples for wind turbine components are: generators, transformers, switchgear, gearboxes, converters,

224

225 **3.7**226 **component test**

227 A component test is defined as a test on a single component, whose necessary functions and
 228 required behaviour are not dependent on other components or systems. (e.g. the protection
 229 device, if this is an independent unit). A test done on component level shall be valid for all
 230 turbine variants where the same component is applied.

231

232 **3.8**233 **Flicker coefficient for continuous operation**

234 Normalized measure of the flicker emission during continuous operation of the power generation
 235 unit or power plant:

236

237

$$c(\psi_k) = P_{st, fic} \times \frac{S_{k, fic}}{S_n}$$

238 Where

239 $c(\psi_k)$ is the flicker coefficient of the PGU or PP for continuous operation

240 $P_{st, fic}$ is the short-term flicker severity from the PGU or PP on the fictitious grid

241 S_n is the nominal apparent power of the PGU or PP

242 $S_{k, fic}$ is the short-circuit apparent power of the fictitious grid

243 NOTE: The flicker severity for continuous operation is the same for a short-term period (10 min) and a long-term
 244 period (2 h).

245 **3.9**246 **Flicker step factor**

247 A normalized measure of the flicker emission due to a single switching operation of the PGU:

248

249 where

250 T_p is the measurement period, long enough to ensure that the transient of the
 251 switching operation has abated, though limited to exclude possible power
 252 fluctuations due to turbulence;

253 $P_{st, fic}$ is the short-term flicker severity from the PGU on the fictitious grid;

254 S_n is the nominal apparent power of the PGU;

255 $S_{k, fic}$ is the short-circuit apparent power of the fictitious grid

256 NOTE: The short-term flicker severity $P_{st, fic}$ is calculated over the time period T_p .

257 **3.10**258 **functionality**

259 ability to perform a specified operation performed by a component or subsystem and a
 260 software program

261 Note 1 to entry: Ability to perform a specified operation performed by a component or subsystem and a software
262 program

263 Note 2 to entry: The activity of performing a function normally employs a system of displays, controls and
264 instrumentation

265 **3.11**

266 **functionality test**

267 measurements carried out to test and validate the specified operation of the component or
268 system against selected parameters.

269 Note: (e.g. Test of different gain factors or protections levels in the component)

270 Note: Functionally tests are typically done without any power production (e.g. the grid protection test is a typical
271 functionality test)

272

273 **3.12**

274 **fault ride through**

275 **FRT**

276 ability of a wind turbine or wind power plant to stay connected during faults in the grid.

277 Note: The term Fault Ride Through is a general definition for grid faults, in this TS we are using the term FRT only
278 for the under and overvoltage grid fault types and the ability to stay connected under the UVRT and OVRT events

279

280 **3.13**

281 **grid emulator**

282 A programmable AC power supply, capable of emulating various grid conditions to facilitate
283 the testing of grid-connected equipment.

284 Note: Sometimes also referred as grid simulator.

285

286 **3.14**

287 **grid following control**

288 Control of the grid side converter, where the active and reactive power production follows the
289 reference values.

290

291 **3.15**

292 **grid forming control**

293 Control of the grid side converter in a way that voltage amplitude and frequency are controlled
294 by the converter.

295

296 **3.16**

297 **higher frequency component**

298 Is applied for voltages and currents and is measured and grouped in accordance with Annex
299 B of IEC 61000-4-7:2002/AMD1:2008 (Equation (B1))

300 **3.17**

301 **Hardware-in-the-Loop**

302 **HiL**

303 A simulation method that allows a hardware under test to interact in a closed loop with a real-
304 time simulation model.

305 Note: See Annex G for explanations on different variants of HiL

306 **3.18**307 **Mechanical-level Hardware-in-the-Loop**308 **mHiL**

309 HiL where the real-time simulation model interfaces the hardware under test on mechanical
310 level.

311 Note: See Annex G for explanations on different variants of HiL

312 **3.19**313 **Nacelle**

314 housing which contains the drive-train and other elements on top of a horizontal axis wind
315 turbine tower

316 [Source: IEC 415-01-07]

317

318 **3.20**319 **negative sequence component of the fundamental**

320 for a three-phase system with phases L₁, L₂ and L₃, the symmetrical sinusoidal three-phase
321 set of voltages or currents having negative frequency the absolute value of which is equal to
322 the fundamental frequency

323 Note 1 to entry: The negative sequence component is defined by the following complex mathematical expression:

324

325

$$\underline{X}_2 = \frac{1}{3} (\underline{X}_{L1} + a^2 \underline{X}_{L2} + a \underline{X}_{L3})$$

326 where $a = e^{j2\pi/3}$ is the 120 degree operator, and X_{L1} , X_{L2} and X_{L3} are the complex expressions of the fundamental
327 frequency phase quantities concerned, that is, current or voltage phasors.

328 Note 2 to entry: Negative sequence voltage or current components may be significant only when the voltages or
329 currents, respectively, are unbalanced. For example, if phase voltage phasors are symmetrical $U_{L1} = Ue^{j\theta}$, $U_{L2} =$
330 $Ue^{j(\theta+4\pi/3)}$ and $U_{L3} = Ue^{j(\theta+2\pi/3)}$ then $U_2 = (Ue^{j\theta} + e^{j4\pi/3} Ue^{j(\theta+4\pi/3)} + e^{j2\pi/3} Ue^{j(\theta+2\pi/3)})/3 = Ue^{j\theta} (1 + e^{j2\pi/3} + e^{j4\pi/3})/3 = 0$

331 [SOURCE: IEC 60050-448:1995, 448-11-28, modified – the term and the definition have been
332 modified and 2 two notes to entry added]

333 **3.21**334 **no load test**

335 Performance validation of the test equipment, with an open electrical connection to the DUT

336 Note to entry: The test can be done with the main transformer, if this has no impact on the test equipment setup and
337 results. The setup needs to be stated in the test report

338 **3.22**339 **nominal apparent power**

340 apparent power from the wind turbine while operating at nominal current and nominal voltage
341 and frequency:

$$342 S_n = \sqrt{3} U_n I_n \text{ at } Q = 0$$

343 where

344 U_n is the nominal voltage;

345 I_n is the nominal current

346 **3.23**347 **nominal current (for wind turbines)**

348 nominal value I_n of wind turbine current, which are calculated from nominal active power P_n

349

350 and nominal voltage U_n according to $I_n = \frac{P_n}{\sqrt{3}U_n}$;

3.24 3**nominal active power**

353 nominal value of wind turbine active power, which are stated by the manufacturer and is used
354 as per-unit base for all powers (active, reactive, apparent)

3.25**overshoot**

357 difference between the maximum value of the response and the steady state final value

358 Note 1 to entry: See Figure 3.

3.26**open loop**

361 A form of control without feedback

362 [SOURCE: IEC 62270, ed. 2.0 (2013)]

3.27**over voltage ride through****OVRT**

366 ability of a wind turbine or wind power plant to stay connected during voltage swells

367 Note 1 to entry: In some publications, the expression "High Voltage Ride Through (HVRT)", is used for the same
368 event.

3.28**performance**

371 describes the steady state and dynamic fulfilment according to the specification of the
372 complete system in relation to the defined parameters

3.29**performance test**

375 Measurements and tests carried out to determine the ability of the DUT against selected
376 parameters to achieve an intended function.

377 Note to entry: The test intends to validate the performance of the control system on the complete system - DUT -,
378 including all subsystems and components, which has a significant influence on the overall performance of the
379 function.

3.30**phase jump**

382 Rapid change in the phase angles of the supply voltage

383 Note: The phase jump test could be a requirement from the grid codes and defines that the DUT must be able to
384 withstand a transitory phase jump without disconnection

3.31**phase shift (IEC Glossary)**

387 Defined as:

388 a) the absolute magnitude of the difference between two phase angles

389 b) the displacement in time of one periodic-waveform relative to other waveforms

390 **3.32**391 **Power Hardware-in-the-Loop**392 **PHiL**

393 HiL where the real-time simulation model interfaces the hardware under test on electrical
394 (power) level.

395 Note: See Annex G for explanations on different variants of HiL

396 **3.33**397 **positive sequence component of the fundamental**

398 for a three-phase system with phases L1, L2 and L3, the symmetrical sinusoidal three-phase
399 set of voltages or currents having positive frequency equal to the fundamental frequency. The
400 positive sequence component is defined by the following complex mathematical expression:

$$401 \quad \underline{x}_1 = \frac{1}{3} (\underline{x}_{L1} + \underline{a} \underline{x}_{L2} + \underline{a}^2 \underline{x}_{L3})$$

402 where $\underline{a} = e^{j2\pi/3}$ is the 120 degree operator, and \underline{x}_{L1} , \underline{x}_{L2} and \underline{x}_{L3} are the complex expressions
403 of the fundamental frequency phase quantities concerned, that is, current or voltage phasors

404 Note 1 to entry In a balanced harmonic-free system, only positive sequence component of the fundamental exists.
405 For example, if phase voltage phasors are symmetrical $U_{L1} = Ue^{j\theta}$, $U_{L2} = Ue^{j(\theta+4\pi/3)}$ and $U_{L3} = Ue^{j(\theta+2\pi/3)}$ then $U_1 = (Ue^{j\theta}$
406 $+ e^{j2\pi/3} Ue^{j(\theta+4\pi/3)} + e^{j4\pi/3} Ue^{j(\theta+2\pi/3)})/3 = (Ue^{j\theta} + Ue^{j\theta} + Ue^{j\theta})/3 = Ue^{j\theta}$.

407 [SOURCE: IEC 60050-448: 448-11-27:1995, modified – the term and the definition have been
408 modified and Note 1 to entry has been added]

409 **3.34**410 **Q-capability**

411 reactive power capability of a wind turbine, which is measured from the capability curve or by
412 a site-specific test or defined from the manufacturer

413 **3.35**414 **quasi steady state of a system**

415 short-term steady state, for instance during a voltage dip or voltage swell which is long
416 enough to include a period where the system state variables can be considered sensibly
417 constant. (Source IEC 61400-27-2)

418 **3.36**419 **ramp-down time**

420 time during which the measured value decreases from 90 % to 10 % of the target value

421 **3.37**422 **reaction time**

423 elapsed time from test command issued until the change in amplitude reaches 10 % of the
424 measured output variable of the step height

425 Note 1 to entry: See Figure 3

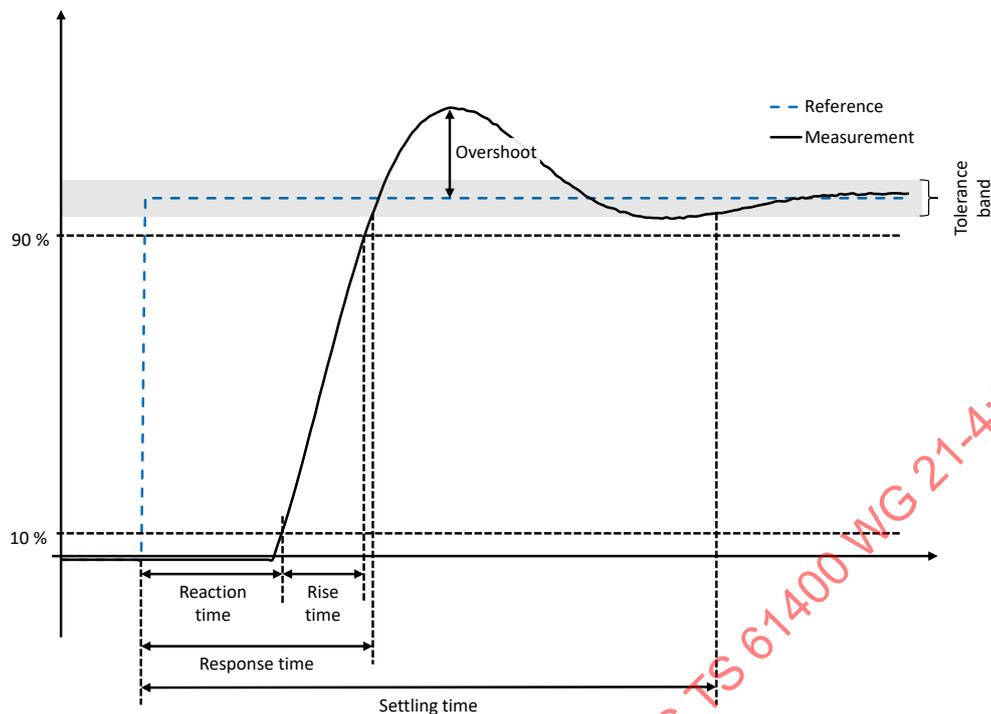


Figure 3 – Example of step response

426

427

428

429 **3.38**

430 **recovery time**

431 time from end of the event after which the measured value is continuously within the
432 predefined tolerance band around the start value before the event.

433 **3.39**

434 **response time**

435 time from the start of event until the observed value enters for the first time the defined steady
436 state tolerance band.

437 Note 1 to entry: See Figure 3

438 **3.40**

439 **rise time**

440 time from the observed value reached 10 % of the step change until the observed value
441 reaches 90 % of the step change.

442 Note 1 to entry: See Figure 3

443 **3.41**

444 **rotor emulation**

445 Real time system that simulates the wind field, Wind turbine rotor and drivetrain components
446 for mHiL operation.

447 **3.42**

448 **settling time**

449 time defined as the elapsed time from the issue of a step change command until the observed
450 value continuously stays within the predefined tolerance band of the target value.

451 Note 1 to entry: See Figure 3

452 **3.43**453 **short-circuit apparent power (IEV 601-01-14)**

454 The product of the current in the short circuit at a point of a system and a conventional voltage,
455 generally the operating voltage.

456 Note: Short-circuit currents and short-circuit impedances may also be determined by system tests. For converter-
457 based grid emulator, the steady state short circuit power S_k can be determined by measuring the voltage variation
458 ΔU in response to power variations.

459

460 **3.44**461 **short-circuit impedance**

462 equivalent impedance at the fault location.

463 Note: The calculation of the short-circuit impedance is generally based on the rated data of the electrical equipment
464 and the topology of the grid.

465 **3.45**466 **short-circuit ratio *SCR***

467 ratio of the short circuit apparent power S_k to the nominal power S_n

$$SCR = \frac{S_k}{S_n}$$

468

469 **3.46**470 **source**

471 electric power supply to feed signals or energy into electrical system or controller.

472 **3.47**473 **start of event**

474 time instant where the stimulus value deviates for the first time outside its defined stimulus
475 tolerance band.

476 Note 1 to entry: Stimulus may be a reference signal or a disturbance.

477 Note 2 to entry: Default stimulus tolerance band is defined to be $\pm 10\%$ of the stimulus increment and centred on
478 the value the stimulus had before the event.

479 **3.48**480 **static error**

481 deviation between the obtained values compared to a requested reference value.

482 **3.49**483 **steady state**

484 status of the system obtained when the settling time has expired.

485 **3.50**486 **sub-group**

487 Grouping method according to IEC 61000-4-7/AMD1:2008. Sub-grouping is used for integer
488 sub-grouped harmonic currents and voltages and for interharmonic centered sub-group
489 currents and voltages.

490 **3.51**491 **sub-group total harmonic current distortion - THC (symbol)**

492 ratio of the r.m.s. value of the harmonic sub-groups (I_h) to the r.m.s. value of the sub-group

493 associated with the nominal current (I_n):

494

495

$$THC = \sqrt{\sum_{h=2}^{50} \left(\frac{I_h}{I_n}\right)^2}$$

496

3.52

497

sub-group total harmonic voltage distortion - $THDS_{U_n}$ (symbol)

498

ratio of the r.m.s. value of the harmonic sub-groups (U_h) to the r.m.s. value of the sub-group

499

associated with the nominal voltage (U_n):

500

501

$$THDS_{U_n} = \sqrt{\sum_{h=2}^{h_{max}} \left(\frac{U_h}{U_n}\right)^2}$$

502

NOTE: In this standard the value of h_{max} is either 50 or 180 as given in the specific requirements.

503

504

3.53

505

sub-system

506

A portion of a system which fulfils a specific function, consisting of several

507

components/elements, which are directly related to each other and are directly interacting for

508

the defined function.

509

3.54

510

sub-system test

511

test on a sub-system, where all necessary functions and performance for the test are

512

available in the sub-system and are not dependent on other components or systems.

513

Note 1 to entry: Test done on a sub-system is valid for all turbine variants, where the sub-system is used.

514

515

3.55

516

tolerance band

517

acceptable deviation range of the measured signal from the defined target value.

518

Note 1 to entry: The steady state target value is usually defined to be equal to the observed signal's reference value

519

or the value towards which the observed signal is converging after the event.

520

Note 2 to entry: Default tolerance band is defined to be $\pm 10\%$ of the nominal value if nothing else is stated

521

3.56

522

validation

523

confirmation, through the provision of objective evidence, that the requirements for a specific

524

intended use or application have been fulfilled.

525

Note: In relation to this TS, the defined test & measurement procedures are validation procedures as the validation

526

is based on experimental data in relation to an intended use.

527

Note: In this TS the defined tests procedures etc. are validation tests, as the TS does not verify that specific

528

requirements are met.

529

[Source: IEC 192-01-18, modified]

530

531 **3.57**532 **verification**

533 confirmation, through the provision of objective evidence, that specified (system)
534 requirements have been fulfilled.

535 Note: In in relation to this TS the measurement results can be used to assess conformity of a design to a specified
536 requirement e.g. verify that the system fulfils e.g. specific grid code requirements.

537

538 **3.58**539 **voltage dip**

540 limited duration non-periodic sudden decrease of the power supply network's voltage
541 magnitude and associated change of its phase.

542 Note 1 to entry: In some articles, publications, etc. the expression "voltage sags" is used for the same event.

543 **3.59**544 **voltage swell**

545 limited duration non-periodic sudden increase of the power supply network's voltage
546 magnitude above its nominal value and associated change of the phase of the voltage.

547 **3.60**548 **unbalance factor**

549 in a three-phase system, the degree of unbalance expressed by the ratio $|\underline{X}_2/\underline{X}_1|$ (in
550 percent) between the values of the negative sequence component \underline{X}_2 and the positive
551 sequence component \underline{X}_1 of voltage or current.

552 [SOURCE: IEC 60050-614:2016 614-01-33,]

553 **3.61**554 **under voltage ride through**555 **UVRT**

556 ability of a wind turbine or wind power plant to stay connected during voltage dips.

557 NOTE 1 to entry: In some publications, the expression "Low Voltage Ride Through (LVRT)", is used for the same
558 event.

559 **3.62**560 **wind turbine terminals**561 **WTT**

562 point that is part of the WT and identified by the WT manufacturer as a point at which the WT
563 may be connected to the power collection system.

564

565 **3.63**566 **zero sequence component of the fundamental**

567 for a three-phase system with phases L1, L2 and L3, the in-phase sinusoidal voltage or
568 current component having the fundamental frequency and equal amplitude in each of the
569 phases.

570 Note 1 to entry: The zero sequence component is defined by the following complex mathematical expression:

$$\underline{X}_0 = \frac{1}{3}(\underline{X}_{L1} + \underline{X}_{L2} + \underline{X}_{L3})$$

571 where \underline{X}_{L1} , \underline{X}_{L2} and \underline{X}_{L3} are the complex expressions of the fundamental frequency phase quantities concerned, that
572 is, current or voltage phasors

573 [IEC 60050-448:1995, 448-11-29, modified – the term and the definition have been modified
574 and the note to entry added]

575

576

577

578

IECNORM.COM : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

579 **4 Symbols and abbreviations**

580 In this part of IEC 61400, the following symbols and units are used.

581 **Symbols (The final update will be done together with the CDV)**

ψ_k	network impedance phase angle (°)
$\alpha_m(t)$	electrical angle of the fundamental of the measured voltage (°)
$c(\psi_k)$	flicker coefficient for continuous operation
d	relative voltage change (%)
d_c	steady-state voltage change as defined in IEC 61000-4-15
d_{\max}	maximum voltage change
f_g	nominal grid frequency (50 Hz or 60 Hz)
$f_{\text{inertia, recovery}}$	frequency threshold where the turbine shall stop boosting active power (Hz)
$f_{\text{inertia, trigger}}$	frequency threshold where the turbine shall start boosting active power (Hz)
f_{over}	overfrequency protection level (Hz)
f_{under}	underfrequency protection level (Hz)
h	harmonic order
$I_{h,i}$	h^{th} order harmonic current distortion of i^{th} wind turbine (A)
$i_m(t)$	measured instantaneous current (A)
I_n	nominal current (A)
IUF	current unbalance factor
P	active power (W)
P_{lt}	long term flicker severity
P_n	nominal active power of the power plant (W)
P_{st}	short term flicker severity
Q	reactive power (var)
S_k	short-circuit apparent power of grid (VA)
$S_{k,\text{fic}}$	short-circuit apparent power of the fictitious grid (VA)
S_n	nominal apparent power (VA)
T_p	transient time period of a switching operation (s)
U	phase-to-phase voltage (V)
U_n	nominal phase-to-phase voltage (V)
U_{under}	undervoltage protection level (V)
U_{over}	overvoltage protection level (V)
U_{pre}	pre-fault voltage (V)
UUF	voltage unbalance factor

582

583

584

Abbreviations

A/D converter	analogue-to-digital converter
Aux.	Auxiliary equipment
DFAG	doubly-fed asynchronous generator (Often referred to as a doubly-fed induction generator (DFIG), but it is not operated as an induction generator when the rotor current is controlled.)
DFT	Discrete Fourier Transformation
DUT	Device under test
FRT	Fault ride through
HiL	Hardware in the loop
HSS	High Speed Shaft
HV	High voltage
HW	Hardware
LSS	Low Speed Shaft
LV	Low voltage
mHiL	mechanical Hardware in the loop
MP	Measurement Point
MV	Medium voltage
OVRT	Overvoltage ride-through
PGU	Power generation unit
PHiL	Power Hardware in the loop
PM	Prime Mover (motor)
POC	Point of connection
PPC	power plant controller
RMS	root mean square

RoCoF	rate of change of frequency
RPM	Revolutions per minute
SCADA	supervisory control and data acquisition
SW	Software
THC	total harmonic current distortion
UVRT	Undervoltage ride-through
WLU	Wind Load Unit
WT	Wind Turbine
WTT	Wind Turbine Terminals

585

586

IECNORM.COM : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

587 **5 Overview of tests**

588 Table 1 gives an overview of the minimum required test levels for the different tests and measurements
 589 as described in this TS - Technical Specification, as well as the minimum recommended requirements
 590 for the test system, where the DUT / WT is connected to.

591 Note: The required test bench system, is always referring to the minimum required system. That means, if a higher
 592 test bench system is used the other levels are automatically included (e.g a test bench system Figure 5 1a, can as
 593 well be used for tests requiring a test bench system in Figure 5 2a or 2b).

594

Table 1 - Overview of tests according to chapter 8

Chapter	Test	Test level - DUT	Minimum Test bench system (c.f. Chapter 7)	Comment
Power Quality Aspects				
8.1.1	Flicker	WT	Field test	
8.1.2	Flicker and voltage change during switching operations	WT	Field test	
8.1.3	Harmonics	Subsystem	2b	
Steady State				
8.2.1	Maximum power	Subsystem	1a	
8.2.2	Reactive power characteristic (Q=0)	Subsystem	2b	
8.2.3	Reactive power capability	Subsystem	2b	
8.2.4	Voltage dependency of PQ diagram	Subsystem	2b	
8.2.5	Unbalance factor	Subsystem	2b	
Control performance				
8.3.1	Active power control	Subsystem	1a	
8.3.2	Active power ramp rate limitation	Subsystem	2a	
8.3.3	Frequency control	Subsystem	2b	
8.3.4	Synthetic inertia	Subsystem	1a	
8.3.5	Reactive power control	Subsystem	2b	
Voltage fault ride through				
8.4.2	FRT - Performance testing according to Strategy 1	Subsystem	1a to 3a	Depending on the test category
8.4.3	Functionality and Capability testing according to Strategy 2	Subsystem	1a to 3a	Depending on the test category
Grid Protection				

8.5.1	Grid protection	Component/ Subsystem	3c	Functionality test of protection system on component level
8.5.2	Rate of change of frequency RoCoF (df/dt)	Component/ Subsystem	3c	Functionality test of protection system on component level
8.5.3	Reconnection time	WT	Field test	

595

596 Table 2 shows the additional tests, which are specified in this technical specification, as these
597 tests are typical performed on a controllable test bench setup.

598

Table 2 - Overview of tests according to chapter 9

Chapter	Test case	Test level - DUT	Test bench system	Comment
Power Quality Aspects				
0	Flicker control	Subsystem	1b	
9.1.2	Flicker and voltage change during switching operations	Subsystem	2b	
9.1.3	Active filter / Sink for harmonics	Subsystem	2b	
9.1.4	Impedance measurements	Subsystem	2b	
Steady State				
9.2.1	Voltage capability	Subsystem	2b	
9.2.2	Frequency capability	Subsystem	2b	
9.2.3	Current Unbalance Factor in an unbalanced system	Subsystem	2b	
Control performance				
9.3.1	Grid Impedance variations	Subsystem	1b	
9.3.2	Island operation	Subsystem	1b	
Dynamic performance				
9.4.1	RoCoF – real df/dt – capability	Subsystem	1b	
9.4.2	Phase jump	Subsystem	1b	

599 A different system level than stated would be acceptable, in cases where minor changes in the
600 subsystems are requesting a refresh of some tests & measurements, or if it has been validated
601 and agreed that the test results are not affected by the different test level. A more detailed
602 guideline in relation to the replacement of components is given in Annex C and a detailed
603 description of the test bench levels are given in Annex B.

604 **6 Definitions of minimum DUT, components and subsystems**

605 **6.1 General**

606 The following chapter defines the minimum test setup of the DUT and the interfaces of the DUT,
607 which are recommended for the validation of the described tests.

608 Furthermore, this chapter defines the different components and subsystems, as well as the
609 controller functionalities, which are responsible for the performance of the different electrical
610 capabilities and control features.

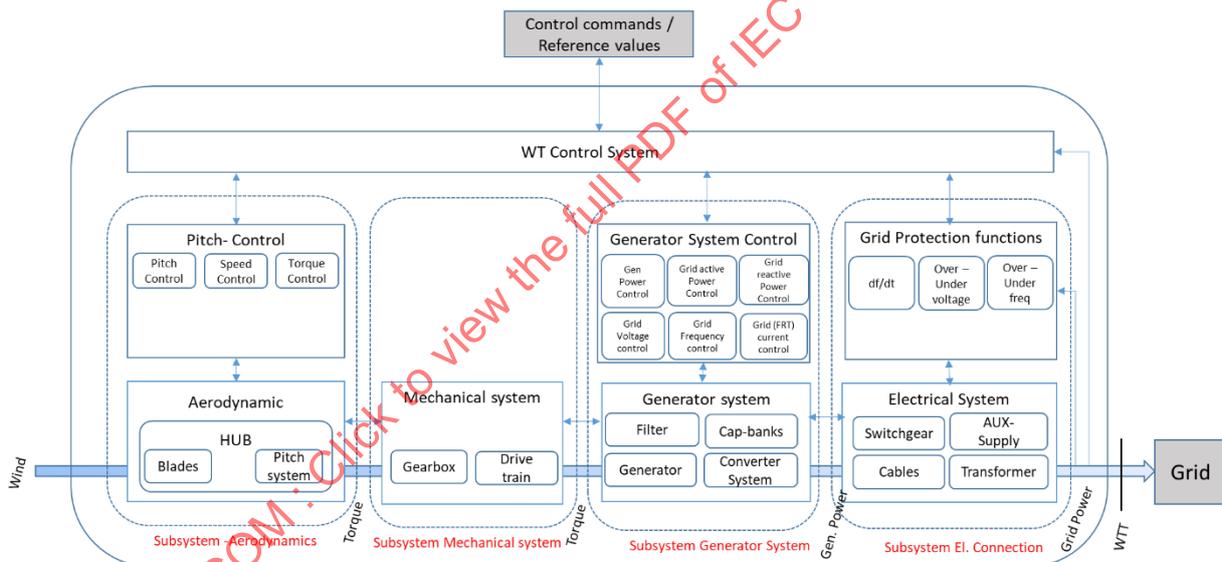
611 The structure follows the modular structure as defined in IEC 61400-27-1.

612 **6.2 Description of components and subsystems**

613 Figure 4 gives an overview of the main components, subsystems and control functions as well as the
614 main input and output parameter, which have an influence in relation to the different test and
615 measurement procedures as described in this technical specification.

616 Note: As an example: For the reactive power capability measurement the subsystems: power conversion system and
617 electrical connection (including the WT type specific components) are influencing the reactive power capability
618 measurements and shall be represented in the DUT. The responsible control system is the grid power control
619 (reactive power control) and shall as well be part of the test setup.

620



621

622

Figure 4 – Generic structure of WT

623

624 Depending on the WT type some of the following main components will be part of the different
625 subsystems for the different WT types.

Subsystem	Main Components	Description
Aerodynamics	Blades	Blades of the WT
	Pitch System	Mechanical / electrical system to rotate the blades
	HUB	fixture for attaching the blades assembly to the rotor shaft
	Control functions	

	Pitch Control	Control system to control the pitch angle of the blades
	Speed control	Control system to control the rotational speed of the main shaft
	Torque control	Control system to control the torque to the main shaft

626

Subsystem	Main Components	Description
Mechanical System	Gearbox	Gearbox
	Drive system	Mechanical drive train - main shaft bearings etc.
	Bearings	

627

Subsystem	Main Components	Description
Generator system	Generator	Generator of the WT – depending on the Type Asynchronous, synchronous, DFIG, etc.
	Converter	Converter system for the Type III and type IV WT
	Filter	Filter system for switch harmonics etc.
	Control functions	
	Gen power control	Active and reactive power control of the power conversion system
	Grid active power control	Active power control of the grid side system
	Grid reactive power control	Reactive power control of the grid side system
	Grid voltage control	Grid voltage control functions
	Grid frequency control	Grid frequency control functions
	Grid (FRT) Current Control	Current control during fault ride through events

628

Subsystem	Main Components	Description
Electrical connection	Transformer	LV to MV transformer
	Cables	Tower cables etc.
	Switchgear	Protection device
	Aux-supply	Supply of the Auxiliary equipment in the WT
	Grid Module	Grid measurement module
	Cap-banks	Reactive power compensation e.g. for type I and type II
	Grid Protection functions	
	Frequency protection	Over and under frequency protection
	Voltage protection	Over and under voltage protection
	df/dt	RoCoF protection

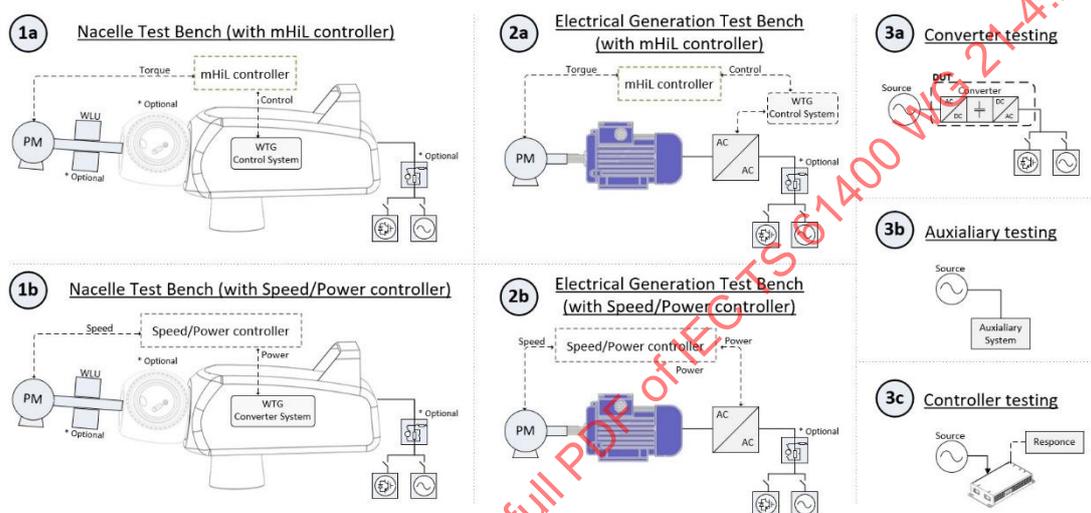
629

630 The detailed description about the operating and test conditions are defined in the respective chapters
 631 of this specification. In Annex B, are the different components and subsystems listed together with the
 632 control functionalities, in relation to the different measurement and test procedures, as described in this
 633 TS in relation to the different turbine types etc.

634 7 Test bench systems

635 7.1 General for test Benches

636 To test electrical characteristics of the wind turbine, test benches of different system levels
 637 and of different complexities can be used. The following chapters describe different test
 638 benches including requirements to obtain valid test results from functionality, capability and
 639 performance testing, when measuring the electrical characteristics.



640 **Figure 5 - Examples of Nacelle Test Benches type 1a, 1b to the left. Examples of**
 641 **Electrical Generation Test Benches type 2a, 2b in the middle and examples of**
 642 **component test benches type 3a, 3b, 3c to the right.**

640

641 7.2 Nacelle test bench type (1a) and (1b)

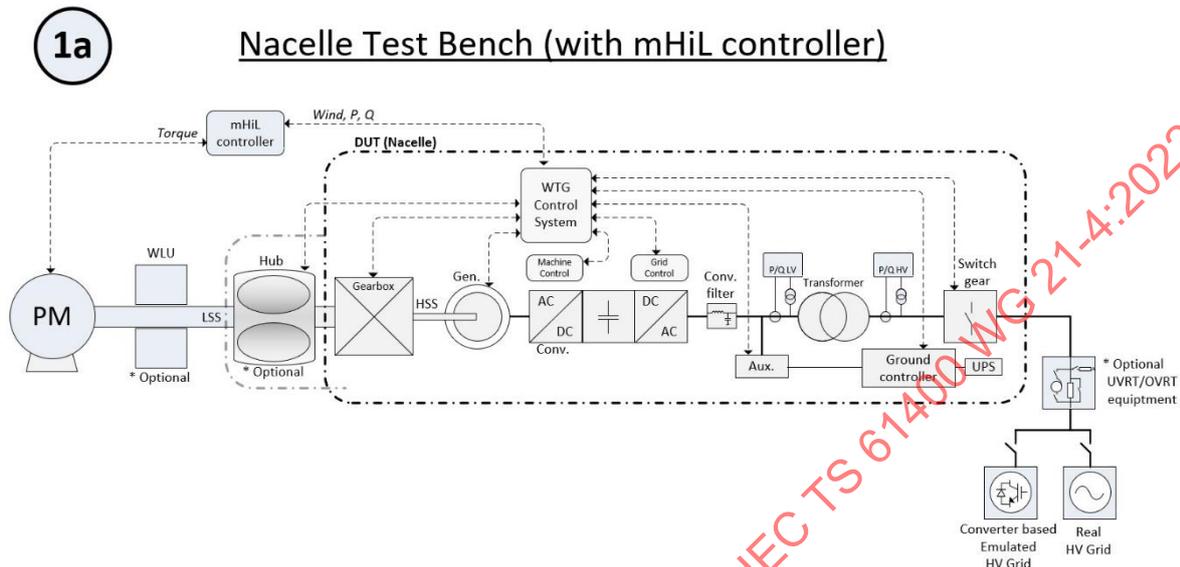
642 Generally when referring to Nacelle Test Benches, the complete nacelle is placed on the test
 643 bench and the different components of the wind turbine (e.g. generator, gearbox, hydraulics,
 644 main bearing(s) and electrical cabinets) are mounted in the nacelle in its original positions
 645 and structures. Hereby, the wind turbine's control system is in operation and the load of the
 646 different electrical systems is equivalent to site operation.

647 If parts of the electrical systems are located in or outside the tower section of the turbine,
 648 these components can be placed next to the test bench, in its original mechanical structure
 649 and frames etc. This ensures correct interfaces and electrical cable lengths as well as
 650 electrical noise properties, which enables valid test results for performance testing.

651

652 7.2.1 Nacelle test benches with mHiL controller (1a)

653 Nacelle test benches are distinguished by two different operation modes. Namely, these are
 654 1a: “Nacelle testing with turbine control system in mHiL mode”, c.f. Figure 6 and mode 1b:
 655 “Nacelle testing in torque/speed mode”, c.f. Figure 7.



656

657 **Figure 6 – Example of Nacelle Test Bench in mHiL control mode (1a)**

658 Note: If the hub is part of the test setup, and the pitch system of the turbine is operational, a more simplified mHiL
 659 control mode can be implemented to achieve the correct operational dynamic response of the turbine during testing.
 660 With verified parameters of the rotor characteristic of the tested WT (wind, pitch angle, RPM, resulting torque) and
 661 an inertia compensation, the dynamic response can be obtained by controlling the prime mover in torque control
 662 mode. Therefore performance testing is also possible in this mode.

663 Note: This type of test bench is typically used for performance testing of the complete system or functionality and
 664 capability testing of individual components and sub-systems.

665 The mHiL controller itself is described in more details in chapter 7.5.1.

666 The prime mover (PM) is described in chapter 7.5.2.

667 The UVRT/OVRT equipment is described in chapter 7.5.3.

668 In the mHiL mode (1a) all the WT's control systems are active during testing, and the response to the
 669 electrical tests are representative to real site operation, because the mHiL controller ensures correct
 670 dynamic response of the turbine and its control systems torque/speed wise. As described in more detail
 671 in 7.5.1, this is done with the help of an emulation of the aerodynamic and mechanic properties of the
 672 rotor, the tower and missing actuators.

673 Furthermore, all the electrical systems that will experience the grid event are present and operational in
 674 the type 1a nacelle test bench. This makes it possible to do performance testing, which is equivalent to
 675 site tests, and can therefore replace site test campaigns.

676 The grid side-converter of the DUT can be connected either to a real grid or to a grid emulator.
 677 The grid emulator is described in chapter 7.5.3.2.

678 7.2.1.1 Requirements on Nacelle Test Benches (1a)

679 In order to achieve results equivalent to site tests, the mHiL operation must be validated. It can be by
680 performing a number of tests with varying wind speeds / wind speed ramps to compare test bench
681 measurements with site measurements or results derived with reliable load simulation models.

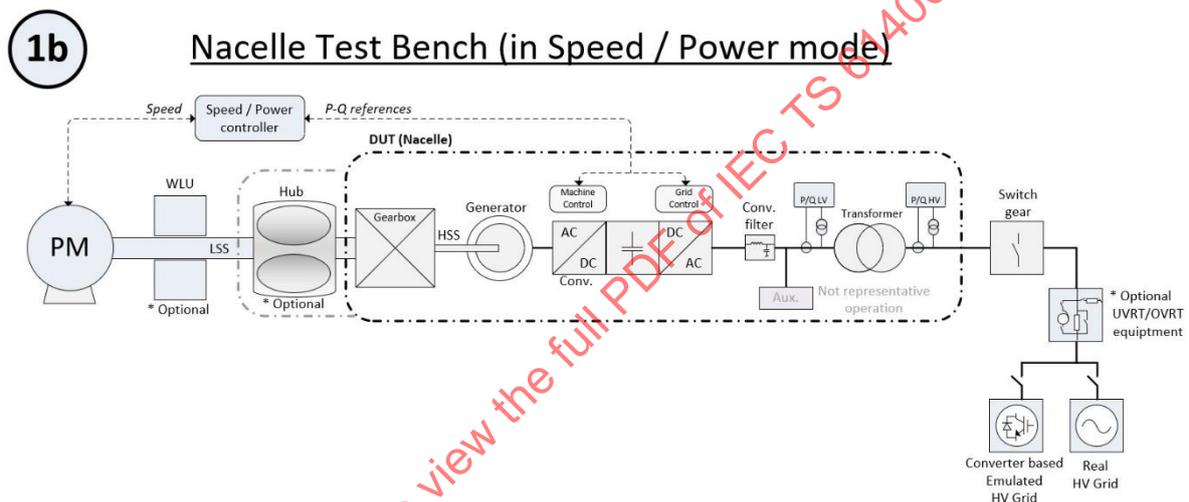
682 The tested wind turbine is operated with its original control system software. No changes to relevant
683 control software are permitted.

684 If parts of the electrical system are left out of the tests (e.g. yaw or pitch) they must be tested separately
685 in order to validate the performance of the final nacelle design.

686

687 7.2.2 Nacelle Test Benches in Speed / Power mode (1b)

688 If the test does not require a correct dynamic speed response of the DUT or that the DUT operates
689 according to its characteristic power/speed curve, the prime mover can be operated in speed/power
690 control mode without mHiL, as illustrated in Figure 7.



691

692

693 **Figure 7 - Example of Nacelle Test Bench in Speed / Power control mode (1b)**

694 Note: This type of test bench is typically used for functionality and capability testing of individual components and
695 sub-systems.

696 In this mode functionality testing and capability testing is possible, to verify that the different
697 systems comply with the requirements.

698 The test setup is controlled with a speed and a power controller, which are setting speed
699 references to the prime mover converters, and active as well as reactive power references to
700 the DUT grid side converter. With that, specific load situations in terms of speed, active and
701 reactive power can be configured and tested. In this test bench configuration, the WT controller
702 and auxiliary systems are not active during testing and therefore the dynamic response, electric
703 performance, and protections are not representative for real on-site operation.

704 7.2.2.1 Requirements for Nacelle Test Benches (1b)

705 In order to verify functionality and capability of the different turbine electrical systems (e.g.
706 converter, filters and generator) the nacelle test bench can be operated in Speed/Power mode.

707 The test bench's speed or power controller must be able to set desired references with sufficient
708 accuracy. The dynamics of the speed/power controller must be sufficient for planned tests.
709

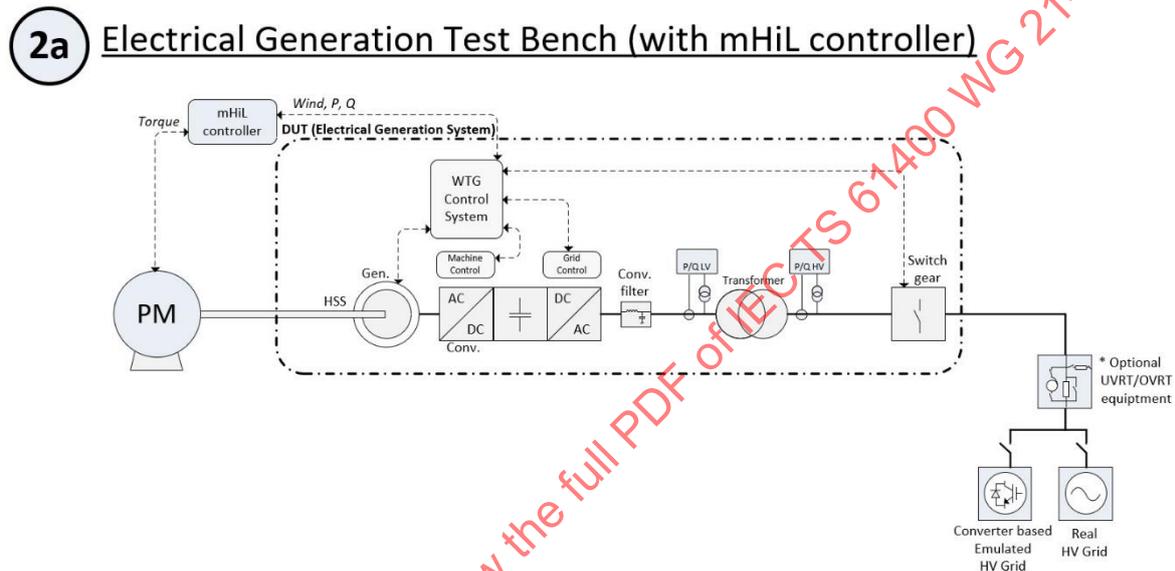
[IECNORM.COM](https://www.iecnorm.com) : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

710 7.3 Electrical generation test bench (2a) and (2b)

711 An Electrical Generation Test Bench includes only selected components of the WT's drive train
 712 in the test setup. Especially mechanical components of the drive train, such as gearbox, main
 713 bearing, and corresponding auxiliaries are not included in this test setup. This may cause some
 714 variation of the test results compared to results derived on a Nacelle Test Bench but reduces
 715 test time preparation and minimized test costs.

716 7.3.1 Electrical generation test bench with mHiL mode (2a)

717 Electrical Generation Test Benches are also distinguished by two different operation modes.
 718 Namely, these are 2a: "Electrical Generation Test Bench with turbine control system in mHiL
 719 mode", c.f. Figure 8 and mode 2b: "Electrical Generation Test Bench in Speed / Power mode",
 720 c.f. Figure 9.



721

722 **Figure 8 - Example of Electrical Generation Test Bench in mHiL control mode (2a)**

723 Note: This type of test bench is typically used for functionality and capability testing of individual components and
 724 sub-systems, as the test setup does not include the auxiliary systems such as lubrication, fans and its protection
 725 systems.

726 In mHiL mode (Figure 8) the DUT at the Electrical Generation Test Bench is operated with its
 727 original control software alongside with the mHiL-controller. The mHiL controller emulates the
 728 dynamic speed response of the wind turbine observed in the field at the test bench. With that,
 729 the DUT on the test bench is characterized by the same dynamic speed response as the
 730 corresponding wind turbine in the field.

731 The mHiL controller itself is described in more details in chapter 7.5.1. Compared to the mHiL
 732 controller used for Nacelle Test Benches, it features an additional simulation model to emulate
 733 the impact of the missing mechanical drive train components.

734

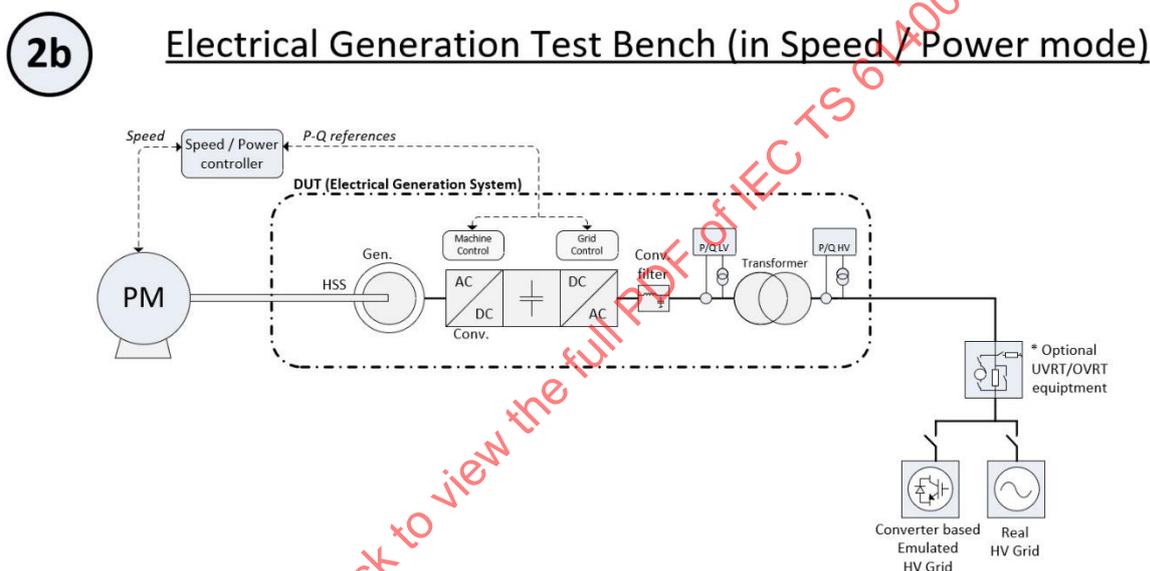
735 7.3.1.1 Requirements for electrical generation test benches(2a)

736 The wind turbine is operated with its original control software with minimum changes. The mHiL-
737 System must be validated against proven simulation models or field data. The test bench's
738 control system must be capable of applying mechanical loads as dynamically as required by
739 the mHiL-System.

740 7.3.2 Electrical generation test bench (2b)

741 If the test bench does not have a mHiL controller and DUT does not have complete WT control system,
742 then the tests can be conducted in a Speed/Power mode following pre-set speed and power references.
743 As for the Nacelle Test Bench in Speed / Power mode (c.f. section 7.2.2) the test setup is controlled by
744 a speed / power controller as illustrated in Figure 9. These controllers are setting the speed references
745 for the prime mover converter as well as the active and reactive power references for the WT converter.

746 As the WT control is not operating, the dynamic speed response is not representative for real on-site
747 operation. Consequently, in this mode only functionality and capability testing, is possible.



748

749 **Figure 9 - Example of electrical generation test bench in speed / power control mode**

750 Note: This type of test bench is typically used for functionality and capability testing of individual components and
751 sub-systems.

752 7.3.2.1 Requirements for electrical generation test benches (2b)

753 Changes to the wind turbine control software are acceptable if they do not influence the results
754 of the planned test. The test bench's speed or torque controller must be able to set desired
755 references with sufficient accuracy. The dynamic of the speed/power controller must be
756 sufficient for planned tests.

757 Chapter 7.5 provides more requirements for the test bench equipment.

758

759 7.4 Component test benches

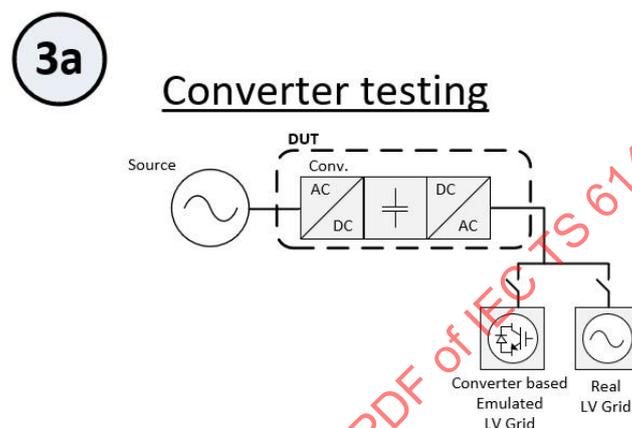
760 To test the functionality of the different components and sub-systems in the turbine, dedicated
761 component test benches can be used.

762 Some examples of different component test benches are described in the following sections.

763 7.4.1 Converter test bench (3a)

764 An electric source can be used to load the machine-side converter to have power flow through
765 the converter. The source will act electrically as the generator in the wind turbine.

766 The grid-converter can be connected either to a real grid or alternative to a grid emulator to
767 verify the functionality and capability of the converter system as illustrated in Figure 10.



768

769 **Figure 10 - Example of Converter Test Bench (3a)**

770 Note: This type of test bench is typically used for functionality and capability testing of individual components and
771 sub-systems.

772 This component test bench can be used for testing of the converter system as a stand-alone
773 system.

774 7.4.1.1 Requirements for converter test bench (3a)

775 To achieve valid results from the tests, the DUT converter including filter and chopper
776 components must be equivalent to the ones used in the WT.

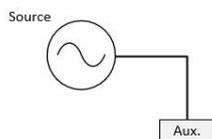
777

778 7.4.2 Auxiliary test bench (3b)

779 To verify the functionality of the auxiliary system(s) of the turbine, the different electrical
780 systems can be connected to an electric source which can replicate the grid events etc.

3b

Auxiliary testing



781

782

Figure 11 - Example of auxiliary test bench (3b)

783 Note: This type of test bench is typically used for functionality and capability testing of individual components and
784 sub-systems.

785 Depended on the test to be executed the test bench must be designed to load the Auxiliary
786 equipment to gain valid results.

7.4.2.1 Requirements for auxiliary test bench (3b)

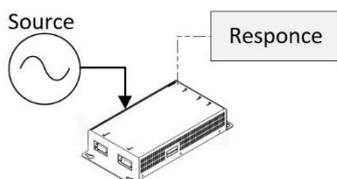
788 To achieve valid results, the Auxiliary equipment must be loaded under worst case operating
789 conditions, meaning fans, pumps, lubrications systems and its control systems must operate
790 with the right pressure, temperature and vibration levels.

7.4.3 Controller test bench (3c)

792 To perform a functionality test on the individual controllers for the WT a controller test bench
793 can be used. For this, the WT original control software is operated on the original controller
794 hardware, i.e. the real combination of software and hardware is considered the DUT. The
795 controller test bench includes several simulations (c.f. Figure 13 or Figure 14), which allow to
796 provide any required signals (e.g. voltage and currents) to the tested WT controller and its
797 response e.g. to electrical events can be observed.

3c

Controller testing



798

799

Figure 12 - Example of controller test bench (3c)

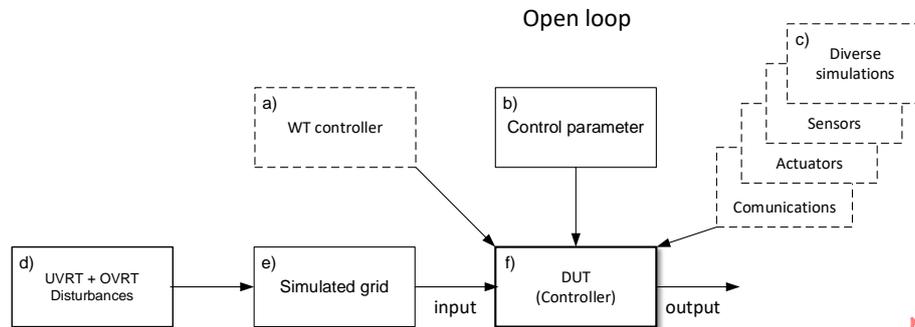
800 Note: This type of test bench is typically used for functionality testing of individual components.

801 Depending on the architecture of the controller and its integration into the overall system, the
802 test bench operates the controller in:

- 803 • Open loop control or
- 804 • Closed loop HiL control (HiL setup)

805 The following pictures show a more detailed representation of the test benches.

806

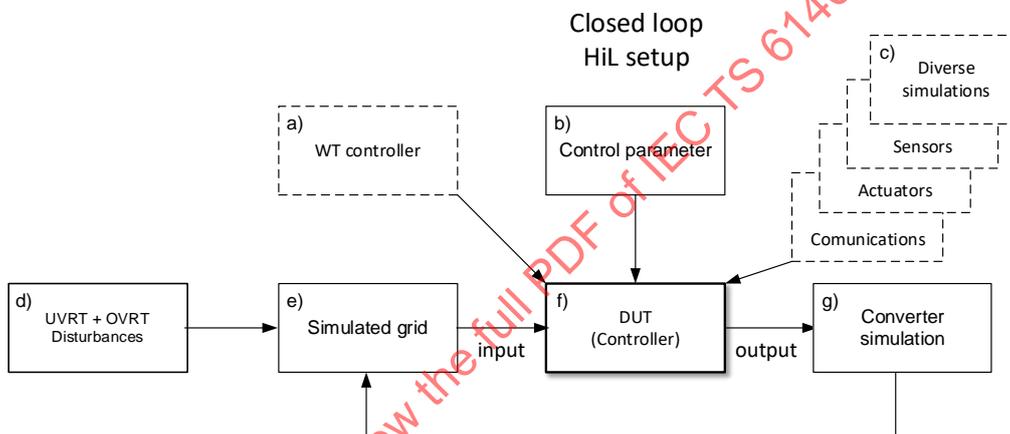


807

808

809 **Figure 13 – Illustration of an exemplary test setup with open loop**

809



810

811

812 **Figure 14 – Illustration of an exemplary controller-HiL test setup**

813 The table below describes the Boxes a to f/g in more detail.

813

Box	Name	Short description
a)	Wind Turbine Controller	Controls and monitor the complete WT with diverse aspects. In this case, it might be needed, to get the set up running or some features related to UVRT or/and OVRT functionalities are implemented in this controller.
b)	Control Parameter	These parameters are needed to configure each individual FRT functionality behavior at the DUT controller. During testing the test relevant parameter needs to be documented.
c)	Diverse Simulation Devices	In such a test setup, different devices, e.g. Sensors, actuators are normally not included, as they are not relevant for this functional test and the effort would be too great. However, they may need to be simulated to get the setup in operation.
d)	UVRT + OVRT Disturbances	This box symbolized the UVRT or/and OVRT voltage events, which will be seen via the simulated grid at the signal input of the DUT, e.g. low voltage measurement signal

e)	Simulated Grid	It's the simulation of the electrical grid, which provides a grid depended feedback to the simulated converter signal output (P, Q,..).
f)	DUT (e.g. controller of the converter)	DUT which shall be the same technical setup (hardware and software), defined by the manufacturer as it will be in the e.g. complete converter
g)	Converter Simulation	If it is desired to analyze the DUT functionalities in a closed loop fashion, this box simulates the converter. This simulation translates the DUT's command signals (output) into a reaction of the converter, which feedback into the simulated grid and hence the DUT's input..

814
815

Figure 15 – Description of the different components of the test set up, illustrated in Figure 13 and Figure 14

816
817
818
819

Basically, the exact structure of the test bench depends on the planned function tests and their further use in the overall validation concept. The DUT needs to be embedded into a technical environment simulation, such that it is able to operate as in a complete WT. This can be individually different, and the setup above describes on possible version.

820

The following measurement values needs to record:

821

- Input and output of the DUT (box f)

822
823

Further measurement signals might be useful to show the functionality and needs to be defined by the manufacturer.

824

7.4.3.1 Requirements for controller test bench (3c)

825
826
827

The controller must operate with the same SW and HW as the turbines in the field to verify correct functionality. The source must replicate the grid events or grid disturbances with a sufficient accuracy to verify the response of the controller.

828

IECNORM.COM : Click to view the full PDF of IEC TS 61400 WG21-4-2022

829 **7.5 Test bench equipment**

830 To make the DUT/WT operate dynamically when installed on the test bench and perform certain
831 electrical tests specific test bench equipment can be used. The following chapters describes
832 the equipment typically used for performing tests and the requirements.

833 **7.5.1 mHiL system**

834 This section addresses the mechanical-level HiL (mHiL) system, which emulates the missing
835 rotor and relevant auxiliary system. This section does not address power-level HiL systems,
836 which may possibly be used for grid emulators.

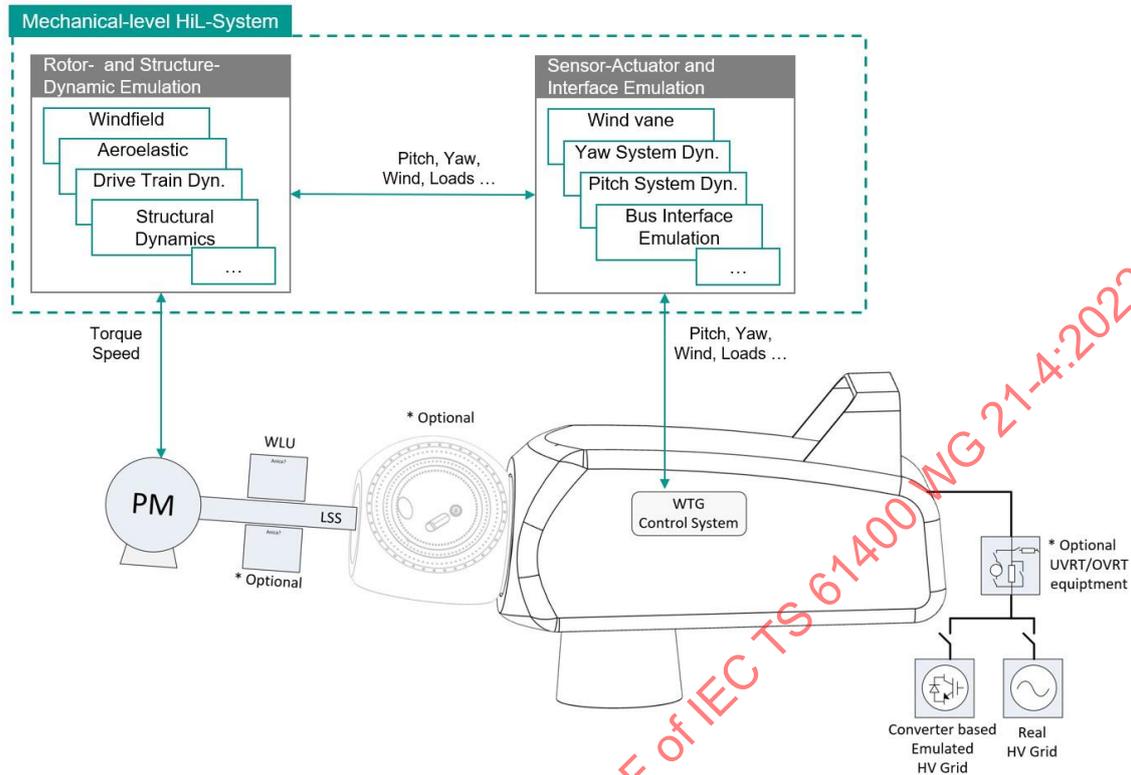
837 Compared to the general overview for mHiL operated test benches, given in Figure 6 and Figure
838 8, a more detailed look in to the mHiL-setup is given in Figure 16. The statements for mHiL
839 made in this section are valid for all types of test benches using a mHiL system.

840 The mHiL system comprises of two major functionalities, the “Rotor- and Structure Emulation”
841 (short “rotor emulation”) and the “Sensor-Actuator and Interface Emulation” (short: “actuator
842 emulation”). The rotor emulation simulates the wind field, aeroelastic, the rotor, the drive train
843 and if needed other structural dynamics, such as tower, in real-time. In a simplified manner one
844 can consider this a real-time wind turbine simulator. Furthermore, it controls the test bench’s
845 prime mover, so that the wind turbine’s drive train behaves according to the rotor’s mechanical
846 properties and the current aerodynamic conditions. Naturally, these conditions depend on
847 signals of the wind turbine’s control system, which is interlinked with the rotor emulation via the
848 actuator emulation.

849 The actuator emulation simulates the signals and dynamics of missing sensors or actuators,
850 such as wind vane, measured bending moments, pitch or yaw actuators in real-time. If required,
851 more signals such as status signals etc. can be emulated separately. The aim of this actuator
852 emulation is to minimize software changes that are required on the WT’s control system.

IECNORM.COM : Click to view the full PDF of IEC 61400-21-4:2022

853



854 **Figure 16 - General block diagram of the mechanical Hardware-in-the-Loop system**
 855 **required to operate nacelle or Electrical Generation System in mHiL-mode.**

856

857 The forthcoming section will give some minimum requirements on the mHiL system and
 858 especially on the models used therein.

859 **7.5.1.1 Requirements for rotor and structure dynamic emulation**

860 The purpose of rotor and structural dynamics emulation is to reproduce the influence of the
 861 rotor on the behaviour of the WT by means of the prime mover of the test bench. In general,
 862 the rotor

- 863 - converts fluid-mechanical energy into rotational energy, depending on the inflow
 864 conditions (wind speed and direction), the pitch angle and the rotational speed and
- 865 - determines the natural frequencies of the mechanical drive train.

866 Accordingly, the Rotor and Structure Dynamic Emulation also has two essential tasks. It
 867 reproduces the aerodynamic properties of the rotor in real-time using a suitable method and
 868 thereby restores the dynamic behaviour of the drive train determined by the rotor inertia. The
 869 required functions within the rotor emulator and corresponding requirements are given in
 870 Table 3.

871 **Table 3 - Functions of the rotor and structure emulation and related requirements.**

Function and Description	Level 1	Level 2
--------------------------	---------	---------

<p>Wind field</p> <ul style="list-style-type: none"> Simulation of wind conditions (mean wind speed and turbulence intensity) generated according to IEC 61400-1 	<p>Spatially resolved 3D wind field (turbulent)</p>	<p>Punctual effective mean wind speed at hub height (turbulent)</p>
<p>Aeroelastic</p> <ul style="list-style-type: none"> Simulation of the aerodynamic properties of the rotor, i.e. transfer of wind power into the induced prime mover torque 	<p>Detailed rotor model (model based on load calculation tools from the type certification process)</p>	<p>Static Cp-Grid (function of rotor speed, pitch angle, wind speed)</p>
<p>Drive Train Dynamics</p> <ul style="list-style-type: none"> Simulation of the coupled rotor-drive train dynamics of the original wind turbine with respect to the rotational degree of freedom on the test bench 	<p>Multi-mass oscillator (emulation of coupled rotor-drive train eigenfrequencies)</p>	<p>Single-mass oscillator (emulation of dynamics, i.e. inert behavior)</p>
<p>Structural Dynamics</p> <ul style="list-style-type: none"> Simulation of the influence of further structural dynamics (e.g. influences of the tower) on the rotational degree of freedom and their coupling 	<p>Detailed structural models (model based on load calculation tools from the type certification process)</p>	<p>without any further structural models</p>

872

873 To ensure consistency in test bench testing, one level should be used throughout all tests. For
874 the execution of individual test items on nacelle and subsystem test benches, the necessary
875 level of detail of the rotor and structural dynamics emulation (level 1 or level 2) and the sensor-
876 actuator emulation must be agreed in each individual case.

877 7.5.1.2 Requirements for sensor-actuator and interface emulation

878 The purpose of the sensor-actuator and interface emulation is to reproduce the signal interface
879 and the dynamic behaviour of sensors and actuators that are not available due to installation
880 on the test bench. How many of these interfaces are required depends on the wind turbine and
881 the agreements of all parties involved. In principle, the smallest possible modification is
882 desirable. In this section, only the systems affected in any case are taken into account.

883 **Table 4 - List of system for which sensor, actuator or interfaces are emulated in order to**
884 **operate WT in mHiL mode.**

System and Required Emulation	Requirements
<p>Pitch System:</p> <ul style="list-style-type: none"> Sensor and actuator Interface emulation; Signal interface to WT controller, i.e. signal conditioning and protocol 	

<ul style="list-style-type: none"> • Actuator emulation for dynamic behaviour; Simulation of the dynamic response of the pitch actuator (simulation at model level if the pitch actuator is not physically operated). 	<p>Inertial forces and external aerodynamic conditions</p> <p>Delay times of the actuators (motor, cylinder)</p>
<p>Yaw System (Optional)</p> <ul style="list-style-type: none"> • Sensor and actuator Interface emulation Signal interface to WT controller, i.e. signal conditioning and protocol • Actuator emulation for Dynamic behaviour Simulation of the dynamic response of the Yaw actuator (simulation at model level if the pitch actuator is not physically operated) 	<p>Inertial forces and external aerodynamic conditions</p> <p>Delay times of the actuators (motor, cylinder)</p>
<p>Wind Sensor</p> <ul style="list-style-type: none"> • Sensor interface emulation Emulate Interface to provide wind information (speed, direction) from HiL-System to WT controller, i.e. signal conditioning and protocol • Sensor Emulation (Optional) Emulation of sensor disturbance by rotor and sensor's dynamic behavior 	<p>No requirements, as of minor importance for testing</p>
<p>Other Sensor (e.g. blade root bending moments, nacelle acceleration...)</p> <ul style="list-style-type: none"> • Sensor interface emulation Emulate Interface to provide required information from HiL-System to WTcontroller • Sensor emulation Emulation of dynamic behaviour of sensor or measured quantity 	<p>If a sensor has relevant dynamic behaviour, it is to consider. If the dynamic of the measured quantity is relevant and not covered by another system, such as e.g. rotor-structural dynamic emulation, it is to consider.</p>
<p>External References (Optional)</p> <ul style="list-style-type: none"> • Interface emulation Emulate Interface to provide external references from HiL-System to WT controller, i.e. signal conditioning and protocol 	<p>No requirements, as of minor importance for testing</p>

885

886 **7.5.1.3 Validation procedure**

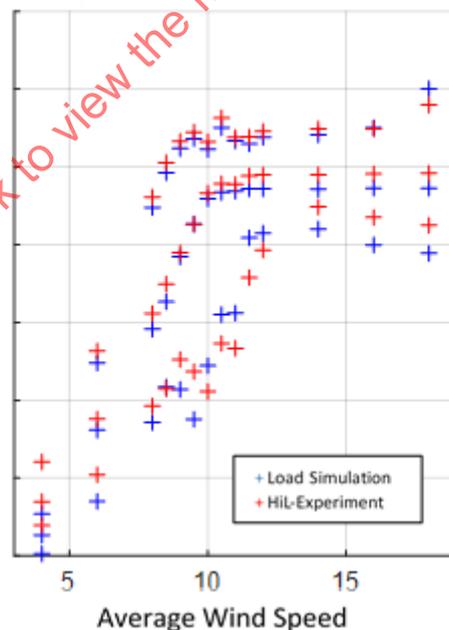
887 The correct emulation of the wind turbine's mechanic and aerodynamic properties by the mHiL
 888 system are crucial for the validity of the measurement results derived at test benches. The
 889 emulation can be considered as reliable if the results of the real-time simulation and load
 890 calculation simulation according to IEC61400-1 and IEC 61400-3 match with sufficient
 891 accuracy.

892 For validation the static and dynamic properties the following procedure is proposed. It is recommended
 893 to operate the wind turbine at different wind speed from cut-in to above rated wind speed in turbulent
 894 (or laminar) conditions and compare the resulting power, generator speed and pitch angle to load
 895 simulation results according to IEC61400-1 and IEC 61400-3. When using turbulent wind conditions, it
 896 is recommended to compare mean, min and max values as illustrated in XXX. Differences below 10%
 897 are acceptable for mechanic quantities. Pitch differences shall remain below 2°.

898 For verifying the dynamic performance of the mHiL system and the test bench, different tests
 899 can be considered. In a first test, the DUT operates at different wind speeds from cut-in to
 900 cut-out in turbulent conditions. The wind speed steps can be up to 4 m/s. For determining the
 901 dynamics, the spectrum of the generator speed or power and is calculated and compared to
 902 simulation results of the same test run.

903 For a type 3 wind turbine, a UVRT test can be carried out to determine the dynamics and
 904 calculate the spectrum, since the voltage drop leads to a step-like excitement of the
 905 mechanical drive train.

906 The difference of the resulting eigenfrequencies should not exceed 5% of its nominal value,
 907 which correlates with tolerances of the mechanical models itself. Eigenfrequencies are typically
 908 only considered up to 2-5 Hz for that purpose.



909

910 **Figure 17 - Suggested reporting on comparison between mHiL-operated test bench and load**
 911 **simulation.**

912

913 7.5.2 Prime mover for test benches

914 A prime mover (PM) can be one or more electric direct drive or high/medium speed motors, or
 915 one or more electrical high speed motors with a slave gearbox. The prime mover is applying
 916 torsional torque to the nacelle or generator via a Low Speed Shaft (test bench type 1) or high
 917 speed shaft (test bench type 2). Optionally a Wind Load Unit (WLU) applies wind loads
 918 (bending/yaw moments and thrust/radial forces). The test bench's low or high speed system
 919 can also include a misalignment and/or safe set coupling (mechanical fuse).

920 7.5.3 UVRT/OVRT HW equipment for test benches

921 The test bench can be equipped with suitable test equipment to perform UVRT and OVRT tests.
 922 Many topologies allow testing the behaviour of the WT in case of an under voltage or an over
 923 voltage event. However, three main solutions have become established, the shunt impedance
 924 or voltage divider based test equipment, the variable transformer and the full converter.

925 7.5.3.1 Voltage divider based test equipment

926 The voltage divider-based test equipment is a basic compliance test topology, which is referred
 927 as an example in IEC 61400-21-1 for under voltage ride-through (UVRT) capability test.
 928 Recently, this structure has been adapted for over voltage ride-through (OVRT) capability test
 929 as well. This test equipment has proven to be a useful tool in the early stages of grid integration
 930 research and characterization of utility-scale wind power. However, it has certain fundamental
 931 limitations, such as dependence on a stronger point of interconnections and an inability to
 932 replicate any evolving grid characteristics. Furthermore, it is limited in the achievable dip-levels,
 933 since it is based on tapping possibilities of the individual components.

934 The voltage divider-based test equipment is placed in between the WT and the WTT. It consists
 935 of a series and a short circuit impedance. Both impedances consist of interconnected coils. By
 936 connecting the series impedance, the fault is decoupled from the rest of the power grid. The
 937 short-circuit impedance is activated by a switch. This switch can be a mechanical circuit breaker
 938 or an electronic circuit breaker.

939 7.5.3.2 Full converter based grid emulator

940 Converter based grid emulators offer an alternative way of generating voltage dips. In contrast
 941 to the voltage divider-based equipment, the voltage dip is emulated by the converter (active
 942 component) and not physically generated by passive components. The connection of the grid
 943 emulator is between the grid connection of the test bench and the WT, as described in Figure
 944 6. The grid emulator emulates the desired voltage behaviour at the WTT. Voltage dip depth and
 945 duration are freely adjustable. This solution makes it possible to generate any type of grid fault
 946 at different frequencies. The converter system needs to be oversized to ensure the UVRT
 947 testing of Type 3 WTs. In order to perform OVRT capability test using a converter-based grid
 948 emulator, step-up tap transformers can be used to generate the required over-voltage ranges.

949 Requirements for converter-based grid emulator

950

951

Table 5 -Requirements for Converter-based Grid Emulator

Operation mode	Requirements	Description
Steady state operation	Voltage and Frequency requirements	1. The Grid emulator shall be able to generate three phase-to-neutral voltages at the terminals of DUT.

		2. The Grid Emulator shall be able to adjust the voltage with an accuracy of +/- 1.5% and the frequency with an accuracy of +/- 1.5%.
	Current requirements	For steady state operation it is recommended the emulator has nominal current capability 1,2 p.u. compared to nominal current of the turbine (20% more). (trip level DUT converter)
	Background harmonics:	It is desirable that the grid emulator has minimum voltage background noise as possible in the whole range of the bandwidth 100HZ – 9kHz
	Harmonic Injection:	This part is an optional application of grid emulator.
	Short circuit power of grid emulator:	The grid emulator will have a natural impedance by the HW components and an emulated impedance. This total short circuit impedance will determine the short circuit power of the emulator. Requirements for the level is found under SCR below.
	Short Circuit Ratio:	The short circuit power of the emulator should be high enough to achieve a $SCR > 2$ in relation to the DUT nominal power. Recommended to implement configurable SCR based on the voltage control of emulator.

953 Dynamic requirements for the grid emulator

Operation mode	Requirements	Description
Dynamic requirements	• Rate of change of voltage (RoCoV):	The grid emulator should be able to simulate over-voltage or under-voltage events very fast according to the IEC 61400-21-1 figure 16 and figure 17.
	• Over-current capability:	Over-sizing of grid emulators for this purpose can be necessary for UVRT testing of Type 3 WTs to handle higher levels of short circuit current contributions.
	• General Dynamic Emulations	The grid emulator shall be able to generate voltages with variable amplitudes, variable frequency and phase jumps
	• Controllable Dynamic Impedance:	This part is an optional application of grid emulator.

954

955 7.5.3.3 Grid emulator in combination with the voltage divider based equipment

956 Another possibility is the combination of the grid emulator with the shunt impedance based
 957 VSG. The voltage divider based test equipment is placed between the grid emulator and the
 958 WT. The combination of the two test devices enables the converter system of the grid emulator
 959 to be considerably smaller since the over-sizing for the UVRT tests of type 3 WTs is no longer
 960 necessary. Nevertheless, it is possible to emulate different grid connection points and
 961 deviations of the grid frequency.

962 7.5.3.4 Autotransformer based test equipment

963 A variable output transformer or autotransformer is another test equipment to perform UVRT or
 964 OVRT tests. It is a transformer in combination with appropriate switching units to connect
 965 another transformer output level to the load. Switching to a different combination of taps
 966 determines the type of fault as well as the depth of the voltage dip.

967 7.5.3.5 Requirements for the UVRT / OVRT HW equipment

- 968
- Voltage dip depths adjustable according to IEC 61400-21-1
 - 969 • Duration of the voltage dips adjustable according to IEC 61400-21-1
 - 970 • In the case of unbalanced faults, the phase relationship on the high voltage side of the
 971 WT transformer should correspond to fault type C according to [2].

972 7.5.4 Measurement systems for test benches

973 The measurement system and equipment used to acquire data from test benches must be
 974 chosen with a sufficient accuracy, following the requirements in IEC 61400-21-1.

975 For both voltage and current transducers Class 1.0 is required.

976 For the data acquisition sufficient sampling frequency must be chosen depended on the test
977 campaign, as defined in IEC 61400-21-1.

978

979

IECNORM.COM : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

980 **8 Measurement and test of electrical characteristics as defined in 61400-21-1**

981 This chapter defines the 61400-21-1 specific tests in relation to power quality, steady state
982 operation, dynamic response and control performance, as well as the documentation
983 requirements and a risk evaluation for the transferability of the test results towards the WT.

984 **8.1 Power Quality aspects**

985 **8.1.1 Flicker during continuous operation**

986 For testing the flicker emission of a wind turbine sufficiently, flicker shall be tested in the field.

987 Note: The flicker emission of a wind turbine can be influenced by many of its components, whereby the interaction
988 of these components is also significant. Some of these components are rotor blades, drivetrain, generator, converter
989 system, control system including pitch and speed control and control of active and reactive power, auxiliary supplies
990 etc.

991 **8.1.2 Flicker and voltage change during switching operations**

992 For testing the flicker and voltage change during switching operations of a wind turbine
993 sufficiently, tests shall be performed in the field.

994 Note: The flicker and voltage change during switching operations of a wind turbine can be influenced by many of its
995 components, whereby the interaction of these components is also significant. Some of these components are rotor
996 blades, drivetrain, generator, converter system, control system including pitch and speed control and control of active
997 and reactive power, auxiliary supplies etc.

998 **8.1.3 Harmonics**

999 **8.1.3.1 Description**

1000 The aim of this performance test is to determine the emission of voltage and current harmonics,
1001 interharmonics and higher frequency components of a DUT during continuous operations
1002 according to IEC 61400-21-1 on subsystem or component level.

1003 Further tests and analysis can be performed according to Annex D of IEC61400-21-1.

1004 **8.1.3.2 Test setup & test conditions**

1005 Two options are available for measuring the harmonics on a test bench:

- 1006 • Option 1: Measurement of harmonics on test bench with grid emulator.
- 1007 • Option 2: Measurement of harmonics on test bench with a connection of the DUT to the public
1008 grid.

1009 The following requirements are placed on the DUT for the measurement of harmonics on a test bench:

- 1010 • The following components have to be taken into account for the performance test according to
1011 Annex B.2
 - 1012 ○ Converter system
 - 1013 ○ Generator
 - 1014 ○ Additional Cap-banks for reactive power compensation (eg for Type 1 or 2 WTs)
 - 1015 ○ Filter
 - 1016 ○ Grid active power control
 - 1017 ○ Grid reactive power control

- 1018 ○ Generator power Control (or speed control)
- 1019 ○ Transformer
- 1020 ○ Drivetrain

1021 The measurement shall at least be performed on a category 2b test bench as described in chapter 7
1022 and meet the following characteristics:

- 1023 • The DUT shall operate within the active power bins 0%, 10%, 20%,..., 100% P_n .
- 1024 • The grid emulator has to fulfill the following requirements for the measurement of the sub-
1025 grouped harmonic voltages at no load condition (see Table 6). The measurement has to be
1026 done according to IEC 61000-21-1.
- 1027 • In case of the connection of the DUT to the public grid (see option 2), the test conditions of
1028 IEC61400-21-1 shall be applied.

1029 **Table 6 - Harmonic emission limits of the grid emulator at no load (disconnected DUT)**

Odd harmonics non-multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Harmonic order h	Harmonic voltage %	Harmonic order h	Harmonic voltage %	Harmonic order h	Harmonic voltage %
5	1,5	3	1,25	2	0,4
7	1,25	9	0,6	4	0,4
11	0,7	15	0,3	6	0,4
13	0,6	21	0,3	8	0,4
17 ≤ h ≤ 49	0,4	21 < h ≤ 49	0,3	10 < h ≤ 49	0,4
THDS _{U,50} shall be below 2% up to 50 th harmonics, THDS _{U,180} up to 180 th harmonics shall be below 3%.					

1030

1031 Note: The limits in Table 6 are based on no-load voltage requirement for LV (IEC61000-4-7). The compatibility level
1032 is the same for LV and MV according IEC61000-3-6 and IEC61000-2-4 (class 2).

1033 If the grid emulator does not fulfill the required limits of Table 6, or the public grid does not fulfill the
1034 required test conditions as given in IEC61400-21-1 then the influence of the background noise on the
1035 DUT harmonics shall be eliminated, either by following Annex E or by other methods, e.g. as given in
1036 Annex D of IEC 61400-21-1 for public grid connection. The method used shall be described in the report.
1037

1038 The upstream fundamental frequency short-circuit impedance seen from the DUT's grid side
1039 converter(s) (including all passive components of the DUT and the grid emulator), shall be in the range
1040 of 5% - 30% considering as base power the nominal power of the DUT.

1041 Note: The test conditions described above are required in order to obtain reliable test results and should not be
1042 viewed as conditions for a reliable connection to the energy supply network and for the operation of the DUT.

1043

1044 **8.1.3.3 Test & measurement procedure**

1045 Background noise measurement:

- 1046 • Before the measurement for option 1 or option 2 can be started, a background noise
1047 measurement shall be done. For this purpose, the DUT is disconnected from the grid emulator
1048 or the public grid.
- 1049 • One 10-minute data set of instantaneous voltage measurement shall be measured.

1050

1051 Measurement procedure for option 1 (see 8.1.3.2):

- 1052 • Set point reactive power: $Q = 0$ var.
1053 Optional: reactive power under- and overexcited at the maximum power bin.
- 1054 • Three 10-minute data sets of instantaneous voltage and current measurements shall be
1055 collected for each 10% power bin (0% P_n – 100% P_n) as the same modulation index as in the
1056 no load tests.
- 1057 • The maximum value from the three measurements and three phases of each power bin shall
1058 be taken.

1059
1060 Measurement procedure for option 2 (see 8.1.3.2):

- 1061 • Set point reactive power: $Q = 0$ var.
1062 Optional: reactive power under- and overexcited at the maximum power bin.
- 1063 • Seven, 10-minute data sets of instantaneous voltage and current measurements shall be
1064 collected for each 10% power bin (0% P_n – 100% P_n) as the same modulation index as in the
1065 no load tests.
- 1066 • The 95 percentile from the seven measurements and three phases of each power bin shall be
1067 taken.

1068 Note: All three phases shall be measured at the same time during the measurements for both options.

1069 A 10-cycle window for 50 Hz and 12-cycle window for 60 Hz power systems is recommended
1070 for the analysis of measurements. The window size shall be stated in the report.

1071 Harmonic currents below 0,1% of I_n for any of the harmonic orders need not be reported.

1072 The Discrete Fourier Transformation (DFT) is applied to each of the measured currents and
1073 voltages with rectangular weightings. The active power shall be evaluated over the same time
1074 window as the harmonics.

1075 The THC and $THDS_{U,50}$ distortion for each 10-cycle window for 50 Hz and 12-cycle window for
1076 60 Hz shall be calculated.

1077 The 10-minute square root of the harmonic mean of the squared 10-cycle (for 50 Hz power
1078 systems) or 12-cycle (for 60 Hz power systems) window values of each frequency band (i.e.
1079 each sub-group harmonic, sub-grouped centered interharmonic, higher frequency current and
1080 voltage component and THC and $THDS_{U,50}$) shall be calculated for each 10-minute time-series.

1081 If harmonics, interharmonics or higher frequency components are clearly influenced by
1082 background distortion, then in case of option 1 (see 8.1.3.2) the procedure of Annex E could be
1083 followed by calculating the DUT harmonic exclusive the background noise. In case of option 2
1084 (see 8.1.3.2) Annex D of IEC 61400-21-1 could be followed.

1085 **8.1.3.4 Documentation**

1086 The emission of current and voltage harmonics, interharmonics and higher frequency components
1087 shall be documented in tables and graphs as shown, for example, in Annex A.

1088
1089 The following parameters shall be given in tables in percentage of U_n for background measurement:
1090

- 1091 • voltage harmonics
- 1092 • voltage interharmonics
- 1093 • higher frequency voltage components
- 1094 • $THDS_U$ up to the 50th harmonic order

1095

1096 The following parameters shall be given in tables in percentage of I_n or U_n and for operation of the
1097 DUT within the active power bins 0%, 10%, 20%, ..., 100% of P_n . (Note: The 0, 10, 20, ..., 100% are
1098 the bin midpoints) for measurements according to IEC 61400-21-1.

1099

1100 Option 1 (see chapter 8.1.3.2):

- 1101 • Max value of current and voltage harmonics
- 1102 • Max value of current and voltage interharmonics
- 1103 • Max value of higher frequency current and voltage components
- 1104 • Max value of THC up to the 50th harmonic order
- 1105 • Max value of THDS_U up to the 50th harmonic order

1106

1107 Option 2 (see chapter 8.1.3.2):

1108

- 1109 • 95th percentile of current and voltage harmonics
- 1110 • 95th percentile of current and voltage interharmonics
- 1111 • 95th percentile of higher frequency current and voltage components
- 1112 • 95th percentile of THC up to the 50th harmonic order
- 1113 • 95th percentile of THDS_U up to the 50th harmonic order

1114

1115 The following information shall be given for the test:

- 1116 • Impedance of the grid emulator up to at least 50th harmonic order and if possible, up to 180th
1117 harmonic order (including the output transformer, filter and converter of the grid emulator)
- 1118 • Impedance of the transformer and the rest passive components of the DUT

1119 Optionally, prevailing phase angles and ratio may be also included, following IEC 61400-21-1:2019
1120 Annex D.

1121

1122 **8.1.3.5 Transferability of test results**

1123 The test results can replace full-scale wind turbine measurements of harmonics.

1124 **8.2 Steady state operation**

1125 The steady-state operation chapter consists of the steady state measurements in relation to
1126 maximum power, reactive power capability, unbalance factor etc.

1127 Measurements shall be sampled during steady-state operation only, i.e.: after having reached
1128 settling time according to IEC 61400-21-1.

1129 **8.2.1 Maximum power**

1130 **8.2.1.1 Description**

1131 The aim of this performance test is to show that the specified value of the active power output
1132 is kept constant in normal operation over different averaging time.

1133 The maximum measured power of the wind turbine shall be specified as a 600 s average value,
1134 P_{600} , a 60 s average value, P_{60} and as a 0,2 s average value, $P_{0,2}$. The maximum active power
1135 peaks are determined from each of the different averaging intervals.

1136 8.2.1.2 Test setup & test conditions

1137 The measurement shall at least be performed on a category 1a test bench as described in
1138 chapter 7. The test bench system shall provide torque variations according to the defined wind
1139 classes of the DUT and under simulated normal wind speed variations and distributions as
1140 described in IEC 61400-1

1141 The DUT shall include at least the components and control functions as defined in Annex B.2.

1142 8.2.1.3 Test & measurement procedure

1143 The overall procedure described in IEC 61400-21-1 section 8.3.3.2 shall be applied.

1144 The test shall be performed at full load with nominal power P_n and with simulated wind speed
1145 around the nominal wind speed according to the defined wind classes of the DUT and under
1146 normal wind speed variations and distributions as described in IEC 61400-1.

1147 8.2.1.4 Documentation

1148 The variables given in IEC 61400-21-1 section 8.3.3.3 shall be calculated.

1149 The data, tables and figures given in IEC 61400-21-1 section 8.3.3.3 and Annex A shall be
1150 documented.

1151 8.2.1.5 Transferability of test results

1152 The test results can replace full-scale wind turbine measurements of maximum power.

1153 8.2.2 Reactive power characteristic ($Q = 0$)**1154 8.2.2.1 Description**

1155 The aim of this measurement is to determine reactive power characteristic of the WT - DUT for
1156 a reference value of $Q = 0$.

1157 8.2.2.2 Test setup & test conditions

1158 The measurement shall at least be performed on a category 2a test bench as described in
1159 chapter 7. The test bench system shall provide torque variations according to the defined wind
1160 classes of the DUT and under simulated normal wind speed variations and distributions as
1161 described in IEC 61400-1.

1162 The DUT shall include at least the components and control functions as defined in Annex B.2.

1163 Different from the general requirement above, for type IV wind turbines, the test can be
1164 performed without generator, on a category 3a test bench.

1165 8.2.2.1 Procedure

1166 Measurements shall be sampled during steady-state operation only.

1167 The procedure described in IEC 61400-21-1 section 8.3.4.2 shall be applied, with the following
1168 exceptions:

- 1169 • measurements shall be taken so that at least one 1-minute time-series of active and
1170 reactive power are collected at each 10 % power bin.

1171 8.2.2.2 Documentation

1172 The variables given in IEC 61400-21-1 section 8.3.4.3 shall be calculated.

1173 The data, tables and figures given in IEC 61400-21-1 section 8.3.4.3 and Annex A shall be
1174 documented.

1175 **8.2.2.3 Transferability of test results**

1176 The test results can replace full-scale wind turbine measurements of reactive power
1177 characteristics.

1178 **8.2.3 Reactive power capability**

1179 **8.2.3.1 Description**

1180 The aim of this measurement is to determine the under- and overexcited reactive power
1181 capability of the WT as a function of the active power output.

1182 **8.2.3.2 Test setup & test conditions**

1183 The measurement of reactive power capability shall at least be performed on a category 2b test
1184 bench as described in chapter 7.

1185 The DUT shall include at least the components and control functions as defined in Annex B.2.

1186 Different from the general requirement above, for type IV wind turbines, the test can be
1187 performed without generator, on a category 3a test bench.

1188 **8.2.3.3 Procedure**

1189 Measurements shall be sampled during steady-state operation only.

1190 The procedure described in IEC 61400-21-1 section 8.3.5.2 shall be applied, with the following
1191 exceptions:

- 1192 • measurements shall be taken so that at least one 1-minute time-series of active and
1193 reactive power are collected at each 10 % power bin;

1194 **8.2.3.4 Documentation**

1195 The variables given in IEC 61400-21-1 section 8.3.5.3 shall be calculated.

1196 The data, tables and figures given in IEC 61400-21-1 section 8.3.5.3 and Annex A shall be
1197 documented.

1198 **8.2.3.5 Transferability of test results**

1199 The test results can replace full-scale wind turbine measurements of the reactive power
1200 capability.

1201 **8.2.4 Voltage dependency of PQ diagram**

1202 **8.2.4.1 Description**

1203 The dependency on the voltage variations at the DUT terminals should be documented
1204 according to the manufacturer's specification. The PQ diagram should be repeated for the
1205 maximum and minimum continuous operation voltage for the wind turbine according to the
1206 manufacturer's specification.

1207 **8.2.4.2 Test setup & test conditions**

1208 The measurement shall at least be performed on a category 2b test bench as described in
1209 chapter 7.

1210 The grid system shall be able to provide a variable stable voltage supply during the test (e.g.
1211 by a grid emulator).

1212 The DUT shall include at least the components and control functions as defined in Annex B.2.

1213 Different from the general requirement above, for type IV wind turbines, the test can be
1214 performed without generator, on a category 3a test bench.

1215 **8.2.4.3 Test & measurement procedure**

1216 Measurements shall be performed at each active power bin from 10 % to 100 % of P_n . The
1217 procedure as defined in IEC 61400-21-1: 2019, chapter 8.3.6.2 shall be applied.

1218 **8.2.4.4 Documentation**

1219 The variables given in IEC 61400-21-1:2019 section 8.3.6.3 shall be calculated.

1220 The data, tables and figures given in IEC 61400-21-1:2019 section 8.3.6.3 and Annex A shall
1221 be documented.

1222 Note: In order to gain higher resolution in certain areas of the PQ diagram, additional measurements can be carried
1223 out defining intermediate points within a power bin with the desired resolution.

1224 **8.2.4.5 Transferability of test results**

1225 The test results can replace full-scale wind turbine measurements of voltage dependency PQ-
1226 diagram.

1227 **8.2.5 Unbalance factor**

1228 **8.2.5.1 Description**

1229 The aim of the measurement is to determine the current unbalance factor in the wind turbine drive
1230 train mounted in a test bench.

1231 **8.2.5.2 Test setup & test conditions**

1232 The measurement shall at least be performed on a category 2b test bench as described in chapter 7.

1233 For the determination of the current unbalance factor, the voltage unbalance factor of the grid or of the
1234 grid emulator shall be as low as possible, at least less than 1% during the entire test (1 min averages).

1235 The DUT shall include at least the components and control functions as defined in Annex B.2

1236 **8.2.5.3 Test & measurement procedure**

1237 For the determination of the current unbalance factor the procedure below shall be followed:

1238
1239 The test shall be done in 10 steady states where the torque is controlled to give active power in steps
1240 of 10%, from 10% to 100%. The drivetrain shall be in a steady state for minimum 1 minute in each
1241 step. The positive sequence reactive power shall be set to zero. 3-phase voltage and currents shall be
1242 recorded, and 1-minute averages of voltage and current unbalances shall be calculated in each step.

1243
1244 The positive sequence voltage U_1 and current I_1 as well as the negative sequence voltage U_2 and
1245 current I_2 shall be calculated according to IEC 61400-21-1.

1246

1247 **8.2.5.4 Documentation**

1248 The measured 1-minute values of the current unbalance and the active power positive sequence
1249 system component are represented as an IUF versus active power diagram. The measurement
1250 results shall be presented in a table as mean values of each power bin, as defined, for example,
1251 in Table 8.2). The maximum current unbalance factor as a 1-minute value shall be explicitly
1252 given.

1253

Table 7 - Current unbalance factor

P [p.u.]	Q [p.u.]	U1 [p.u.]	U2 [p.u.]	UUF	I1 [p.u.]	I2 [p.u.]	IUF
~0,1	~0,0						
~0,2	~0,0						
~0,3	~0,0						

~0,4	~0,0						
~0,5	~0,0						
~0,6	~0,0						
~0,7	~0,0						
~0,8	~0,0						
~0,9	~0,0						
~1.0	~0,0						

1254

1255 **8.2.5.5 Transferability of test results**

1256 The test results can replace full-scale wind turbine measurements of unbalance.

1257 **8.3 Control performance**1258 **8.3.1 Active power control**1259 **8.3.1.1 Description**

1260 The ability of the wind turbine to operate in active power control mode shall be characterized
 1261 for various reference values given by the control interface. The aim of this test is to determine
 1262 the response of the WT to reference commands regarding the static error, the rise time and the
 1263 settling time of active power, for both steady-state conditions and under dynamic response
 1264 conditions.

1265 **8.3.1.2 Test setup & test conditions**

1266 The test shall at least be performed on a category 2a test bench test setup according to
 1267 chapter 7. The test shall be carried out in the wind speed range from the cut_in and cut_out
 1268 wind speed, in the power range of the DUT from 0 to 100 % and can be carried out in simulated
 1269 laminar wind conditions.

1270 The DUT shall include at least the components and control functions as defined in Annex B.2.

1271 **8.3.1.3 Test & measurement procedure**1272 **Static error test**

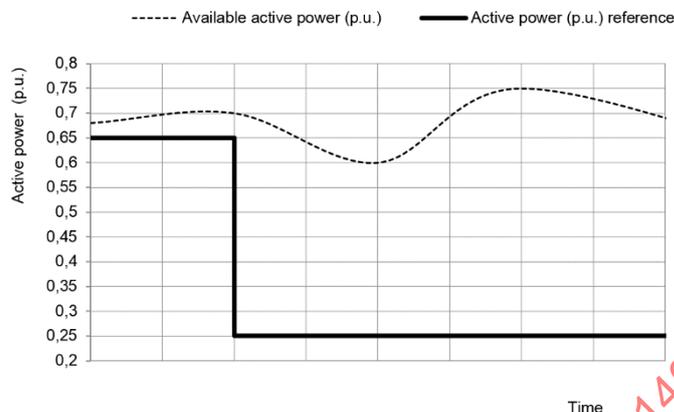
1273 For the test of the static error, the following test procedure is recommended: a reference value
 1274 shall request active power reduction from 1,0 p.u. to 0,20 p.u. in steps of 0,20 p.u. with at least
 1275 2-minute operation at each reference value in accordance with IEC 61400-21-1: 2019 chapter
 1276 8.3.4 - Figure 8.

1277 The calculation of the 1-minute block-average values for the test report shall be carried out
 1278 after steady state is reached. The time of steady state will be defined as the last 1 minute at
 1279 each step.

- 1280 • The absolute static error of the active power shall be measured.
- 1281 • The simulated wind speed should be such that the available active power output of the
 1282 DUT is at least 0,1 p.u. higher than the targeted reference value, but not less than 0,5 p.u.
 1283 during the entire test procedure. For the reference value of 1,0 p.u. the WT shall operate
 1284 with nominal active power.
- 1285 • The test has to be carried out continuously, i.e. it is not allowed to connect disjoint
 1286 measurements.
- 1287 • The sampled data for the active power shall be one fundamental period average data.

1288 Dynamic response test – step down

1289 This test will be used to determine the dynamic behaviour of the WT by observing the step
 1290 response characteristics (i.e. settling time, ramp-down time, reaction time). For this test a step
 1291 of the active power reference with a minimum step size of 0,4 p.u. of the nominal active power
 1292 is commanded, according to Figure 18.



1293

1294

Figure 18 - Example of active power response step

- 1295 • The tolerance band is $\pm 0,05$ p.u. for the calculation of the settling time.

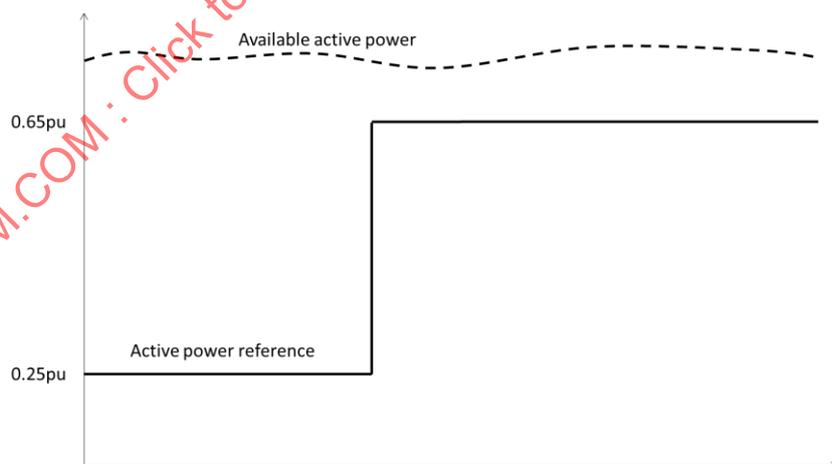
1296 The sampled data for active power shall be calculated over one fundamental period
 1297 (average data).

1298

1299 Ramp rate limitations shall be deactivated during the test. If this is not possible, the ramp
 1300 rate limitation has to be adjusted to the highest value (that causes the fastest reaction of
 1301 the WT).

1302

Dynamic response test – step up



1303

1304

Figure 19 - Active power dynamic step response

1305 This test will be used to determine the dynamic behaviour of the DUT by observing the step
 1306 response characteristics (i.e. settling time, ramp-up time, reaction time). For this test a step of
 1307 the active power reference with a minimum step size of 0,4 p.u. of the nominal active power is
 1308 commanded, according to Figure 19.

- 1309 • The tolerance band is $\pm 0,05$ p.u. for the calculation of the settling time.
- 1310 • The sampled data for active power shall be calculated over one fundamental period
- 1311 (average data).
- 1312 Ramp rate limitations shall be deactivated during the test. If this is not possible, the ramp
- 1313 rate limitation has to be adjusted to the highest value (that causes the fastest reaction of
- 1314 the WT).
- 1315 • The available power value that is internally calculated by the WT according to the given
- 1316 wind speed and other internal parameters will be provided for measurement.

1317

1318 **8.3.1.4 Documentation**

1319 The following parameters shall be calculated and documented in a test report:

1320 Time-series of:

- 1321 • Reference values sent to the DUT as P (p.u.)
- 1322 • Simulated wind speed given to the DUT/WT and the test bench
- 1323 • Available active power provided by the DUT controller
- 1324 • Measured positive sequence active power output at the grid connection point

1325 **8.3.1.5 Transferability of test results**

1326 The test results provide an overview of the control performance in relation active power control.

1327 The test results can replace full-scale wind turbine measurements.

1328 **8.3.2 Active power ramp rate limitation**

1329 **8.3.2.1 Description**

1330 The aim of this measurement is to show the capability of the WT to follow given active power

1331 gradients, with positive and negative ramp rate:

1332 The manufacturer shall declare the possible settings (reference values or setting range) of the

1333 ramp rates of the WT. The tests shall be adapted to the possible settings of the ramp rates of

1334 the WT.

1335 **8.3.2.2 Test setup & test conditions**

1336 The measurement shall at least be performed on a category 2a test bench as described in

1337 chapter 7.

1338 The test shall be carried out in the wind speed range from the cut_in and cut_out wind speed

1339 and in the power range of the DUT from 0 to 100 % and can be carried out in simulated laminar

1340 wind conditions.

1341 The DUT shall include at least the components and control functions as defined in Annex B.2.

1342 **8.3.2.3 Test & measurement procedure**

- 1343 • The simulated wind speed shall be high enough for active power production higher than
- 1344 0,7 p.u. for the entire test.
- 1345 • Data should be recorded from 10 s before the ramp rate command and until steady state
- 1346 condition is reached.

- 1347 • At the beginning of the test, the DUT shall be operated in normal operation mode. The
- 1348 active power of the WT can be set to an adequate start value above 0,5 p.u. of the
- 1349 nominal active power. Then the following two tests with different ramp rates shall be
- 1350 performed.
- 1351 • Test 1 (slow ramp rate), e.g. +/- 10 % P_n /minute
- 1352 • Test 2 (fast ramp rate), e.g. +/- 2 % P_n /s
- 1353 • The test shall be carried out with at least $P=0,2$ p.u. of the nominal active power between
- 1354 each reference value.

1355

8.3.2.4 Documentation

1356

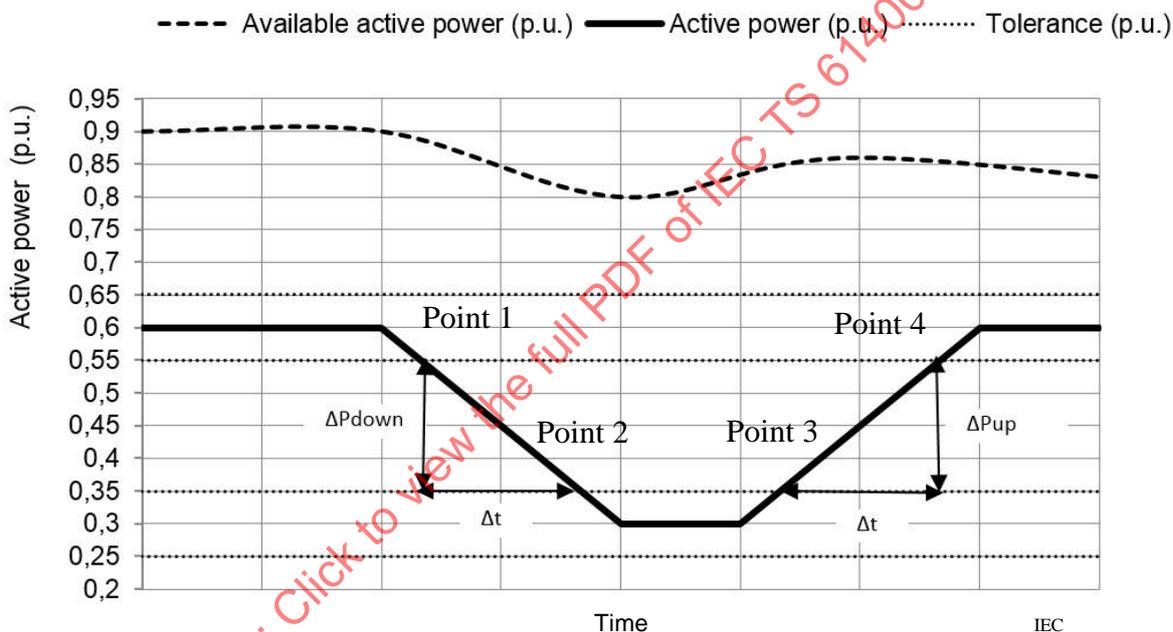
1357 The ability of the DUT to operate in ramp rate limitation control mode shall be characterized by

1358 test results presented in a graph. The graph shall show the available and measured active

1359 power output during the operational state. Figure 20 gives an example of a step with a negative

1360 ramp rate and of a step with a positive ramp rate. The steps are achieved by switching the DUT

1361 from one reference value to another reference value and back.



1362

Figure 20 - Example of available active power and active power in ramp rate limitation mode

1363

1364

1365 The positive and negative active power gradient shall be calculated from the 0,2 s average of

1366 the measured active power from respectively two different points during the ramp rate activation

1367 (point 1 and point 2 for the calculation of the negative gradient and point 3 and point 4 for the

1368 calculation of the positive gradient, in accordance with Figure 20.

1369

Table 8 - Active power ramp rate calculation

	Requested reference value P_{set} [p.u.]	Requested active power ramp rate $\Delta P/\Delta t$ [p.u./s]	Measured active power ramp rate $\Delta P/\Delta t$ [p.u./s]
Point 1			
Point 2			

Point 3			
Point 4			

1370

1371 • Requested and measured ramp rate characteristic shall be given in the test report in
1372 accordance with Table 8.

1373 • The available and measured active power output shall be represented in a graph in
1374 accordance with Figure 20.

1375 • A declaration of the ramp rate setting procedure by the manufacturer shall be described in
1376 the test report.

1377 The following parameters shall be calculated and documented in a test report:

1378 Time-series of:

1379 • Active power reference values sent to the DUT in p.u.

1380 • Simulated wind speed given to the DUT and the test bench

1381 • Available active power provided by the DUT controller

1382 • Measured positive sequence active power output at the grid connection point

1383 8.3.2.5 Transferability of test results

1384 The test results provide an overview of the control performance in relation active power control.

1385 The test results can replace full-scale wind turbine measurements.

1386 8.3.3 Frequency control

1387 8.3.3.1 Description

1388 With this test, the active power reduction as a function of the grid over-frequency shall be
1389 measured and documented.

1390 NOTE The defined frequency test includes only over-frequency and no under frequency tests, as the described
1391 procedure mainly validate the functionality of the frequency control and not the real performance in relation to
1392 frequency changes. The underfrequency test can be performed in a similar way as defined in the procedure. The real
1393 frequency capability test is defined in chapter 9.2.2.

1394 The wind turbine frequency dependent active power control capability shall be declared by the
1395 manufacturer and document in terms of e.g. dead band, slope, release conditions.

1396 8.3.3.2 Test setup & test conditions

1397 The measurement shall at least be performed on a category 2a test bench as described in
1398 chapter 7. In the wind speed range from cut_in to cut_out wind speeds, in the power range of
1399 the DUT from 0 to 100 % and under simulated laminar wind conditions.

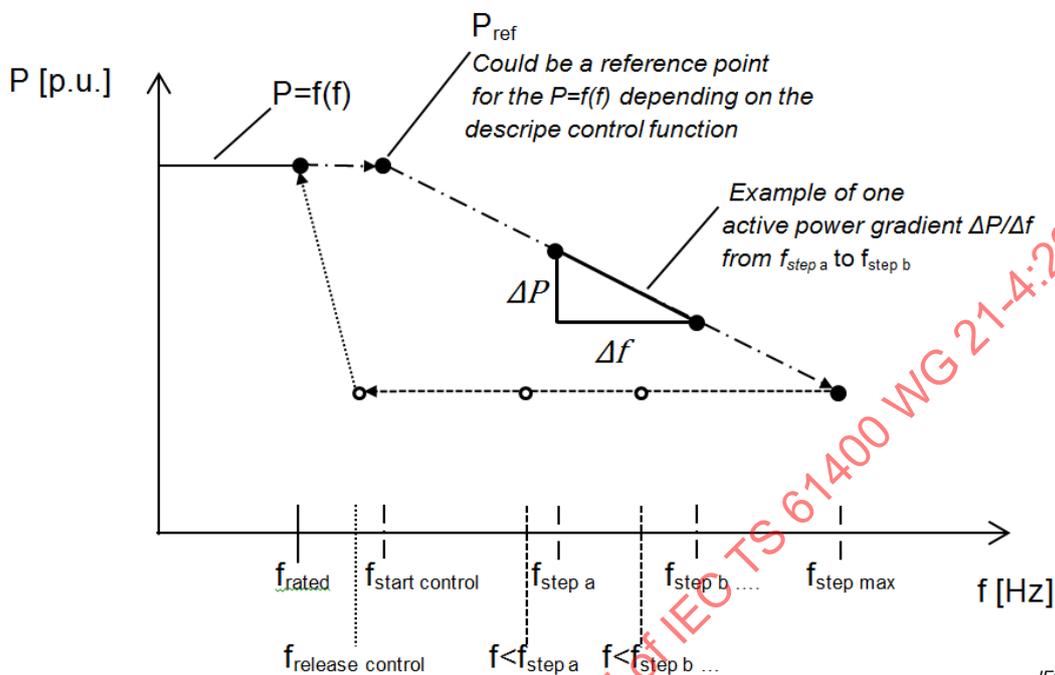
1400 The DUT shall include at least the components and control functions as defined in Annex B.2.

1401 8.3.3.3 Test & measurement procedure

1402 The procedure to test frequency control involves pairs of frequency and active power which
1403 begin from a starting point at "First measurement point" to the maximum possible frequency
1404 reference value at "step max" and back to the starting point "Step release control" according to
1405 the chosen function of the controller. The following tests verify the control capability of the WT
1406 to perform a frequency dependent power control, with a given gradient.

1407 The Figure 21 shows an example of an active power control function $P = f(f)$.

1408 It is up to the DUT manufacturer to define the kind of control function that shall be tested. The
 1409 number of frequency steps and frequency values is variable and depends on the control function
 1410 to be tested.



1411

IEC

1412 **Figure 21 – Example of an active power control function $P=f(f)$, with the different**
 1413 **measurement points and related steps of frequency**

1414 The test shall be performed at two different power levels, at

- 1415 a) $P > 0,8$ p.u.
 1416 b) P between $0,25$ p.u. and $0,5$ p.u.

1417 Each frequency step should be held for at least 30 seconds.

1418 If the controller allows different settings concerning the response time or the delay time for the
 1419 frequency-dependent active power reduction, then the fastest possible setting has to be chosen.

1420 For the test itself, one of the following procedures shall be used:

- 1421 a) Change the frequency of the grid, e.g. with a grid emulator.
 1422 b) Provide an internal or external input at the control unit to add a frequency reference value
 1423 offset to the nominal frequency. The software shall be adapted to calculate a resulting
 1424 frequency (nominal frequency + offset signal) and to react to this signal. For this test, also
 1425 the additional offset shall be measured.

1426 The grid protection settings of the DUT shall not be changed during the test.

1427 8.3.3.4 Documentation

1428 The following information shall be given:

- 1429 • The frequency control function declared by the manufacturer
 1430 • Description of the test setup / Real time simulator setup
 1431 • Measurement setup according to chosen test procedure

1432 The following parameters shall be documented in tables and graphs as shown in for example Annex A

- 1433 • The measured frequency together with the reference signal has to be documented. The
1434 active power output of the DUT as block average time values (0,2 s) and the available
1435 active power have to be documented.
- 1436 • The active power and the frequency change over time shall be presented in the report.
- 1437 • The results of the test "frequency increase at nominal active power" have to be
1438 documented in a table. This includes the measured frequency and active power and the
1439 calculated active power gradient.
- 1440 • The active power gradient between two consecutive measurement points shall be
1441 determined by calculation of $\Delta P/\Delta f$, as can be seen in Figure 21 as an example.
- 1442 • The results of the test "frequency increase at partial power" have to be documented in a
1443 table. This includes the measured frequency and active power and the calculated active
1444 power gradient.
- 1445 • The active power shall be plotted over the frequency increase. Frequency increase is the
1446 difference between the measured frequency and the nominal frequency of wind turbine.
- 1447 • For nominal as well as for partial power, an average gradient of active power shall be
1448 calculated and reported based on the determined gradients given in Table 9.

1449 Every change of parameter shall be documented.

1450 **Table 9 – Example of settings for the frequency dependent active power function**

Step of the Measurement	Measured Grid frequency [Hz]	Frequency reference [Hz]	Measured Active power [p.u.]	Active power gradient [p.u./Hz]
First measurement point	f_{rated}	-----		-----
Step start control				
Step $f_{step\ a}$				
Step $f_{step\ b}$				
Step max				
Step $f < f_{step\ b}$				
Step $f < f_{step\ a}$				
Step release control				

1451 .

1452 8.3.3.5 Transferability of test results

1453 The test results provide an overview of the control performance in relation to the frequency
1454 depended active power control.

1455 The test results can replace full-scale wind turbine measurements.

1456 8.3.4 Synthetic inertia

1457 The aim of this test is to document the wind turbine ability to provide a synthetic inertia in the
1458 case of fast frequency events in the power system.

1459 **8.3.4.1 Description**

1460 The aim of the test is to determine the control performance of the Wind turbine to provide
 1461 synthetic inertia in case of under frequency events, as basis for the simulation model of the
 1462 Wind power plant.

1463 **8.3.4.2 Test setup & test conditions**

1464 The measurement shall at least be performed on a category 2a test bench as described in
 1465 chapter 7. In the simulated wind speed ranges from the cut_in and cut_out wind speed, in the
 1466 power range of the DUT from 0 to 100 % and can be carried out in simulated laminar wind
 1467 conditions according to IEC 61400-1.

1468 The grid emulator – shall be able to vary the frequency with a frequency change of minimum 5
 1469 Hz/s in the range of +/- 10 % of the nominal grid frequency. Alternative a simulated frequency
 1470 signal shall be applied to the WT control system.

1471 The DUT shall include at least the components and control functions as defined in Annex B.2.

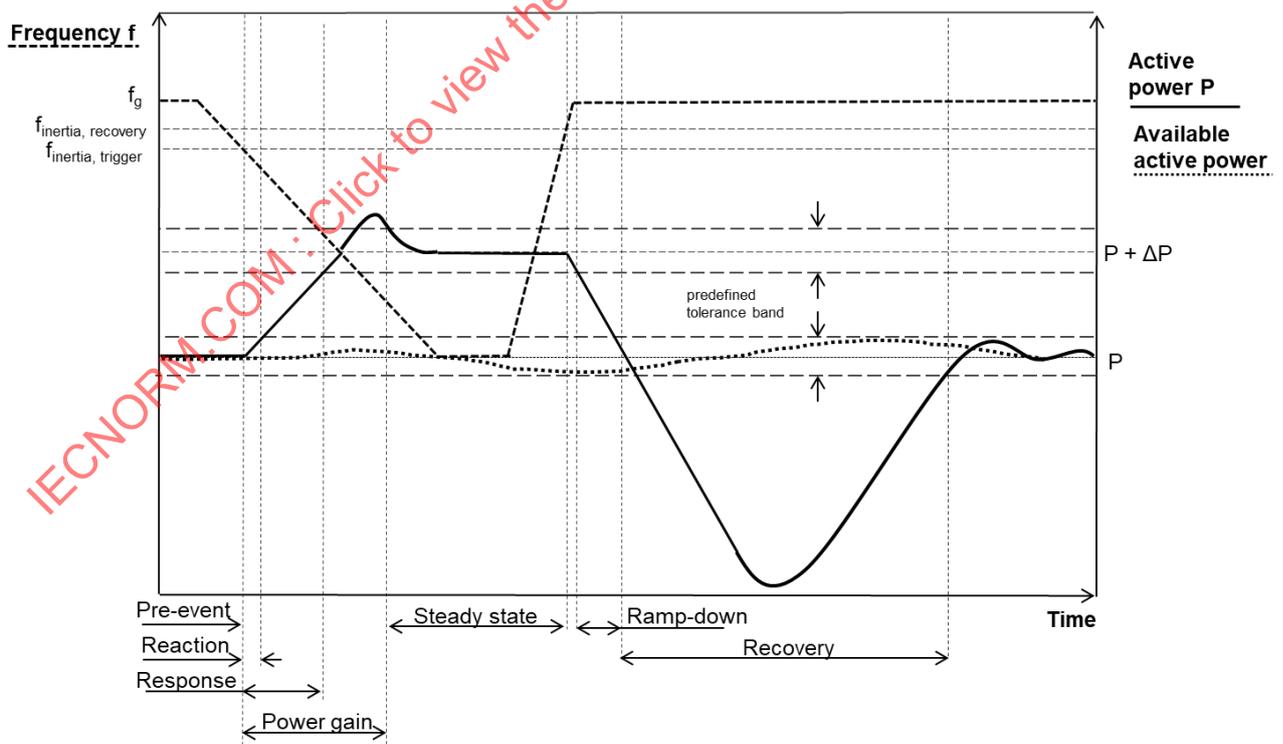
1472 **8.3.4.3 Test & measurement procedure**

1473 The test shall be performed under the following conditions:

- 1474 a) At partial load with an active power output of 0,3, 0,5, 0,8 and 1.0 P_n with an simulation of
 1475 constant wind speed / fixed torque
- 1476 b) At full load with 1,0 P_n with wind speed above 20 % of the nominal wind speed
- 1477 c) At full load with 1,0 P_n with varying wind speed of +/- 10 % around the nominal wind
 1478 speed. The wind speed shall decrease/ increase together with the frequency variation

1479

1480



1481

1482

Figure 22 - Synthetic inertia – example response and definition

1483 The stated response shall include results from at least 2 tests for each case - a, b and c.

1484 The analysis of the measurement consists of 4 intervals of active power output behaviour:

- 1485 1. **power gain** This interval starts from the point in time of detection of the event
1486 (Δ frequency, df/dt , frequency point, etc.) until a pre-defined value, whether it is an
1487 agreed change in active power ΔP , 90% of the agreed change in active power P (as
1488 shown in Figure 22), a defined time limit or a defined frequency, etc.
- 1489 2. **steady state:** This interval runs between the end of the power gain interval until a
1490 defined value such as a time interval limit, a defined frequency level or change has
1491 been reached, etc.
- 1492 3. **ramp-down:** This interval starts from the end of the steady state interval until a
1493 defined value has been reached such as the available active power output, the pre-
1494 event power output or a defined time limit, etc.
- 1495 4. **recovery:** Interval from the end of the ramp-down interval until a defined value has
1496 been reached such as a time limit. This interval essentially covers the time taken for
1497 the DUT to stabilize.

1498 Data recording and measurement accuracy shall follow the specification in chapter 7.5.4

1499 8.3.4.4 Documentation

1500 The following parameters shall be calculated and documented in a test report:

- 1501 • Setting of synthetic inertia control parameters according to
- 1502 • Table 10

1503 **Table 10 – synthetic inertia settings**

Parameter	Set value
Default active power gain ΔP (p.u.)	
Gradient of active power boost dP/dt (rising) in kW/s (p.u./s)	
Gradient of active power boost dP/dt (falling) in kW/s (p.u./s)	
$f_{inertia, trigger}$ in Hz	
$f_{inertia, recovery}$ in Hz	

1504

1505 Time-series of:

- 1506 • Measured positive sequence active power output at the grid connection point
- 1507 • Measured rotational speed of the DUT at the rotor shaft
- 1508 • Measured frequency or the frequency reference value f_{sim} , measured as 0,1 s average
1509 value at the grid connection point.
- 1510 • Available active power provided by the WT controller

1511 For 5 s prior to the start of the synthetic inertia event and at least 5 s after the active power
1512 recovery phase of the DUT has terminated.

1513 Calculated parameters according to Table 11

1514

Table 11 - Synthetic Inertia results

Period of measurements						
Operational mode of the DUT during the test						
Active power range resp. wind speed range	$0,3 P_n$	$0,5 P_n$	$0,8 P_n$	$1,0 P_n$	$v > v_n$ Constant wind speed	$v > v_n$ Varying wind speed
Test number	1	2	3	4	5	6
Pre-event: steady state average output power in p.u.						
Pre-event: steady state maximum output power in p.u.						
Pre-event steady state minimum output power in p.u.						
Response time in ms						
Settling time in ms						
Steady-state time in ms						
Ramp-down time in ms						
Recovery time in ms						
Recovery period minimum power in p.u.						
Recovery period average output power in p.u.						

1515

1516 A report template is given in Annex A.

1517 **8.3.4.5 Transferability of test results**1518 The test results provide an overview of the control performance in relation to fast frequency
1519 changes / events.1520 The test results can replace full-scale wind turbine measurements of the synthetic Inertia
1521 response.1522 **8.3.5 Reactive power control**1523 **8.3.5.1 Description**1524 The aim of this test is to determine the reactive power control response of the DUT to reference
1525 commands. The control behavior will be determined in relation to the static error, the rise time
1526 and the settling time of reactive power using either reactive power, voltage or $\cos \varphi$ reference
1527 values, depending on the wind turbine control system as specified by the manufacturer.1528 **8.3.5.2 Test setup & test conditions**1529 The measurement shall at least be performed on a category 2b test bench as described in
1530 chapter 7.

1531 The DUT shall include at least the components and control functions as defined in Annex B.2.

1532 Different from the general requirement above, for type IV wind turbines, the test can be
1533 performed without generator, on a category 3a test bench.

1534

1535 **8.3.5.3 Test & measurement procedure**

1536 The test procedure as described in IEC 61400-21-1 section 8.4.6.1 for the steady state and
1537 dynamic response test shall be applied.

1538 **8.3.5.4 Documentation**

1539 The variables given in IEC 61400-21-1: 2019 section 8.4.6.3 shall be calculated.

1540 The data, tables and figures given in IEC 61400-21-1 section 8.4.6.3 and Annex A shall be
1541 documented.

1542 **8.3.5.5 Transferability of test results**

1543 The test results can replace full-scale wind turbine measurements of the reactive power control
1544 performance.

1545 The reactive power demand of the transformer and cables can be added by calculations to the
1546 final result, based on the data and measurement reports of these components.

1547 **8.4 Voltage fault ride through**

1548 **8.4.1.1 General**

1549 The following chapter describes the test procedures according to:

- 1550 - Strategy 1: Performance tests at nacelle level
- 1551 - Strategy 2: Functionality and capability tests on subsystem and/or component level

1552 As e.g. shown in Figure 2.

1553 In subchapter 8.4.2, strategy 1 is taken up, in which FRT tests are typically described at nacelle
1554 level, which can be used directly, taking a transferability assessment into account, instead of a
1555 field test. If validated results can be shown on test benches of other classes (e.g., test bench
1556 category 2a), it is also possible to perform the performance test on this test benches (see
1557 chapter 5).

1558 In subchapter 8.4.3, strategy 2 is taken up, which considers the idea of the division into
1559 functionality and capability tests. In combination with performance tests or field tests, an
1560 assessment of the ability to ride through undervoltage and overvoltage events in the grid and
1561 support it according to the requirements is possible.

1562 Field tests cover the full scope of FRT testing. Performance testing also covers the full scope
1563 of testing and can be equated with detailed documentation of the missing components on the
1564 test benches including an associated risk assessment for the transferability assessment of
1565 results.

1566 Capability tests and functionality tests can replace certain tests. Some test examples are
1567 described in subchapter 8.4.3. A combination of capability tests, functionality test and
1568 performance tests can reduce the test effort on the test bench for performance testing or in the
1569 field. These tests can be performed on different test benches and within different stages of WT
1570 development process. The results are combined at the end and proven by individual
1571 performance tests or field tests.

1572

1573 **8.4.2 FRT - Performance testing according to Strategy 1**

1574 The following objective is to describe the proof for riding through grid faults and to validate the
 1575 performance of dynamic grid support. Undervoltage events and overvoltage events are
 1576 described in subchapter 8.4.2.1 and subchapter 8.4.2.3. Due to the capabilities of modern grid
 1577 emulators not only to adjust voltages and frequencies according to the specifications, but also
 1578 to emulate a grid impedance in the controlled mode of operation, there are two described
 1579 variants of the test execution.

1580 Variant 1 describes the tests with definitions of IEC 61400-21-1 with regard to the voltage
 1581 requirements.

1582 Variant 2 describes the tests with the definitions of IEC 61400-21-1 with regard to the voltage
 1583 requirements and also concretizes the requirements on the dynamic grid impedance changes,
 1584 from a grid emulator.

1585 The chapters have a uniform structure starting with a very brief introduction; the description of
 1586 the test setup and description of the components to be emulated; the actual description and
 1587 definition of the tests; the measurement data to be recorded for the purpose of documentation;
 1588 and the explicit identification of special features of the respective test execution, so that a final
 1589 classification and evaluation of the tests can be carried out.

1590 **8.4.2.1 Fault ride through without impedance control (Variant 1)**

1591 **8.4.2.2 Description**

1592 The following chapter describes the test setup and test methodology for demonstrating the
 1593 overvoltage and undervoltage performance of a DUT with a specified voltage shape according
 1594 to IEC 61400-21-1 without dynamic impedance control.

1595 **8.4.2.2.1 Test setup & test conditions**

1596 To perform the FRT tests, requirements are specified for the DUT and the test bench, which are
 1597 needed to prove the FRT performance of the DUT.

Overview of components, subsystems and control functions for FRT performance tests

Type of Test	Chapter	test bench system	Functionality test	Capability test	Performance test	Converter System	Generator	Additional Cap. banks	Filter	Grid Power Control (active Power)	Grid Power Control (reactive Power)	Generator Power Control (or speed controller / torque control)	Switch Gear (Circuit breaker / Contactor)	Transformer	Aux. equip.	Grid (FRT) Current Control	Grid Voltage Control	Frequency Control	Grid protection functions	Hub	Blades (always emulated)	Pitch system	Pitch controller	Drive train (Incl. Gearbox)
UVRT	8.4.2	1a	x	x	x	x	x	x	x	x	x	x	x ²	x	x	x	x	3	4	x ¹	x ¹	x ¹	x ¹	x ¹
OVRT	8.4.2	1a	x	x	x	x	x	x	x	x	x	x	x ²	x	x	x	x	3	4	x ¹	x ¹	x ¹	x ¹	x ¹

¹ = can be either emulated or physical available
² = if not physically at the test bench, the trigger signal could be measured
³ = Not necessary if the manufacturer can declare that this function has no effect on the FRT.
⁴ = If the trigger signal for switch gear shall be recorded, the grid protection functions are needed

1598

1599 **Figure 23 - Overview of DUT components for FRT-performance test**

1600 Figure 23 provides an overview of which components must be set up as a hardware component
 1601 on the test bench and has to be emulated during the tests. Furthermore, a test bench system
 1602 is selected.

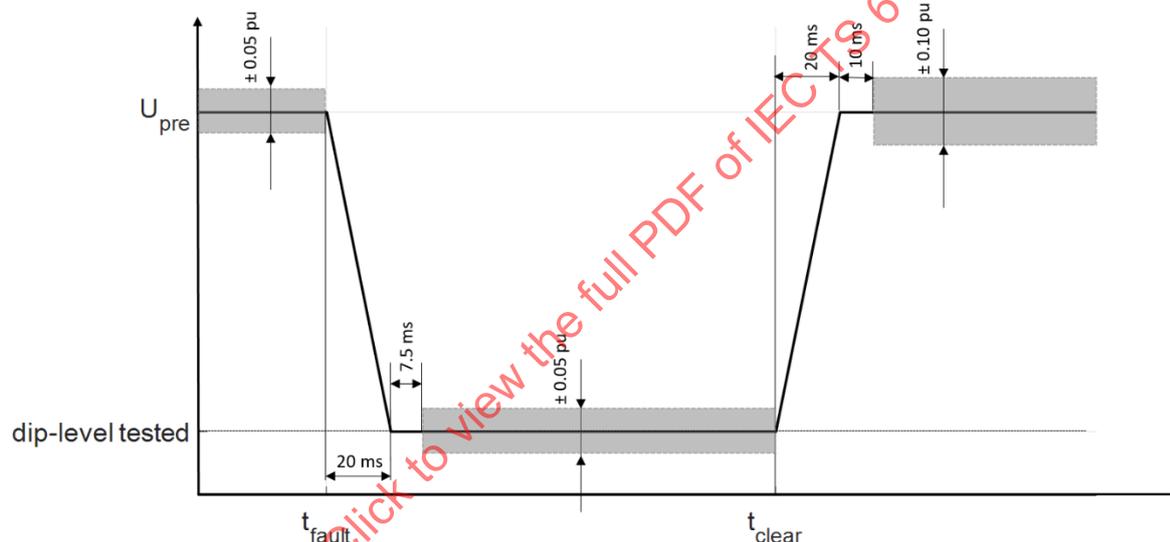
1603 The FRT-tests have to be performed on a category 1a test bench as describes in
 1604 chapter 7 (Figure 6). Test can be done at other test bench classes with mHiL system if the
 1605 validity of the measurements can be shown. The test bench must meet the following
 1606 characteristics:

1607 For type IV wind turbine, a quasi-stationary model for rotor emulation, as well as a laminar wind
 1608 conditions, are sufficient. Hence, the rotor and structure emulation can correspond to level 2 of
 1609 Table 3.

1610 For type III wind turbine the rotor and structure emulation must correspond to level 1 of Table 3.

1611 UVRT/OVRT HW equipment as described in chapter 7.5.3 is required to perform the FRT tests.
 1612 Figure 24 is based on Figure 16 of IEC 61400-21-1: 2019 and describes the tolerance of the
 1613 positive sequence voltage for an undervoltage event with disconnected DUT under test. It is
 1614 stated as per unit of the pre fault voltage.

1615 Annex D shows some examples of the transferability of the transient voltage transition between
 1616 the field measurement and test bench measurement campaigns. Annex D also explains why the
 1617 tolerance band for the dynamic range in Figure 16 of IEC 61400-21-1 is no longer available.



1618

1619 **Figure 24 - Tolerance of the positive sequence voltage for the undervoltage event with**
 1620 **disconnected DUT under test**

1621 Description of Figure 24:

- 1622 • There are three areas, the pre-fault voltage, the fault case and the post-fault voltage
 - 1623 o In the pre-fault range, the voltage may differ from the set point by $\pm 0,05$ p.u.
 - 1624 o The most important value is the tested dip-level. Here again, a deviation of
 1625 $\pm 0,05$ p.u. is possible.
 - 1626 o After the fault, a deviation of $\pm 0,1$ p.u. from the pre-fault value is permissible.
- 1627 • The transition between the areas requires at least 20 ms in the positive sequence
 1628 system.

- 1629 o There is a tolerance of total 7,5 ms for the positive sequence voltage during
1630 the dip. After this time, the positive sequence voltage needs to be within the
1631 tolerance band around the tested dip-level.
- 1632 o The tolerance on the positive sequence voltage during the recovery is 10 ms.
1633 After this time, the positive sequence voltage needs to be within the tolerance
1634 band around the post-fault voltage.
- 1635 • The time from t_{fault} to t_{clear} describes the fault duration.
- 1636 • Further requirements:
- 1637 o The transient voltage transition in the instantaneous phase voltage is linear,
1638 with a constant slope.
- 1639 o The dip starts at the same time in all affected phases.

1640 Note: If the exact behavior of a voltage divider based test equipment should be represented the performance of real
1641 circuit breakers needs to be considered. That means during fault clearance, the voltage return for three-phase faults
1642 is performed via a two-phase fault.

1643

1644 **8.4.2.2.2 Test & measurement procedure for UVRT-Tests**

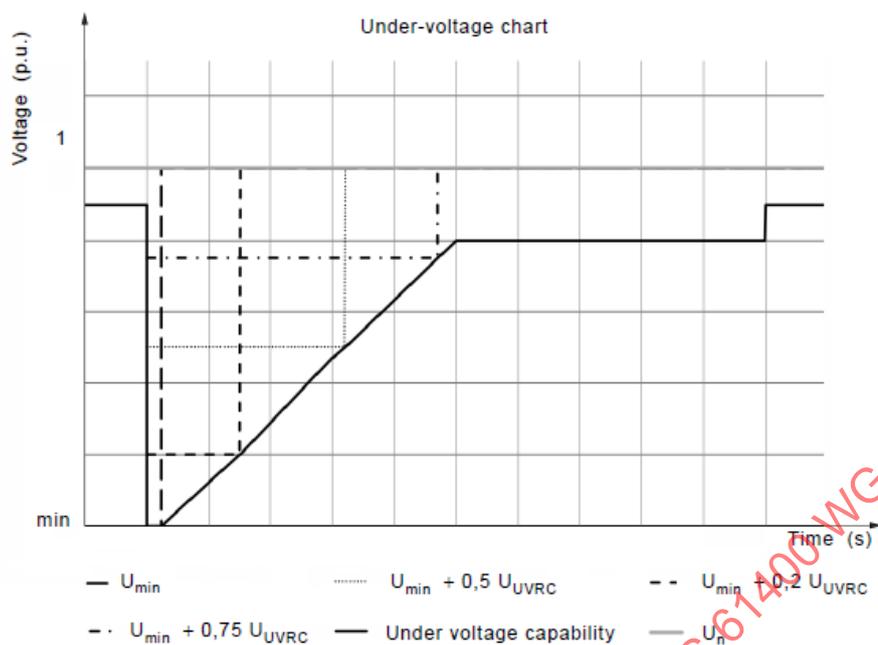
1645 The number of tests and operational modes needs to be defined and describes by the
1646 manufacturer in order to document the capability of the DUT. It is recommended to test at four
1647 different undervoltage levels:

- 1648 • minimum voltage the DUT can ride through U_{min} ,
- 1649 • $U_{\text{min}} + 0,2$ p.u. of the under voltage range capability U_{UVRC} ,
- 1650 • $U_{\text{min}} + 0,5$ p.u. U_{UVRC} and
- 1651 • $U_{\text{min}} + 0,75$ p.u. U_{UVRC} .

1652 Each dip should be repeated twice in a row.

1653 The definition of the number of the voltage levels and the exact duration of the dips is given by the
1654 manufacturer capability chart as shown in Figure 25.

1655



IEC

1656

1657

Figure 25 - Example of an undervoltage test chart

1658 Table 12 in IEC 61400-21:2019 shows the specified magnitudes and durations for the
 1659 undervoltage event occurring by doing a no-load test. The duration is defined according to the
 1660 given capability curve. Figure 24 describes the tolerance of the no-load tests. In case of a grid
 1661 emulator, chapter 8.4.2.2.1 specifies further test conditions.

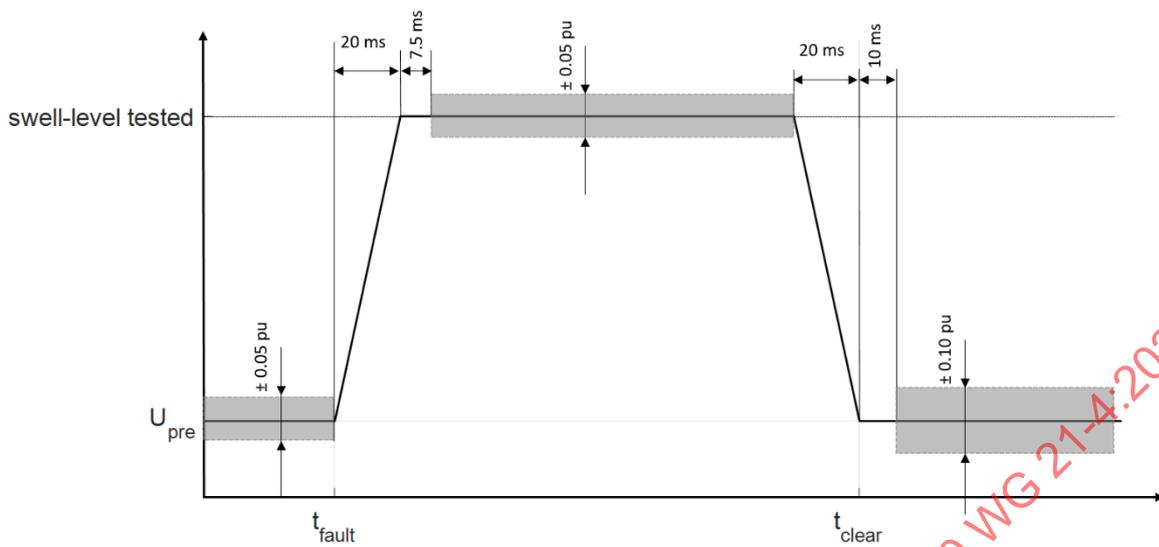
1662 The length of the time-series is defined as from stable conditions prior to the voltage dip or
 1663 swell and until the effect of the undervoltage or overvoltage event has abated. Typically, 10 s
 1664 prior and 10 s post fault.

1665 Further, the test shall be carried out for the DUT operating at partial load, between 0,25 p.u.
 1666 and 0,5 p.u. and under full load conditions, above 0,9 p.u. of the nominal active power.

1667 8.4.2.2.3 Test & measurement procedure for OVRT-Tests

1668 The number of tests and operational modes needs to be defined and describes by the
 1669 manufacturer in order to document the capability of the DUT.

1670 Each swell should be repeated twice in a row.



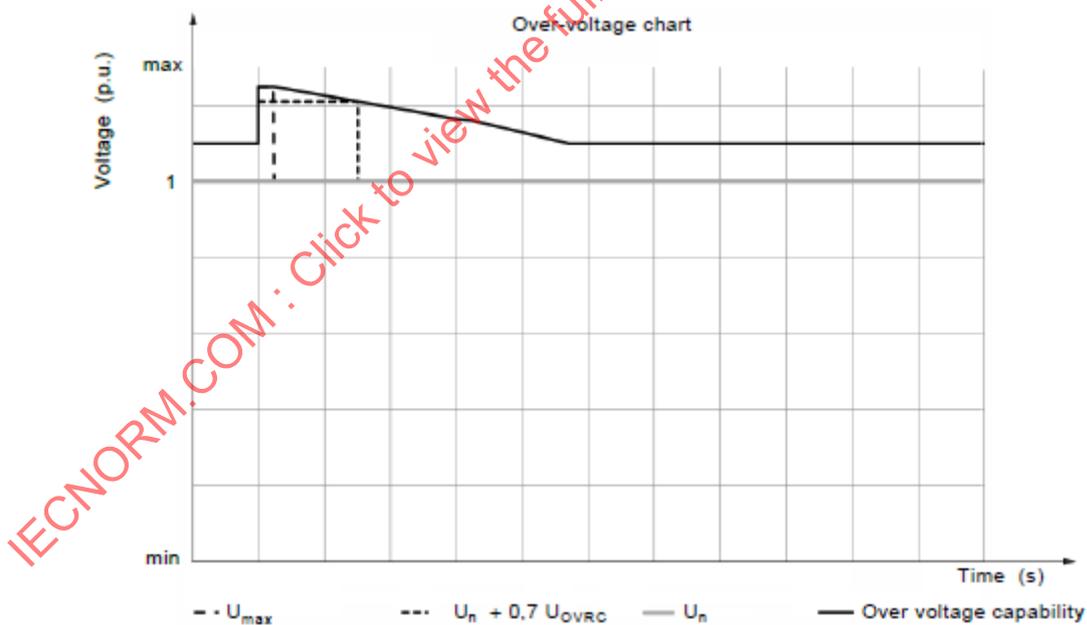
1671

1672 **Figure 26 - Tolerance of the positive sequence voltage for the overvoltage event with**
 1673 **disconnected DUT**

1674

1675 The definition of the number of the voltage levels and the exact duration of the swell is given
 1676 by the manufacturer capability chart as shown in Figure 27.

1677



1678

1679 **Figure 27 - Example of an over voltage capability chart**

1680 Table 13 in IEC 61400-21-1:2019 shows the specified magnitudes and durations for the
 1681 overvoltage event occurring by doing a no-load test. Figure 26 describes the tolerance of the
 1682 no-load tests. The duration is defined according to the given capability curve. In case of a grid
 1683 emulator, chapter 8.4.2.2.1 specifies further test conditions.

1684 The test shall be carried out for the WT operating at partial load, between 0,25 p.u. and 0,5 p.u.
1685 and under full load conditions, above 0,9 p.u. of the nominal active power.

1686 It is recommended to conduct and evaluate no-load tests before performing measurements with
1687 converter-based test equipment. Check whether the required dynamic is maintained during
1688 voltage dip and voltage recovery. Furthermore, the resulting voltage level and the phase angle
1689 of the voltage during the dip must be verified and documented. The specified setpoint must also
1690 be stated.

1691 **8.4.2.2.4 Documentation**

1692 The following information shall be given and documented:

- 1693 • Description of the test setup / Real time simulator setup
- 1694 • Description of the impedance of the test bench system and the passive components of the
1695 DUT
- 1696 • Signals for validation of rotor emulation, for example emulated wind speed, emulated torque,
1697 Torque measures
- 1698 • Adjusted parameters at the grid emulator for the voltage dip and the voltage recovery

1699 The following parameters and measurements must be documented for the DUT:

- 1700 • positive and negative sequence voltage,
- 1701 • positive and negative sequence currents,
- 1702 • active power,
- 1703 • reactive power,
- 1704 • active current,
- 1705 • reactive current,
- 1706 • simulated wind speed or available power
- 1707 • phase angles
- 1708 • set points for active and reactive power

1709 The positive sequence and negative sequence values shall be calculated in accordance with Annex C
1710 of IEC61400-21-1:2019.

1711 All measurements per unit are referred to the nominal values. Further the calculation of the trigger
1712 point of fault start must be document.

1713 **8.4.2.2.5 Transferability of test results**

1714 The results of performance testing can replace full-scale wind turbine measurements of UVRT
1715 and OVRT.

1716 If the tests in the field and on the test bench are performed with the same test setup, no further
1717 considerations are necessary. If a different setup is used on the test bench, it must be described
1718 and further consideration is necessary as shown in Appendix C.

1719 8.4.2.3 Fault ride through with impedance control

1720 8.4.2.4 Description

1721 To demonstrate the FRT capability of a DUT according to IEC 61400-21-1 on a subsystem or
 1722 component level, the test bench has to emulate the test procedure like a voltage-divider based
 1723 test equipment. This chapter is representing equivalent testing procedure according to voltage-
 1724 divider based test equipment testing in field.

1725 8.4.2.4.1 Test setup & test conditions

1726 To perform the FRT tests, requirements are specified for the DUT and the test bench, which
 1727 are needed to prove the FRT performance of the DUT.

1728 Figure 23 provides an overview of which components must be set up as a hardware component
 1729 on the test bench and has to be emulated during the tests. Furthermore, a test bench system
 1730 is selected.

1731 The FRT-tests have to be performed on a category 1a test bench as describes in
 1732 chapter 7 (Figure 6). Test can be done at other test bench classes with mHiL system if the
 1733 validity of the measurements can be shown. The test bench must meet the following
 1734 characteristics:

1735 For type IV wind turbine, a quasi-stationary model for rotor emulation, as well as a laminar wind
 1736 conditions, are sufficient. Hence, the rotor and structure emulation can correspond to level 2 of
 1737 Table 3.

1738 For type III wind turbine the rotor and structure emulation must correspond to level 1 of Table 3.

1739 UVRT/OVRT HW equipment as described in chapter 7.5.3 is required to perform the FRT tests.

1740 Figure 24 is based on Figure 16 of IEC 61400-21-1: 2019 and describes the tolerance of the
 1741 positive sequence voltage for an undervoltage event with disconnected DUT. It is stated as per
 1742 unit of the pre fault voltage.

1743 The requirements for full converter-based grid emulators with dynamic impedance control are
 1744 described in the following.

1745 Methodology of impedance control:

1746 The impedance at the connection point of the WT changes dynamically during field tests with
 1747 the voltage divider-based test equipment due to the connected and disconnected impedances.
 1748 Figure 28 demonstrates the impedance profile at the connection point of the WT using the
 1749 voltage divider-based test equipment.

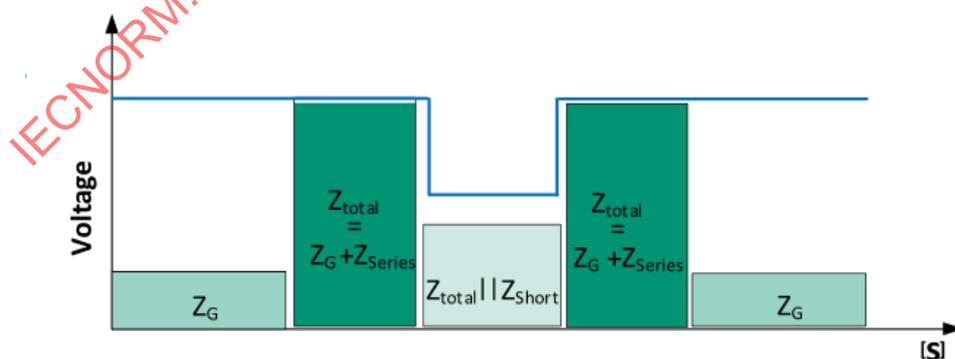


Figure 28 - FRT Impedance profile

1750 Grid emulators provide the additional option of virtual impedance adjustment. This allows the
1751 voltage divider-based test method's behaviour to be reproduced on the test bench. For this
1752 purpose, not only the voltage magnitude and phase are adjusted during the tests, but also the
1753 emulated grid impedance.

1754 Note: The behaviour of the voltage divider-based test device can be reproduced by a complete reproduction of the
1755 impedance curve, including all dynamic changes. Another way to consider the different resulting impedances in the
1756 fault case is to set the fault impedance $Z_{total} || Z_{short}$ once at the beginning of the test series. This eliminates the need
1757 to dynamically adjust the impedance during the test. Nevertheless, various grid short-circuit powers depending on
1758 the fault depth are taken into account using this approach.

1759 Annex D shows some examples of the transferability of the transient voltage transition between
1760 the field measurement and test bench measurement campaigns.

1761 **8.4.2.4.2 Test & measurement procedure for UVRT-Tests**

1762 The test procedure is the same as described in subchapter 8.4.2.2.2.

1763 **8.4.2.4.3 Test & measurement procedure for OVRT-Tests**

1764 The test procedure is the same as described in subchapter 8.4.2.2.3.

1765 **8.4.2.4.4 Documentation**

1766 It is recommended to conduct and evaluate no-load tests before performing measurements with
1767 converter-based test equipment. Check whether the required dynamic is maintained during
1768 voltage dip and voltage recovery. Furthermore, the resulting voltage level and the phase angle
1769 of the voltage during the dip must be verified and documented. The specified setpoint must also
1770 be stated.

1771 The documentation is the same as described in subchapter 8.4.2.2.4.

1772 Additional documentation of parameters and measurements for the test bench:

- 1773 • Emulated impedance

1774 **8.4.2.4.5 Transferability of test results**

1775 The transferability procedure is the same as described in subchapter 8.4.2.2.5

1776 **8.4.3 Functionality and Capability testing according to Strategy 2**

1777 In chapter 6 a general classification and naming of components is made. Reference is then
1778 made to the tables in Appendix B.2, which show that UVRT and OVRT tests can be divided into
1779 the following three classifications:

1780 a) Functionality tests

1781 b) Capability tests

1782 c) Performance tests

1783 The tests of class a) and b) will now be discussed in more detail below.

1784 **8.4.3.1 Definition of the DUT**

1785 In general, from the list of components in the tables in Annex B.2, the component must be
1786 determined by e.g. the manufacturer, which are suitable for the functionality or capability tests
1787 described here. This can be assessed differently depending on the wind turbine design.

1788 For the basic description of the procedure in the following subchapters, the components were
1789 selected as follows:

- 1790 • Controller for functionality tests
- 1791 • Converter for capability tests

1792 The focus is of course on UVRT and OVRT tests.

1793 It is not further specified whether it is the converter or the wind turbine controller. The decisive
1794 factor is in which controller the corresponding functionalities are implemented.

1795 The following components from Figure 4 are discussed here:

- 1796 • WT control system
- 1797 • FRT control
- 1798 • Convert system + filter system (the filter was also included, as it may be an integrated
1799 part of the converter. This can vary depending on the manufacturer.)

1800 It should also be mentioned again that the controller level represents the lowest testing level
1801 and only functionality tests can be carried out on this level and no e.g. capability tests.

1802 However, one level higher (e.g. converter level) functionality and capability tests can be carried
1803 out. Figure 29 provides an overview of the components on which functional tests can be
1804 performed.

Overview of components, subsystems and control functions for GFRT functionality tests

Type of Test	Chapter	Test bench system	Functionality test	Capability test	Performance test	Converter System	Generator	Additional Cap. bank	Filter	Grid Power Control (reactive Power)	Grid Power Control (active Power)	Generator Power Control (reactive Power)	Generator Power Control (or speed controller / torque control)	Switch Gear (Circuit breaker / Contactor)	Transformer	Aux. equip.	Grid Current Control	Grid Voltage Control	Frequency Control	Grid protection functions	Hub	Blades (always enabled)	Pitch system	Pitch controller	Drive train (incl. Gearbox)
UVRT	8.4.3	3c	X							X	X	X	X			X	X								
OVRT	8.4.3	3c	X							X	X	X	X			X	X								

³ = not necessary if the manufacturer can declare that this function has no effect on the FRT.

Figure 29 - Overview components for FRT functional tests

1805

1806

1807 Figure 30 provides an overview of the components on which capability tests can be performed.

Overview of components, subsystems and control functions for GFRT capability tests

Type of Test	Chapter	Test bench system	Functionality test	Capability test	Performance test	Converter System	Generator	Additional Cap. banks	filter	Grid Power Control (active Power)	Grid Power Control (reactive Power)	Generator Power Control (or speed controller / torque control)	Switch Gear (Circuit breaker / Contactor)	Transformer	Aux. equip.	Grid Current Control	Grid Voltage Control	Frequency Control	Grid protection functions	Hub	Blades (always emulated)	Pitch system	Pitch controller	Drive train (incl. gearbox)
UVRT	8.4.3	3a		X		X	X ¹		X	X	X	X				X	X			X ¹	X ¹	X ¹	X ¹	X ¹
OVRT	8.4.3	3a		X		X	X ^{1,2}		X	X	X	X				X	X			X ¹	X ¹	X ¹	X ¹	X ¹

¹ = can be either emulated or physical available
² = not necessary if the manufacturer can declare that this function has no effect on the FRT.
³ = if the trigger signal for switch gear shall be recorded, the grid protection functions are needed
⁴ = can be emulated for Type IV turbines, if the manufacturer can show validation results

Figure 30 - Overview components for FRT capability tests

1808

1809

1810

1811 **8.4.3.2 Functionality testing**

1812 **8.4.3.2.1 Introduction**

1813 The terminology functionality in relation to UVRT and OVRT tests is addressing controller
 1814 (software) functions and consequently some form of controller testing.

1815 The following functionalities are examples that are of greater importance in order to meet grid
 1816 requirements. Other functionalities are conceivable and can also be tested based on the
 1817 procedure described here.

1818 Example of functionalities:

- 1819 • Detection of FRT
- 1820 • Deadband of current support
- 1821 • K-factor
- 1822 • Prioritization of contribute with reactive or/and active current
- 1823 • Controlling of positive and negative symmetrical system (each phase)
- 1824 • Controlling of the active power ramp rate (P_ramp_rate) post fault
- 1825 • Handling of eventually a frequency shift due to a phase jump

1826 In order to ensure a common understanding of the nature of such functionalities, the above
 1827 listed functions are explained in more detail in Annex F.

1828 **8.4.3.2.2 Test setup & test conditions**

1829 The measurement shall at least be performed on a category 3c test bench as described in
 1830 chapter 7.

1831 The DUT shall include at least the components and control functions as defined in Annex B.2.

1832 **8.4.3.2.3 Test & measurement procedure**

1833 In general, the functionality tests should complement the capability and performance tests (see
 1834 Figure 2. The test plan and its test parameters need to be developed individually.

1835 In principle, the tests could be carried out as described in chapter 8.4.2.2.2 and 8.4.2.2.3,
1836 respectively and in IEC 61400-21-1:2019 section 8.5 and possibly supplemented by further
1837 tests, depending on the functionalities to be verified.

1838 The number of tests and operational modes need to be defined and described by the
1839 manufacturer in order to document the functionality.

1840 Preconditions:

- 1841 • The mode and therefore the control parameter need to be send to the DUT
- 1842 • The parameter (voltage and frequency) of the emulated grid is set to nominal values
- 1843 • All emulations and hardware dummies need to be in operation

1844 Test procedure:

- 1845 • The DUT needs to be start up to a steady state operation point (e.g. 100% active power)
- 1846 • Start of measurement
- 1847 • After a certain time (e.g. 5 sec) the desired UVRT or OVRT event (box e in Figure 14)
1848 is triggered
- 1849 • After the fault (e.g. 5 sec.) the measurement can be stopped

1850 **8.4.3.2.4 Documentation**

1851 The following must at least be documented:

- 1852 • Description of the entire test bench
- 1853 • Description of the DUT
- 1854 • Description of the functionality to be checked
- 1855 • Description of the measurement data recording (measurement system, sampling times,
1856 etc.)
- 1857 • Representation of the input and output signals as a time plot
- 1858 • Possibly further representations, which are necessary to show the functionality

1859

1860 **8.4.3.3 Capability testing**

1861 **8.4.3.3.1 Introduction**

1862 Capability testing in relation to FRT tests can be carried out at converter hardware level.

1863 The following capabilities are examples, which were of greater importance in the past to meet
1864 grid requirements. Further capabilities are conceivable and can be tested based on the
1865 procedure described here.

1866 Example of capabilities:

- 1867 • Run through, e.g. without disconnection
- 1868 • Operate the max. capability curve, e.g. to support with reactive current

- 1869 • Shows the correct post fault behaviour
- 1870 • Converter – UPS works (if available)
- 1871 • Run through
- 1872 • Side Components for the converter like (e.g. UPS, Crowbar, Chopper, etc. support as
1873 needed)
- 1874 • Operate multi faults
- 1875 • Handling of dynamic side aspects (e.g. phase jumps, impedance jumps, inrush effects,
1876 etc.)
- 1877 • Operate the specified grid frequency 50Hz or/and 60Hz

1878 **8.4.3.3.2 Test setup & test conditions**

1879 The measurement shall at least be performed on a category 3a test bench as described in
1880 chapter 7.

1881 The DUT shall include at least the components and control functions as defined in Annex B.2.

1882 **8.4.3.3.3 Test & measurement procedure**

1883 The tests can be performed as describes in subchapter 8.4.2.4.2 and subchapter 8.4.2.4.3. The
1884 operation modes must be specified and described by the manufacturer in order to document
1885 the capability.

1886 **8.4.3.3.4 Documentation**

1887 The following must at least be documented:

- 1888 • Description of the entire test bench
- 1889 • Description of the DUT
- 1890 • Description of the capability to be checked
- 1891 • Description of the measurement data recording (measurement system, sampling times,
1892 etc.)
- 1893 • Representation of the input and output signals as a time plot
- 1894 • Possibly further representations, which are necessary to show the functionality

1895 **8.4.3.4 Performance testing according to strategy 2**

1896 To complete the FRT testing according to strategy 2 (cf. Figure 2), the functionality and
1897 capability testing described before are complemented by a performance test. This performance
1898 test includes only worst-case scenarios, which verify the dynamic behaviour of the DUT.
1899 Performance tests can be carried out at type 1a test benches or in the field. This performance
1900 test can be done at other test bench classes with mHiL system if the validity of the
1901 measurements can be shown.

1902 The worst-case scenario must be defined by the manufacturer.

1903 **8.4.3.5 Transferability of combined test results to field level**

1904 Since there is limited experience on combining different classifications of test cases on different
1905 system levels for grid compliance testing, this sections is of theoretical nature. More specific
1906 description through practical experience is required in the future.

1907 The aspects discussed in more detail in the following paragraphs should already be mentioned
1908 today.

1909 1. Transparent, continuous documentation of the entire process

1910 The entire process that is carried out by the manufacturer with regard to strategy 2 must
1911 be described transparently and in detail. This includes the listing of the systems and /
1912 or components and the test bench used in each case. The DUT (hardware and software)
1913 and its parameters as well as any emulations used for components that were not actually
1914 tested (e.g. pitch system, rotor, etc.) must be documented in detail. The description of
1915 the framework conditions of the simulated electrical network and, if the performance test
1916 takes place in the field test, the real network data to compare them are also important.
1917 The validation of the emulations with the real measurements must be shown and
1918 assessed.

1919 2. Validation of maximum capability according to the manufacturer specification

1920 The entire process should demonstrate the electrical performance specified by the
1921 manufacturer. This means that it must at least be shown on the basis of appropriate
1922 tests that the maximum capability curve can be handled as expected and that the
1923 auxiliary systems such as (e.g. UPS for the converter controller, crowbar protection,
1924 chopper system, self-protection system, etc.) are working correctly and do not lead to
1925 the overall system tripping. In addition, it must be checked whether the expected
1926 electrical behaviour, such as voltage support through reactive current feed, occurs in
1927 accordance with the parameter settings in the DUT or whether, for example,
1928 overvoltage's do lead to destruction and thus failure.

1929 In addition, this method offers a more detailed examination of performances such as the
1930 behavior in extreme network conditions, for example with regard to the network short-
1931 circuit power or the examination of different nominal network frequencies of the voltage.

1932 3. Proof of functionalities

1933 One means of reducing the performance test is to carry out functionality tests as
1934 described in Chapter 8.4.3 on a lower component level. This must be specifically
1935 described by the manufacturer in the overall context of how these are combined with
1936 the capability and / or performance test. It makes sense for the manufacturer to carry
1937 out worst case scans as a performance test and combine this with the functionality tests.

1938 4. Validation of applied hardware emulations within this procedure

1939 It is possible to emulate hardware for this process. The overall concept of these
1940 individual procedures must consider that these emulations are valid. Corresponding
1941 UVRT or OVRT tests, e.g. field tests, must show the correct dynamic behaviour of the
1942 rotor system in relation to the emulation. In general, it must be shown that the emulations
1943 are comparable with the real behaviour within a certain tolerance band.

1944 5. Risk analysis

1945 The method offers new possibilities in the future to sufficiently prove the requirements
1946 for the wind turbines (e.g. considering more extensive the corresponding frequency
1947 system (50Hz/60Hz), phase jumps and/or impedance changes during FRT, different grid
1948 short-circuit power, etc.). It is only now possible to test certain extreme points that could
1949 not be tested in the past. However, it must be avoided that there are increased risks
1950 that incorrect behavior due to systematic design errors is no longer recognized. For this
1951 purpose, the manufacturer must create a risk analysis that describes in detail which

1952 risks his chosen concept could contain, to show this incorrect behavior no longer or
1953 strongly falsified.

1954 6. Uncertainty analysis

1955 In addition to the risk analysis, an indication of the uncertainties of the important result
1956 parameters, such as reactive current delivery, power ramps on return of voltage, etc.,
1957 when using test bench measurements compared to field measurements, must also be
1958 given.

1959 **8.5 Disconnection from the grid**

1960 This chapter describes the measurement and test procedures to prove the correct operation of
1961 the different grid protection systems in the DUT as well as the reconnection procedures.

1962 **8.5.1 Grid protection**

1963 **8.5.1.1 Description**

1964 The purpose of grid protection is to disconnect the DUT from the grid during abnormal voltage
1965 or frequency conditions.

1966 The aim of these tests is to prove the correct operation of this protection, as defined in IEC
1967 61400-21-1.

1968 **8.5.1.2 Test setup & conditions**

1969 The test shall at least be performed on a category 3c test bench test setup according to
1970 chapter 7.

1971 The DUT shall include at least the components and control functions as defined in Annex B.2.

1972 The test can be performed on the subsystem level (if the grid protection is realised by a separate
1973 unit, like a separate grid protection relay) or on a hardware in the loop test of the grid protection
1974 system of the DUT, as described in IEC 61400-21-1: 2019 section 8.6.2.1

1975 The protective system under test including voltage transformers, grid measuring device, trip
1976 circuit and main circuit breaker shall be of identical type to that applied in the corresponding
1977 WT type.

1978 The protection test set, including transformer, used for secondary injection of voltage and
1979 frequency changes shall fulfil the accuracies as described IEC 61400-21-1 or defined in
1980 IEC 60255-181 and IEC 60255-127.

1981 The trip signal from the grid protection system shall be connected as an input to the protection
1982 test set in order to prove the pick-up value as well as to measure the time delay.

1983 **8.5.1.3 Test procedure**

1984 The scope of these tests as well as the test procedure are defined in the IEC 61400-21-1
1985 sections 8.6.2.2 and 8.6.2.3. and shall be applied to the DUT.

1986 **8.5.1.4 Documentation**

1987 The applied settings as well as the results of these tests shall be documented as defined in IEC
1988 61400-21-1 section 8.6.2.4 and IEC 61400-21-1 Annex A.

1989 If a separate measurement system is used, it is recommended to record the following channels:

- 1990 • Voltages at the DUT terminals
- 1991 • frequency at the DUT terminals

- 1992 • trip signal of the DUT
- 1993 • digital or analogue signal showing point in time of frequency change (output from
- 1994 protection test set)
- 1995 • main circuit breaker auxiliary contact (if used for full trip test).

1996

1997 In addition the following shall be documented as shown in Table 12, a report template is given

1998 in Annex A.

1999

Table 12 - Documentation requirements for grid protection test

Grid protection system	Manufacturer:	
	Type:	
	Serial number:	
	Software version:	
Voltage transformers	Manufacturer:	
	Type:	
	Serial numbers:	
	Location of measurement point (high side/low side of PGU step-up transformer):	
	Primary voltage:	
	Ratio:	
Main circuit breaker	Manufacturer:	
	Type:	
	Serial number:	

2000

2001 **8.5.1.5 Transferability of test results**

2002 The test results can replace full-scale wind turbine measurements.

2003 **8.5.2 RoCoF protection**

2004 **8.5.2.1 Description**

2005 The DUT behaviour during grid events that cause a fast change of frequency in a short time

2006 frame shall be tested. The DUT protection shall trip when an excessive rate of change of

2007 frequency (RoCoF) is encountered. The aim of these tests is to prove the correct operation of

2008 this protection, as defined in IEC 61400-21-1.

2009 **8.5.2.2 Test setup & test conditions**

2010 The test shall at least be performed on a category 3c test bench test setup according to
2011 chapter 7.

2012 The DUT shall include at least the components and control functions as defined in Annex B.2.

2013 The protective system under test including voltage transformers, grid measuring device, trip
2014 circuit and main circuit breaker shall be of identical type to that applied in the corresponding
2015 WT type.

2016 **8.5.2.3 Test setup & procedure**

2017 The protection test system, including transformer, used for secondary injection shall fulfil the
2018 accuracies as described IEC 61400-21-1 or defined in IEC 60255-181.

2019 The trip signal from the grid protection system shall be connected as an input to the protection
2020 test system in order to prove the protection settings and to measure the protection time delay.

2021 The scope of these tests as well as the test procedure are defined in the IEC 61400-21-1:2019
2022 section 8.6.3.2. and shall be applied to the DUT.

2023 **8.5.2.4 Documentation**

2024 The applied settings as well as the results of these tests shall be documented as defined in IEC
2025 61400-21-1:2019 section 8.6.3.3 and IEC 61400-21-1 Annex A.

2026 If a separate measurement system is used, it is recommended to record the following
2027 parameter:

- 2028 • Voltages at the DUT terminals
- 2029 • frequency at the DUT terminals
- 2030 • trip signal of the DUT
- 2031 • digital or analogue signal showing point in time of frequency change (output from
2032 protection test set)
- 2033 • main circuit breaker auxiliary contact (if used for full trip test)

2034

2035 In addition the following shall be documented as shown in Table 13, a report template is given
2036 in Annex A.

2037

Table 13 - Documentation requirements for RoCoF test

Grid protection system	Manufacturer:	
	Type:	
	Serial number:	
	Software version:	
Voltage transformers	Manufacturer:	
	Type:	

	Serial numbers:	
	Location of measurement point (high side/low side of PGU step-up transformer):	
	Primary voltage:	
	Ratio:	
Main circuit breaker	Manufacturer:	
	Type:	
	Serial number:	

2038

2039 **8.5.2.5 Transferability of test results**

2040 The test results can replace full-scale wind turbine measurements.

2041 **8.5.3 Reconnection time**

2042 The aim of the reconnection time test is to show that the turbine automatically reconnects after
 2043 a grid outage of up to 10 minutes after which the power is ramped up following a predefined
 2044 ramp rate.

2045 Due to the large number of UPSs and auxiliary systems (e.g. pitch motors) involved here and
 2046 the resulting low transferability of these test results, this test shall only be carried out with the
 2047 complete WT in operation.

2048

IECNORM.COM : Click to view the full PDF of IECTS 61400 WG 21-4:2022

2049 **9 Additional measurement and test of electrical characteristics under**
2050 **controllable test conditions**

2051 This chapter defines additional tests, which are only possible in a controlled test bench setup
2052 as described in this TS in relation to power quality, steady state operation, dynamic response
2053 and control performance, as well as the documentation requirements and a guidance for the
2054 transferability of the test results towards the WT.

2055 **9.1 Power quality aspects**

2056 **9.1.1 Flicker Control**

2057 **9.1.1.1 Description**

2058 This chapter gives guidance for testing of flicker mitigation due to control issues at a test bench.
2059 These tests are optional. The aim of the measurement is to determine the voltage flicker during
2060 continuous operation at the terminals of the DUT.

2061 The test results are shown for short term P_{st} values, but are also be valid for long term P_{lt}
2062 values.

2063 **9.1.1.2 Test setup & test conditions**

2064 The measurement shall at least be performed on a category 1b test bench as described in
2065 chapter 7.

2066 The DUT shall include at least the components and control functions as defined in Annex B.2

2067 For these tests a grid emulator is recommended. In order to obtain more realistic view of the
2068 DUT flicker emission, it is recommended that the DUT sees the emulated voltage fluctuations
2069 behind an impedance $Z = R + jX$.

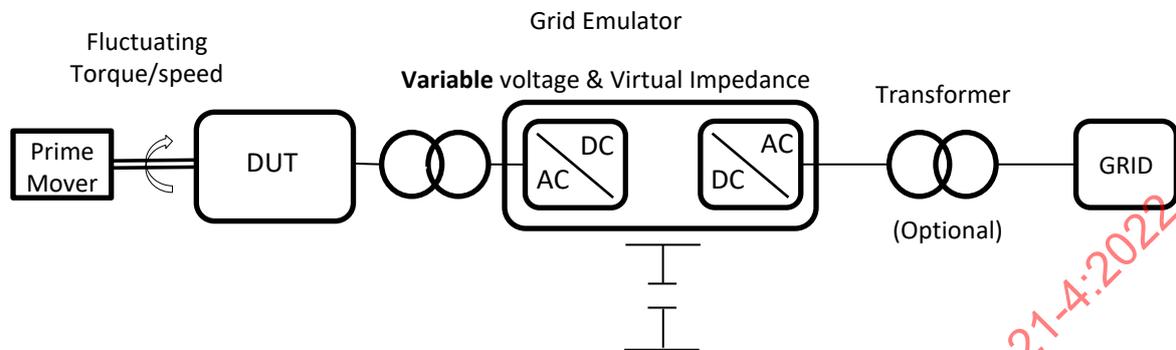
2070 The following possibilities are proposed:

- 2071 a) Use of a Variable Voltage – Emulated Impedance (Z) Grid Emulator Figure 31.
2072 b) Use a constant voltage and impedance Grid Emulator and add the variable series
2073 impedance Z and a controllable fluctuating shunt load, ohmic or inductive Figure 32

2074

2075

2076

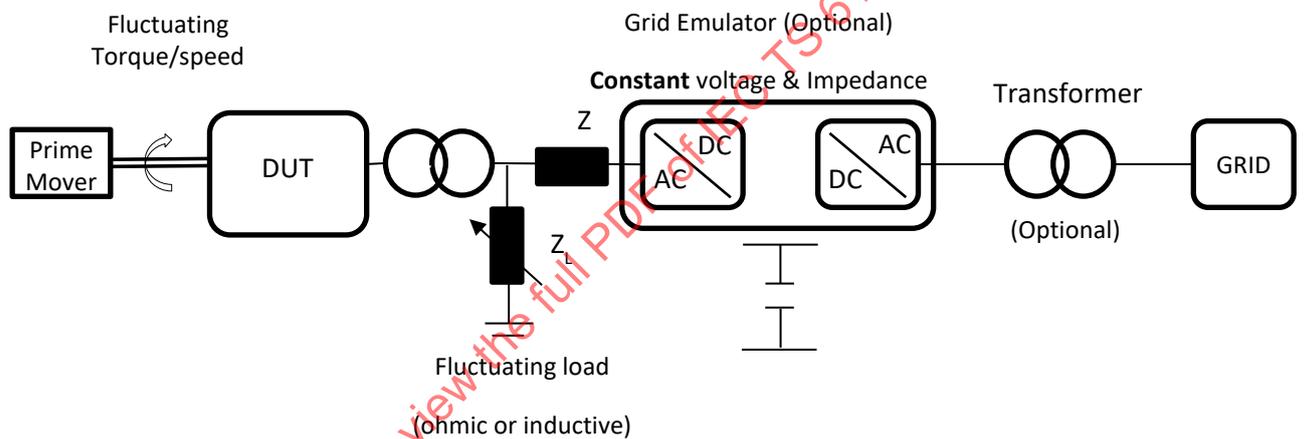


2077

2078

Figure 31 - Variable voltage and impedance grid emulator (case a)

2079



2080

Figure 32 - Constant voltage and impedance grid emulator with controllable load

2082

(case b)

2083

2084 The magnitude of the impedance Z including the impedance of the grid emulator (and of the
 2085 grid) for cases a) and b) should be in the range giving adequate P_{st} values. The impedance
 2086 phase angles ψ_k ($\psi_k = \arctan(X/R)$) must be $\psi_k = 30^\circ, 50^\circ, 70^\circ$ and 85° with a tolerance of $\pm 5^\circ$,
 2087 where R is the resistive and X the inductive component of the total impedance.

2088 For case b), Figure 32, the grid emulator may be omitted, so that the impedance Z is directly
 2089 connected to the grid.

2090

2091 9.1.1.3 Test & measurement procedure

2092 The following tests for the flicker mitigation due to control issues shall be performed:

2093 It is recommended that the test setup a) or b) generates predefined voltage fluctuations at the
2094 DUT with frequencies of:

- 2095 - 0,5 Hz
2096 - 1.5 Hz
2097 - 3.5 Hz
2098 - 8.8 Hz
2099

2100 The DUT shall be in voltage control mode and compensates the voltage fluctuations by control
2101 of reactive power.

2102 The power output of the DUT shall be 30% to 50% of P_n for partial load and 90% to 100% of P_n
2103 for full load testing.

2104 For each test case, one test with constant and one test with fluctuating power output shall be
2105 performed.

2106 The voltage flicker P_{st} as 10-minute values without and with the DUT at the terminal of the DUT
2107 shall be measured and compared with each other

2108 **Table 14 - Range of input relative voltage fluctuation $\Delta U/U_n$ for P_{st} output range about**
2109 **0,2 and 0,5 for $U_n = 230\text{ V}$**

Frequency	Sinusoidal fluctuations	Rectangular fluctuations
f [Hz]	dU/U [%]	dU/U [%]
0,5	0,67 – 1,69	0,16 – 0,41
1,5	0,30 – 0,76	
3,5		0,10 – 0,24
8,8	0,07 – 0,18	0,06 – 0,14

2110

2111 9.1.1.4 Documentation

2112 **A.** Show results of voltage flicker severity index (P_{st}) with and without the DUT

2113

2114 Presentation of the results in a table as a function of different impedances and frequencies of voltage
2115 fluctuations, e.g.

2116

2117 **Table 15 - Flicker P_{st} per power range and fluctuation frequency**

Impedance angle		30°		50°		70°		85°	
Impedance	R								
	X								
Load in % of P_n	Frequency in Hz	Without DUT	With DUT						
Partial load (30% to 50% of P_n)	0,5 Hz								
	1,5 Hz								
	3,5 Hz								

	8,8 Hz								
Full load (90% to 100% of P _n)	0,5 Hz								
	1,5 Hz								
	3,5 Hz								
	8,8 Hz								
Maximum									
Period of measurements									
Operational mode (reactive control $Q=0$ / others)									

2118 A report template is given in Annex A.

2119 **B. Flicker mitigation factor (ratio $F=P_{st_with_DUT}/P_{st_without_DUT}$)**

2120

2121 Presentation of the results in a table as a function of different impedances and frequencies of voltage
2122 fluctuations, e.g.

2123 **Table 16 - Flicker mitigation factor (F) per power range and fluctuation frequency**

Impedance angle		30°	50°	70°	85°
Load in % of P _n	Frequency in Hz	Flicker mitigation factor (ratio $F=P_{st_with_DUT}/P_{st_without_DUT}$)			
Partial load (30% to 50% of P _n)	0,5 Hz				
	1,5 Hz				
	3,5 Hz				
	8,8 Hz				
Full load (90% to 100% of P _n)	0,5 Hz				
	1,5 Hz				
	3,5 Hz				
	8,8 Hz				
Maximum					

2124

2125 A report template is given in Annex A.

2126 9.1.1.5 Transferability of test results

2127 The test results are supplementary to the full-scale wind turbine flicker measurements.

2128 9.1.2 Flicker and voltage change during switching operations

2129 9.1.2.1 Description

2130 This chapter is to give guidance for testing of flicker and voltage change due to switching at a
2131 test bench. These tests are optional and can be performed in case the converter of the DUT is
2132 changed.

2133

2134 Note: Similar to the testing of flicker during continuous operation, for testing the effect of the switching operations of
2135 a wind turbine sufficiently, it shall be tested in the free field, so that the influence of the aerodynamic part is thoroughly
2136 incorporated (see the note for flicker during continuous operation).

2137

2138 9.1.2.2 Test setup & test conditions

2139 The measurement shall at least be performed on a category 2b test bench as described in
2140 chapter 7.

2141 The DUT shall include at least the components and control functions as defined in Annex B.2

2142 For the connection of the DUT either a grid emulator or the public grid can be used.

2143 9.1.2.3 Test & measurement procedure

2144 The characteristics shall be stated for the following types of switching operations:

2145 a) One start-up of the DUT at power of 10% of P_n shall be performed

2146 b) One start-up of the DUT at nominal power P_n shall be performed

2147 For each of the above types of switching operations, the values of flicker step factor $k_f(\psi_k)$ and
2148 voltage change factor for the network impedance phase angles $\psi_k = 30^\circ, 50^\circ, 70^\circ$ and 85° shall
2149 be stated, as defined in IEC 61400-21-1.

2150 To determine the voltage change factor $k_u(\psi_k)$, and the flicker step factor $k_f(\psi_k)$, the maximum
2151 of the three phases for each type of switching operation shall be calculated.

2152 NOTE 1 Further information on the measurement procedure for voltage changes and flicker during switching
2153 operations can be found in IEC 61400-21-1, chapters 8.2.2.2, 8.2.3, B.2, B.4.2 and B.4.3.

2154

2155 9.1.2.4 Documentation

2156 The following parameters have to be reported as a function of the impedance phase angle, for each
2157 measured case:

- 2158 • Flicker step factor
- 2159 • Voltage change factor

2160 It can be documented for example in a Table as described in Annex A.

2161 Furthermore, time series of the voltage, current, active and reactive power shall be documented in
2162 graphs for both switching events.

2163 9.1.2.5 Transferability of test results

2164 The test results are supplementary to the full-scale wind turbine measurements of switching
2165 operations

2166 9.1.3 Active filter / sink for harmonics

2167 9.1.3.1 Description

2168 Modern wind turbines can potentially actively improve the power system's quality of power. In
2169 case of resonance networks such as wind power plants, it is critical that the harmonic injection
2170 by wind turbines is very small and controlled.

2171 Active filter functionality can be understood very broadly. Several technical solutions could be
2172 introduced in grid-connected converter functionality depending on the expected outcome, e.g.
2173 reduction of either harmonic current or voltage at the wind turbine terminal or at the remote bus.
2174 Among many others, the following active filtering functionalities could be, inter alia, specified:

- 2175 • Local resonance damping: the aim of active filter is to mitigate or damp internal
2176 resonances within the wind turbine's internal circuit.
- 2177 • Local harmonic current compensation: the task of active filter is to minimize the current
2178 flow between the wind turbine converter and the public grid.
- 2179 • Local harmonic voltage distortion mitigation: the goal of active filter is to improve and
2180 minimize as much as possible the voltage distortion level at the converter terminals.
- 2181 • Resonance damping at the remote bus: the wind turbines is programmed to damp
2182 prominent resonances in the wind power plant network leading to lower harmonic voltage
2183 distortion level.
- 2184 • Harmonic compensation at the remote bus: the active filter in wind turbines leading to
2185 maintain the harmonic voltage distortion level at a selected bus bar.

2186 Note: The purpose of this test is to carry out active filtering evaluation without knowing the exact control function
2187 being implemented.

2188 9.1.3.2 Test setup & test conditions

2189 The measurement shall at least be performed on a category 2b test bench as described in
2190 chapter 7.

2191 The DUT shall include at least the components and control functions as defined in Annex B.2.
2192 Additional the components as specified for the harmonics evaluation in Annex E have to be
2193 taken into account for the active filter functionality test.

2194 Grid emulator: The grid emulator shall be able to provide harmonic disturbances in the required
2195 frequency range and shall provide the harmonic contribution in open loop control, to avoid
2196 interactions with the harmonic control functionality of the DUT.

2197 9.1.3.3 Test & measurement procedure

2198 Harmonic background distortion measurement is required before the test is performed, to be
2199 able to evaluate the impact of the public grid on the test results.

2200 Note: Please make sure that the harmonics of interest, e.g. the 5th, 7th, are measured at the DUT terminals, i.e.
2201 caused by the grid emulator, the public grid or the DUT itself.

2202 The test shall be performed in two steps:

- 2203 • **Step 1:** harmonic measurements at the DUT terminals before the active filter is activated
- 2204 • **Step 2:** harmonic measurements at the DUT terminals after the active filter is activated.

2205 Measurement procedure of active filtering functionality of the DUT:

- 2206 • Set point reactive power: $Q = 0$ var.
2207 Optional: reactive power under- and overexcited at the maximum power bin.
- 2208 • **Grid emulator:** Three, 10-minute data sets of instantaneous voltage and current
2209 measurements shall be collected for each 10% power bin ($0\% P_n - 100\% P_n$), and shall be
2210 performed with the same operational conditions as for the no load tests.
- 2211 • **Public grid:** Seven, 10-minute data sets of instantaneous voltage and current measurements
2212 shall be collected for each 10% power bin ($0\% P_n - 100\% P_n$)
- 2213 • The maximum value from the three or seven measurements of each power bin shall be taken.

2214 Note: All three phases shall be measured at the same time during the measurements.

2215 **DUT:** The following values shall be measured and reported in percentage of I_n and U_n respectively and
 2216 for operation of the DUT within the active power bins 0, 10, 20, ... 100% of P_n .

- 2217 • Values of the individual current components
- 2218 • Total current distortion up to the 50th harmonic order
- 2219 • Values of the individual voltage components
- 2220 • Total voltage distortion up to the 50th harmonic order

2221 A synchronized to power system fundamental frequency rectangular 10-cycle window for 50 Hz and
 2222 12-cycle window for 60 Hz power systems is recommended for the analysis of measurements.

2223 The DFT is applied to each of the measured currents and voltages with rectangular weightings.
 2224 The active power shall be evaluated over the same time window as the harmonics.

2225 9.1.3.4 Documentation

2226 The tests results shall be reported in a table including measurements at the DUT terminals
 2227 before the active filter (**Step 1**) and after the active filter (**Step 2**) is activated.

2228 The emission of the magnitude voltage and current harmonics shall be documented in tables
 2229 and graphs according to Annex A.

2230 **Public grid:** The 95th percentile of current and voltage harmonics shall be measured and
 2231 reported for public grid measurement.

2232 **Grid emulator:** The max value of current and voltage harmonics shall be measured and
 2233 reported for grid emulator measurement.

2234 **Table 17 - Active filtering (AF) evaluation table for voltage as current harmonics**

Harmonic order \ Power bin	0%		10%		20%		...		100%	
	w AF	w/o AF								
2										
3										
4										
5										
...										
50										

2235

2236 9.1.3.5 Transferability of test results

2237 The test results can replace full-scale wind turbine test of active filtering functionality.

2238 9.1.4 Frequency depended Impedance measurement

2239 9.1.4.1 Introduction

2240 The wind turbine frequency-dependent equivalent impedance is crucial in harmonic propagation
2241 and small-signal stability studies. Small-signal wind turbine impedance is a part of the Thevenin
2242 or Norton model described in IEC 61400-21-3.

2243 Therefore, impedance measurement tests are required for harmonic modelling as well as
2244 harmonic model validation for wind turbines and converters.

2245 The aim of this chapter is to provide a general test methodology for the harmonic impedance
2246 measurement based on voltage or current perturbations in a test environment.

2247 Note: Different methods, rather than the proposed test method in this chapter, might be used for the impedance
2248 measurement and harmonic model validation. However, the applied methods shall provide a procedure to verify the
2249 accuracy and reliability of the results.

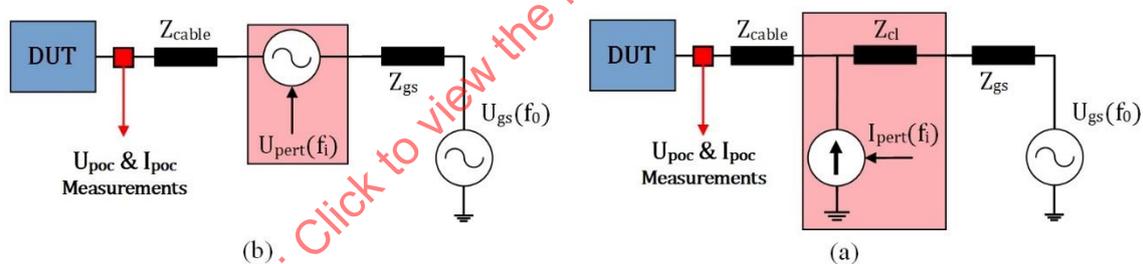
2250 9.1.4.2 Test setup & test conditions

2251 The measurement shall at least be performed on a category 2b test bench as described in
2252 chapter 7.

2253 The DUT shall include at least the components and control functions as defined in Annex B.2.

2254 A test device with capability of small-signal current or voltage perturbation injections is required
2255 as illustrated in Figure 33 respectively. Accordingly, the perturbation test device can be a
2256 separate unit in series or parallel connection with the DUT. Each perturbation is a single-
2257 frequency component (single-tone) or a group of frequencies (multi-tone) with small amplitudes.
2258 The measurement equipment should have high resolution to measure the small-signal response
2259 of the DUT against perturbations.

2260

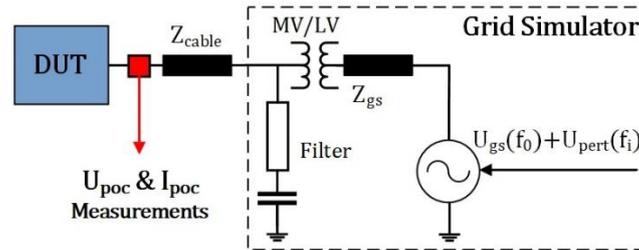


2261

2262 **Figure 33 - Generic topology of (a) current and (b) voltage perturbation tests [1].**

2263 Alternative a grid emulator, as shown in Figure 34, for emulation of the AC grid ($U_{gs}(f_0)$) as well
2264 as the voltage perturbation ($U_{pert}(f_i)$) can be used.

2265



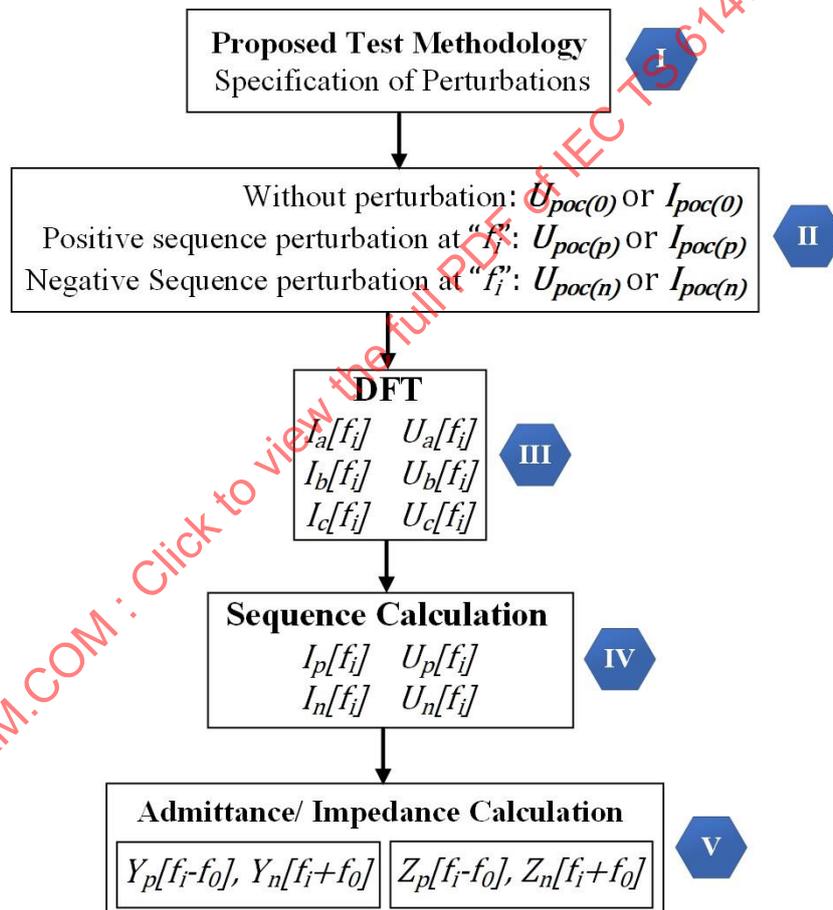
2266

2267 **Figure 34 - Example of a grid emulator structure for voltage perturbation application [1].**

2268 Note: To minimize the coupling effects of the grid emulator on the test result, it is recommended to perform the test
 2269 with an open-loop control for the perturbations, which means using set points for $U_{pert}(f_i)$ without control feed-backs.
 2270 However, special considerations might be required for open-loop voltage injections. Thus, it is recommended to
 2271 evaluate the test procedure in no-load condition first and then perform the tests with DUT. Depending on the output
 2272 filter, transformer characteristics and switching frequency of the grid emulator, it is possible to perform voltage
 2273 perturbation tests for an acceptable range of frequencies

2274 **9.1.4.3 Test & measurement procedure**

2275 The impedance measurement test methodology is given Figure 35.



2276

2277 **Figure 35 - Impedance measurement test methodology for wind turbines using**
2278 **perturbation tests**

2279 The methodology consists of five steps as follows:

2280 1) *Specification of Perturbations:*

2281 First, the specification of perturbations should be chosen based on the DUT characteristics and
 2282 application of the test results. In Table 18, the test specification is categorized based on the
 2283 voltage or current perturbation methods and frequency ranges. Accordingly, the maximum
 2284 amplitude of the perturbations, frequency steps and power set-points should be specified for
 2285 the test procedure as follows:

- 2286 • Within the given range for voltage ($U_{poc}(f_i)$) or current ($I_{poc}(f_i)$) perturbation tests, smaller
 2287 values can be chosen for testing of Type III WTs. In addition, higher values within the
 2288 given range can be chosen for the grid emulators with lower short circuit ratio.
- 2289 • The perturbation frequency shall start from the minimum frequency (f_{min}) and increase with
 2290 the frequency steps (e.g., 9Hz, 9+2Hz, 9+4Hz...). Lower frequency steps can be used for
 2291 more precise impedance measurements locally near the potential resonance frequencies.
- 2292 • It is recommended to choose the maximum frequency perturbation to less than cut-off
 2293 frequency of the grid emulator's output filter ($f_{pmax} < f_{cut-off(gs)}$).
- 2294 • To achieve an accurate impedance model, different power set-points shall be tested.
- 2295 • The period of injections is preferably 3 seconds to achieve 1Hz or 0,5Hz resolutions in
 2296 DFT calculations. It can be chosen up to 11 seconds to provide 0,1Hz resolution.

2297 **Table 18 - Specification of voltage or current perturbation tests**

Frequency range	$f_{min} < f_p < f_0$	$f_0 < f_p < 2f_0$	$2f_0 \leq f_p$
Voltage perturbation ($U_{poc}(f_i)$)	0,4%-0,8% p.u.	1%-2% p.u.	1%-2% p.u.
Current perturbation ($I_{poc}(f_i)$)	4%-8% p.u.	2%-4% p.u.	1%-2% p.u.
Minimum frequency f_{min} (Hz)	9Hz	f_0+1 Hz	$2f_0+1$ Hz
Maximum frequency steps (Hz)	2Hz		
Power set-points (p.u.)	0,1; 0,5; 1,0		
Perturbation duration	3-11 seconds		

2298

2299 *II) Positive and Negative Sequence Perturbations:*

2300 In order to measure a full response of the DUT against perturbations, it is required to perform
 2301 tests for positive and negative sequence perturbations separately. The sequence-domain
 2302 impedance is recommended since it can be used for power system stability studies easily.

2303 In Figure 35, $U_{poc(p)}$ and $I_{poc(p)}$ are referring to three-phase positive sequence voltage or current
 2304 perturbations for a range of frequencies. Similarly, $U_{poc(n)}$ and $I_{poc(n)}$ depict the negative
 2305 sequence injections. The time-domain three-phase currents and voltages shall be measured for
 2306 each perturbation.

2307 *III) Discrete-Fourier Transform (DFT):*

2308 The DFT of the three-phase measured data for each perturbation shall be calculated according
 2309 to IEC 61400-21-1. To achieve 1Hz resolution in the harmonic spectrum, 1 second DFT window
 2310 is recommended.

2311 *IV) Sequence calculations:*

2312 In this step, the positive and negative sequence voltage and currents shall be calculated for
 2313 each perturbation frequency from the three-phase voltage and current harmonic spectrums. In
 2314 this way, $U_{p(p)}[f]$, $U_{n(p)}[f]$, $I_{p(p)}[f]$, $I_{n(p)}[f]$ shall be derived from positive sequence perturbations and
 2315 $U_{p(n)}[f]$, $U_{n(n)}[f]$, $I_{p(n)}[f]$, $I_{n(n)}[f]$ shall be calculated from negative sequence perturbation tests. The
 2316 sequence-domain transformation of three-phase voltages can be calculated as follows:

$$2317 \begin{bmatrix} U_p \\ U_n \\ U_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix}$$

2318 Where $\alpha = 1 \angle 120^\circ$. Similar calculations can be performed for current components.

2319 *V) Admittance or Impedance Calculations:*

2320 According to the proposed methodology in Figure 35, the calculation of admittance or
 2321 impedance matrices shall be based on the sequence-domain calculations of the three different
 2322 measurement data sets:

- 2323 (1) Normal operation without perturbation ($U_{p(0)}, U_{n(0)}, I_{p(0)}, I_{n(0)}$).
- 2324 (2) Positive sequence perturbation test at f_i ($U_{p(p)}, U_{n(p)}, I_{p(p)}, I_{n(p)}$).
- 2325 (3) Negative sequence perturbation test at f_i ($U_{p(n)}, U_{n(n)}, I_{p(n)}, I_{n(n)}$).

2326 The admittance matrices shall be derived as follows:

$$2327 Y_{pp}(f_i - f_0) = \frac{I_{p(p)} - I_{p(0)}}{U_{p(p)} - U_{p(0)}} = \frac{\Delta I_{p(p)}}{\Delta U_{p(p)}}$$

$$2328 Y_{nn}(f_i + f_0) = \frac{I_{n(n)} - I_{n(0)}}{U_{n(n)} - U_{n(0)}} = \frac{\Delta I_{n(n)}}{\Delta U_{n(n)}}$$

2329 Similarly, the impedance matrices shall be derived as follows:

$$2330 Z_{pp}(f_i - f_0) = \frac{U_{p(p)} - U_{p(0)}}{I_{p(p)} - I_{p(0)}} = \frac{\Delta U_{p(p)}}{\Delta I_{p(p)}}$$

$$2331 Z_{nn}(f_i + f_0) = \frac{U_{n(n)} - U_{n(0)}}{I_{n(n)} - I_{n(0)}} = \frac{\Delta U_{n(n)}}{\Delta I_{n(n)}}$$

2332 Note: Using the positive sequence perturbation data at frequency of " f_i ", the positive sequence admittance/impedance
 2333 can be calculated at " $f_i - f_0$ " ($Y_{pp}(f_i - f_0), Z_{pp}(f_i - f_0)$). While, using negative sequence perturbation test data at " f_i ", the
 2334 calculated negative sequence admittance/impedance shall be for " $f_i + f_0$ " ($Y_{nn}(f_i + f_0), Z_{nn}(f_i + f_0)$). Further
 2335 investigations on the test results are out of the scope of this chapter and can be found in [1].

2336 Note: For higher frequencies ($f_p > f_{cut-off}$), the perturbation tests are optional and the admittance/impedance can be
 2337 calculated by performing the test procedure (Fig.4) on simulation models.

2338 Note: In the case of model validation applications, the extracted model from the test methodology shall be compared
 2339 with the model given by the DUT owner. Multi-tone perturbation tests can be used for model validation application
 2340 as well. Note that the model validation procedure is out of the scope of this chapter.

2341

2342 9.1.4.4 Measurement data assessment

2343 The accuracy of measured data depends on the measurement equipment resolution and
 2344 potential environment noise level. Since the tests shall be done in the small-signal range, high
 2345 precision measurement equipment is required. Class I measurement instruments are
 2346 recommended for current and voltage measurements according to IEC 61000-4-7. The
 2347 measurement instruments with higher precision can be used optional for a better accuracy.

2348 1) Effects of Test Procedure:

2349 The results of the test and measurement data depends on the perturbation method, frequency
 2350 couplings and potential undesired distortions. Therefore, three evaluation criteria are suggested
 2351 as follows:

2352 a) Total Harmonic Distortion (THD) of Voltage and Amplitude of the Intended Perturbation: If a
 2353 perturbation contains undesired harmonic components in a considerable level, the result of
 2354 tests would have frequency couplings with the undesired harmonic components and would lead
 2355 to wrong data and calculations. Therefore, amplitude of the injection and the THD of the voltage
 2356 excluding the intended perturbation could be considered as trust criteria for the measurement
 2357 data.

2358 b) Vicinity Harmonic Components: In addition to THD, the undesired harmonic components in
 2359 the vicinity of the intended perturbation can affect the trustworthiness of the test results. The main
 2360 couplings can be observed for " $2f_0 \pm f_i$ " and " $f_i \pm f_0$ " frequencies. Therefore, the injections should
 2361 not contain considerable undesired harmonic components in the vicinity of the intended
 2362 perturbation frequency, especially in the range of absolute values of $|f_i \pm 2f_0|$. However, in the
 2363 case of high frequency ranges, inevitable switching harmonics would be observed, but it should
 2364 be proven that such harmonics are not results of the perturbation tests.

2365 c) Differential Phase Angle: A stable phase angle between harmonic components of voltage
 2366 and current over the injection period can be another trust criterion which confirms steady-state
 2367 and stable condition of the converter response against the injection. This factor can be
 2368 evaluated by time-domain illustrations or a probability factor over the injection period.

2369 9.1.4.5 Documentation

2370 The applied perturbation method and settings as well as the results of these test must be
 2371 documented in the test reports, including:

- 2372 • Description of the test setup / Real time simulator setup
- 2373 • Measurement setup according to chosen test procedure
- 2374 • Documentation of the control mode / operational mode of the DUT.
- 2375 • Table of the calculated frequency dependent positive and negative sequence (Thevenin or
 2376 Norton) Impedance for each power level as stated Table 18, in the validated frequency range
 2377 as shown in e.g. Table 19

2378 **Table 19 - Example of representation of the harmonic impedance**

Harmonic / order	Frequency	Harmonic impedance – positive sequence		Harmonics impedance – negative sequence	
		Resistance, R [Ω]	Reactance, X [Ω]	Resistance, R [Ω]	Reactance, X [Ω]
2	100				
3	150				
4	200				

5	250				
...	...				

2379

2380 Note: The equivalent harmonic impedance representation of the DUT is a small-signal representation and therefore
2381 sensible to the applied control mode/ operational mode of the DUT .

2382 A report template is given in Annex A.

2383 **9.1.4.6 Transferability of test results**

2384 The test results can replace full-scale wind turbine measurements.

2385 **9.2 Steady state operation**

2386 **9.2.1 Voltage capability**

2387 The aim of this test is to validate the capability of the DUT to operate within a defined voltage
2388 range.

2389 **9.2.1.1 Description**

2390 In this test, the voltage range capability of the DUT under steady state conditions shall be
2391 validated, against the capability chart given from the manufacturer.

2392 **9.2.1.2 Test setup & test conditions**

2393 The measurement shall at least be performed on a category 2b test bench as described in
2394 chapter 7.

2395 The test bench grid system shall be able to vary and provide a stable voltage supply in the
2396 range of min +/- 2 % of the desired voltage capability of the DUT.

2397 The grid system shall be able to adjust the voltage operating points with a maximum error of
2398 1 % of U_n .

2399 The DUT shall include at least the components and control functions as defined in Annex B.2.

2400 Components not affected by voltage variations can be excluded from the test.

2401 **9.2.1.3 Test & measurement procedure**

2402

2403 The test shall be carried out with the following start conditions:

- 2404 • The DUT shall be operated at nominal voltage and nominal power as declared by the
2405 manufacturer.
- 2406 • The DUT shall operate at the nominal power factor for the operating point as stated by the
2407 manufacturer.

2408 At least 2 tests shall be conducted, one at each voltage capability limit.

2409 The voltage at the terminals of the DUT shall be changed according to the following sequence:

- 2410 • The voltage shall be reduced to the minimum voltage and maintained for a minimum of 10
2411 min or the defined minimum capability time of the DUT.
- 2412 • The voltage shall be increased to its nominal value and maintained for a minimum of 10
2413 min;
- 2414 • The voltage shall be increased to its maximum limit and maintained for a minimum of 10
2415 min time or the defined maximum capability time of the DUT;
- 2416 • The voltage shall be decreased to the nominal value.

2417 The voltage shall be maintained stable during the entire test and the voltage variations during
2418 the test shall not exceed 1 % of U_n .

2419 During the test the positive sequence voltage and active and reactive power shall be measured
2420 at the terminals of the DUT with an average time of 0,2 s

2421 Note: Additional test of specific voltage levels, can be performed with the same procedure.

2422 **9.2.1.4 Documentation**

2423 The following parameters shall be documented in tables and graphs as shown in for example
2424 Annex A:

- 2425 • DUT documentation of the voltage capability range including their nominal voltage and
2426 limits
- 2427 • Positive sequence voltage measured at the DUT terminals with and average time of 0,2 s
- 2428 • Measured active and reactive power with and average time of 0,2 s

2429

2430 **9.2.1.5 Transferability of test results**

2431 The test results are supplementary to the wind turbine measurements and the test results can
2432 replace full-scale wind turbine measurement.

2433 **9.2.2 Frequency capability**

2434 The aim of this test is to validate the capability of the DUT to operate within a defined frequency
2435 range.

2436 **9.2.2.1 Description**

2437 In this test, the frequency range capability under steady state conditions shall be validated,
2438 against the frequency range capabilities given from the manufacturer.

2439 **9.2.2.2 Test setup & test conditions**

2440 The measurement shall at least be performed on a category 2b test bench as described in
2441 chapter 7.

2442 The test bench grid emulator shall be able to vary and provide a stable frequency and voltage
2443 supply in the range of min +/- 0,5 Hz of the desired frequency capability of the DUT.

2444 The DUT shall include at least the components and control functions as defined in Annex B.2.

2445 Components not affected by frequency variations can be excluded from the test.

2446 **9.2.2.3 Test & measurement procedure**

2447

2448 For the determination of the frequency capability the following procedure shall be applied:

2449 The test shall be carried out with the following start conditions:

- 2450 • The DUT shall be operated at nominal frequency, nominal voltage and nominal power as
2451 declared by the manufacturer.
- 2452 • The DUT shall operate at the nominal power factor for the operating point as stated by the
2453 manufacturer.

2454

2455 At least 2 test shall be conducted one at each frequency capability limit / frequency level (e.g.
2456 47 and 52 Hz)

2457 The frequency at the terminals of the DUT shall be slowly changed according to the following
2458 sequence:

- 2459 • The frequency shall be reduced to the minimum frequency level and maintained for a
2460 minimum of 10 min or the defined min capability time of the DUT.
- 2461 • The frequency shall be increased to its nominal value and maintained for a minimum of
2462 10 min;
- 2463 • The frequency shall be increased to its maximum limit and maintained for a minimum of
2464 10 min time or the defined minimum capability time of the DUT.
- 2465 • The frequency shall be decreased to the voltage nominal value.

2466
2467 The frequency shall be maintained stable during the entire test and the frequency variations during the
2468 test shall not exceed 0,1 Hz.

2469
2470 During the test the frequency, positive sequence voltage, active and reactive power shall be measured
2471 at the terminals of the DUT with an average time of 0,2 s.

2472 Note: Additional test of specific frequency levels, can be performed with the same procedure.

2473 **9.2.2.4 Documentation**

2474 The following parameters shall be documented in tables and graphs as shown in Annex A:

- 2475 • DUT documentation of the frequency capability range including their nominal frequency
2476 and limits
- 2477 • Frequency at the DUT terminals measured with an average time of 0,2 s
- 2478 • Positive sequence voltage measured at the DUT terminals with an average time of 0,2 s
- 2479 • Measured active and reactive power with an average time of 0,2 s

2480

2481 **9.2.2.5 Transferability of test results**

2482 The test results are supplementary to the wind turbine measurements and the test results can
2483 replace full-scale wind turbine measurement.

2484 **9.2.3 Current Unbalance Factor in an unbalanced system**

2485 **9.2.3.1 Description**

2486 The aim of the measurement is to determine the current unbalance factor of the PGU when the
2487 voltage unbalance induced by the grid emulator is set to a specific value (e.g. 2%±0,5 %).

2488 **9.2.3.2 Test setup & test conditions**

2489 The measurement shall at least be performed on a category 2b test bench as described in
2490 chapter 7.

2491 The DUT shall include at least the components and control functions as defined in Annex B.2.

2492 For the generation of a voltage unbalance system the following possibilities are proposed:

- 2493 a) Use of Grid Emulator with a voltage unbalance, see Figure 31 in chapter 9.1.1.2
- 2494 b) Use a constant voltage and impedance Grid Emulator and add the voltage unbalance
2495 by a shunt load, ohmic or inductive see Figure 32 in chapter 9.1.1.2.

2496 The grid emulator or the shunt load shall at least be able to set the voltage unbalance factor to
2497 at least 2% with an accuracy of ± 0,5%.

2498 9.2.3.3 Test & measurement procedure

2499 The current unbalance factor of the DUT is determined, while the DUT is operating in an
2500 unbalanced system.

- 2501 • The test shall be done in steady states at 10, 20, 30, ... 100% P_n .
- 2502 • The positive sequence reactive power shall be set to zero.
- 2503 • The drivetrain shall be in a steady state for minimum 1 minute in each step.
- 2504 • 3-phase voltage and currents shall be recorded, and 1-minute averages of voltage and
2505 current unbalances shall be calculated in each step.

2506

2507 The positive sequence voltage U_1 and current I_1 as well as the negative sequence voltage U_2
2508 and current I_2 shall be calculated according to IEC 61400-21-1.

2509 9.2.3.4 Documentation

2510 The measured 1-minute values of the current unbalance and the active power positive sequence
2511 system component are represented as an IUF-P diagram. The measurement results shall be
2512 presented in a table as mean values of each power bin, as defined, for example, in Table 20.
2513 The maximum current unbalance factor as a 1-minute value shall be explicitly given.

2514

Table 20 - Current unbalance factor in an unbalanced system

P [p.u.]	Q [p.u.]	U_1 [p.u.]	U_2 [p.u.]	UUF	I_1 [p.u.]	I_2 [p.u.]	IUF
~0,1	~0,0			2% ± 0,5%			
~0,2	~0,0			2% ± 0,5%			
~0,3	~0,0			2% ± 0,5%			
~0,4	~0,0			2% ± 0,5%			
~0,5	~0,0			2% ± 0,5%			
~0,6	~0,0			2% ± 0,5%			
~0,7	~0,0			2% ± 0,5%			
~0,8	~0,0			2% ± 0,5%			
~0,9	~0,0			2% ± 0,5%			
~1.0	~0,0						

2515

2516 9.2.3.5 Transferability of test results

2517 The test results are supplementary to the wind turbine measurements and the test results can
2518 replace full-scale wind turbine measurement as supplement the results from chapter 8.2.5.

2519 9.3 Control performance

2520 9.3.1 Grid Impedance variations

2521 9.3.1.1 Description

2522 The aim of the measurement is to determine the stability of the DUT controller due to impedance
2523 variations in the grid.

2524 9.3.1.2 Test setup & test conditions

2525 The measurement shall at least be performed on a category 1b test bench as described in
2526 chapter 7.

2527 The grid emulator shall be able to, variate the grid impedance / reduce the short circuit ratio
2528 (SCR) and weaken the grid strength down to a predefined level e.g. to 1 with respect to the S_n
2529 of the DUT.

2530 Alternative the impedance variation can be performed with physical impedances.

2531 The DUT shall include at least the components and control functions as defined in Annex B.2.

2532 9.3.1.3 Test & measurement procedure

2533 The test shall be carried out at minimum at two different test levels, with the following start
2534 conditions:

2535 Test condition 1 (100 % of P_n):

- 2536 • The DUT shall be operated at nominal voltage and nominal power as declared by the
2537 manufacturer.
- 2538 • The DUT shall operate at the nominal power factor for the operating point as stated by the
2539 manufacturer.

2540

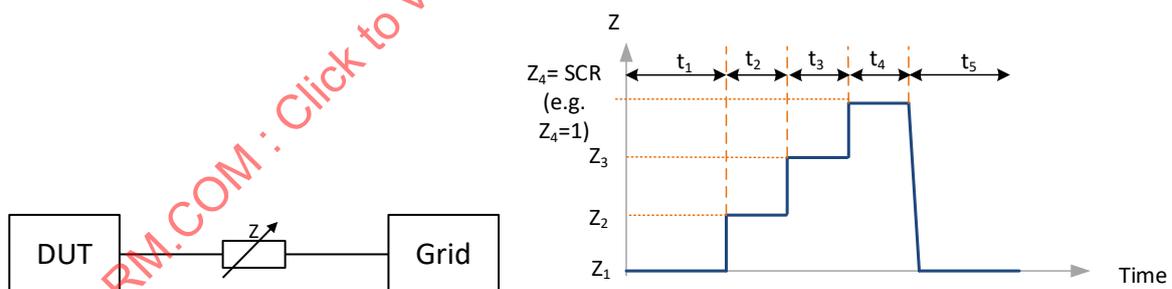
2541 Test condition 2 (50 % of P_n):

- 2542 • The DUT shall be operated at nominal voltage and 50 % of P_n nominal power as declared
2543 by the manufacturer.
- 2544 • The DUT shall operate at the power factor for the operating point as stated by the
2545 manufacturer.

2546

2547 During the test the impedance shall be varied in the following way, for both test conditions
2548 stated above:

- 2549 • The impedance of the grid is increased step-wise from a starting impedance Z_1 (SCR
2550 around 10) to a maximum impedance Z_n (e.g. SCR = 1). The impedance steps shall be
2551 chosen to cover equally the SCR range with the respective X/R ratio.
- 2552 • The time duration for the steps should be chosen long enough to ensure that the
2553 system has been stabilized.



2554

2555 **Figure 36 - Impedance variation – example of steady state procedure & stepwise**
2556 **impedance increase**

2557 The grid impedance variations as shown above can be performed with a grid emulator or physical
2558 impedances.

2559 The impedance / SCR setting shall be maintained stable during the entire test and the variations
2560 during the test shall not exceed 1 % of the defined impedance.

2561 During the test the positive sequence voltage and active and reactive power shall be measured
2562 at the terminals of the DUT with an average time of 0,2 s, with a sample rate of 20 kHz.

2563

2564 9.3.1.4 Documentation

2565 The following parameters shall be documented in tables and graphs as shown in for example
2566 Annex A:

- 2567 • Impedance steps and values as complex value
- 2568 • Positive sequence voltage measured at the DUT terminals with and average time of 0,2 s
- 2569 • Measured positive and negative sequence current with and average time of 0,2 s
- 2570 • Measured active and reactive power with and average time of 0,2 s

2571

2572 9.3.1.5 Transferability of test results

2573 The test results are supplementary to the wind turbine measurements and the test results can
2574 replace full-scale wind turbine measurements.

2575 9.3.2 Island operation

2576 9.3.2.1 Introduction

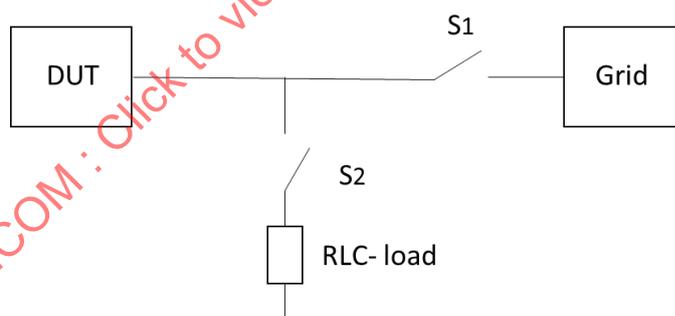
2577 The aim of the test is to validate the DUT behaviour under Island operation, where the DUT is
2578 disconnected from the main power supply. The described test procedure defines the procedure
2579 for testing the stand-alone islanding operation and describes not the island detection or re-
2580 synchronization.

2581 9.3.2.2 Test setup & test conditions

2582 The measurement shall at least be performed on a category 1b test bench as described in
2583 chapter 7.

2584 The test can be performed with passive tuned RLC loads or with a grid emulator, which is
2585 capable to emulate a fixed RLC load. Figure 37 shows the setup with a variable RLC-load.

2586 The DUT shall include at least the components and control functions as defined in Annex B.2.



2587

2588 **Figure 37 - Single line diagram of RLC load connected with DUT**

2589 9.3.2.3 Test & measurement procedure

2590 The test shall be carried out with the following start conditions:

- 2591 • The DUT shall be operated at nominal frequency, nominal voltage and an active power
2592 setting according to the defined test level.
- 2593 • The DUT shall operate at the nominal power factor for the operating point as stated by the
2594 manufacturer.

2595 It is recommended to do the test at minimum three power levels for $P_n \geq 20\%$, $> 50\%$ and $>$
2596 80% of the nominal power of the DUT.

2597 The following test sequence shall be applied for the defined test levels:

- 2598 1. Stable operation of the DUT at the defined output power
- 2599 2. Tuning of RLC loads / to be equal to the power production
- 2600 3. Opening of the grid circuit breaker / switch grid emulator operation to a fixed RLC- load
2601 operation
- 2602 4. DUT operation in islanding mode
- 2603 5. After the system has been stabilized the DUT shall be disconnected.

2604 **9.3.2.4 Documentation**

2605 The following information shall be given for the test:

- 2606 • Description of the test setup / Real time simulator setup
- 2607 • Description of the impedance of the transformer and the passive components of the DUT
- 2608 • Impedance or emulated RLC load and power production of the DUT

2609 The following parameters shall be documented in tables and graphs as shown in for example Annex A

- 2610 • Measured frequency at the DUT
- 2611 • Measured positive and negative sequence voltage measured at the DUT
- 2612 • Measured positive and negative sequence current
- 2613 • Measured active and reactive power from the DUT

2614 All variables shall be measured from 1 s before the Island operation until 5 s after the system has
2615 been stabilized.

2616 **9.3.2.5 Transferability of test results**

2617 The test results are supplementary to the wind turbine measurements and the test results can
2618 replace full-scale wind turbine measurement.

2619

2620 **9.4 Dynamic performance**

2621 **9.4.1 RoCoF – real df/dt – capability**

2622 **9.4.1.1 Description**

2623 The DUT behavior during grid events that cause a fast change of frequency in a short time
2624 frame shall be tested.

2625 The aim of these tests is to prove the DUT's capability to operate through fast changes of
2626 frequency (RoCoF).

2627 **9.4.1.2 Test setup & test conditions**

2628 The measurement shall at least be performed on a category 1b test bench as described in
2629 chapter 7.

2630 The grid emulator must be able to control the frequency of the emulated grid with required
2631 dynamics, typically 1 Hz/s to 6 Hz/s.

2632 The DUT shall include at least the components and control functions as defined in Annex B.2.

2633 **9.4.1.3 Test & measurement procedure**

2634 The test sequence consists of a rapid change of the frequency typically in a range of 1 Hz/s to
2635 6 Hz/s starting from the nominal frequency.

2636 The test shall be carried out, by increasing or decreasing the grid frequency by the specified
2637 constant rate of change of frequency (df/dt) from rated frequency. The test has to be occurred
2638 so that the DUT does not trip, with increasing the test slope (df/dt) condition in 1,0 Hz/s steps,
2639 as e.g. defined in IEC 61400-21-1: 2019, up to the RoCof capability defined by the manufacture.

2640 **9.4.1.4 Documentation**

2641 The applied settings as well as the results of these test must be listed in the test reports, a
2642 report template is given in Annex A.

- 2643 • Reference value of the protection level and release time
- 2644 • Description of control settings / operational mode

2645 Time-series of:

- 2646 • Measured positive sequence active power output at the grid connection point
- 2647 • Measured frequency or the frequency reference value f_{sim} , measured as 0,1 s average
2648 value at the grid connection point.

2649 Measurements include data 5 s prior and 5 s after to the start of the RoCoF (df/dt) event.

2650 **9.4.1.5 Transferability of test results**

2651 The test results are supplementary to the wind turbine measurements and the test results can
2652 replace full-scale wind turbine measurement.

2653 **9.4.2 Phase jump**

2654 **9.4.2.1 Description**

2655 Phase jump is used for Verification of the insensibility on automatic reconnections in case of
2656 phase discordance. The DUT behaviour during grid events that cause a fast change of the
2657 voltage vector surge in a short time frame shall be tested.

2658 The aim of these tests is to prove the correct operation of the DUT without tipping during
2659 operation.

2660 **9.4.2.2 Test setup & test conditions**

2661 The measurement shall at least be performed on a category 1b test bench as described in
2662 chapter 7.

2663 The DUT shall include at least the components and control functions as defined in Annex B.2.

2664 **9.4.2.3 Test & measurement procedure**

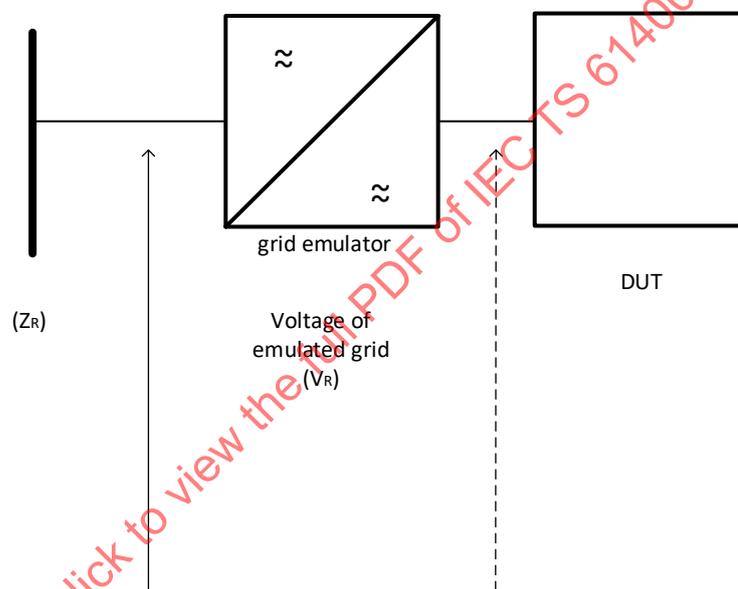
2665

2666 The test can be performed with either:

- 2667 a) A grid emulator connected to the DUT
2668 b) Or the DUT connected to the public grid

2669

2670 **9.4.2.3.1 Test with a grid emulator (option a)**



2671

2672

Figure 38 - Example of a test setup with the grid emulator.

2673 With reference to the diagram shown in Figure 38 - use of emulated grid:

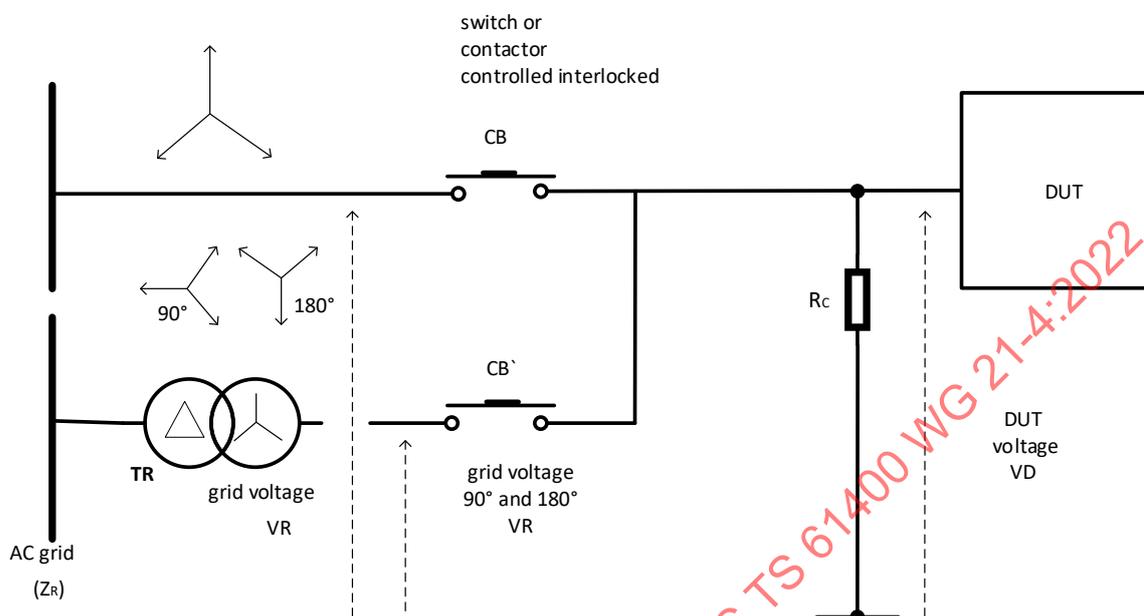
- 2674 • The grid emulator must be capable of producing a voltage phase jump on the output
2675 terminals of the converter of 90° and 180°, respectively.
- 2676 • Generator operating at power level compatible with the characteristics of the test circuit
2677 and with a unitary power factor.
- 2678 • V_R : voltage of emulated grid;

2679 The DUT must be brought into operation at nominal power. The DUT shall operate under the
2680 conditions set for at least 5 minutes.

2681 At the end of the stabilization period, 2 tests must be conducted in sequence, inducing a
2682 transient which produces suddenly a phase angle displacement on the V_R simulated grid voltage
2683 of the grid emulator about 180° in a time range $\leq 10\text{ms}$ and 90° in a time range $\leq 5\text{ms}$.

2684 **9.4.2.3.2 Test on real grid (option b)**

2685 Test on distribution grid through coupling transformer:



2686

2687 **Figure 39 - Circuit for the verification of the immunity on automatic reconnection in**
2688 **case of phase discordance through coupling transformer.**

2689 With reference to the diagram shown in Figure 39 use of a coupling transformer:

- 2690 • TR: transformer with open columns, to be configured YYn or DYn depending on the test to
- 2691 be performed.
- 2692 • DUT operating at a level of power compatible with the characteristics of the test circuit and
- 2693 with unitary power factor.
- 2694 • R_c: resistive load ballast weight with power equal to the nominal power of the DUT.
- 2695 • V_R: voltage of the distribution grid.
- 2696 • V_{R'}: voltage phase shifted relative to the distribution grid of 90° and 180° depending on the
- 2697 test to be performed.
- 2698 • V_D: voltage applied to the DUT.

2699 The DUT must be set into operation at the nominal power. The DUT shall operate under the
2700 conditions set for at least 5 minutes

2701 Check that, for at least 1 minute, the current through the CB switch is below 2% of the nominal
2702 current. The value measured must be included in the test report.

2703 Open the CB contactor and close the CB' contactor, in a coordinated and instantaneous manner
2704 (less than the difference on the opening and closing times). The ballast resistance damps the
2705 electrical transients on the output of the DUT and prevents a possible disconnection from the
2706 grid.

2707 The disconnection of the DUT or the protections tripping can only occur downstream of the
2708 complete closing of the CB' contactor.

2709 Two (2) tests must be conducted, with phase angle shift at closing of 180° and 90° respectively.
2710 For this purpose, the vector group of the TR transformed must be reconfigured appropriately.

2711 9.4.2.4 Documentation

2712 The following information shall be given and stated as part of the test report,

- 2713 • Description of the test setup / Real time simulator setup
- 2714 • The angle between the voltage before and after the phase jump, with a measurement
2715 error of max 1°.
- 2716 • Measured positive and negative sequence voltage measured at the DUT
- 2717 • Measured positive and negative sequence current
- 2718 • Measured active and reactive power from the DUT
- 2719 • Instantaneous voltage and current measurements from 20 ms before the phase jump event
2720 until min 200 ms after the event.

2721 The measurements results shall be in graphs and tables as e.g. defined in Annex A.

2722

2723 9.4.2.5 Transferability of test results

2724 The test results are supplementary to the wind turbine measurements and the test results can
2725 replace full-scale wind turbine measurement.

2726 9.5 Grid forming operation (Optional)

2727 9.5.1 Description

2728 Grid forming operation is a converter capability aiming to control voltage amplitude and
2729 frequency – both in island mode or when connected to a grid with additional power sources.
2730 Grid forming control of converter is usually intended to provide – besides active and reactive
2731 power – a contribution to the services (e.g. providing inertia and short circuit power) needed to
2732 run a grid equipped with loads or grid following converter systems.

2733 Grid forming control

- 2734 - of converters (in power plants, HVDC substations or STATCOMs) is needed if 100%
2735 converter based power generation without synchronous generators or synchronous
2736 condensers is intended.
- 2737 - with inertia and short circuit power provision is needed to provide black start capability
2738 to re-energize large grids. For black start capability, additional energy sources are
2739 needed to start up a wind turbine.
- 2740 - can be tested both at turbine or component level (or a possible combination of both).
- 2741 - typically responds to voltage amplitude or frequency (voltage angle) changes within
2742 less than ¼ line period. Therefore, some extensions of test setups described before
2743 are necessary to evaluate grid forming capabilities of converters.

2744 Specific requirements for grid control may depend on the grid operator. FNN [15] proposes the
2745 following tests:

- 2746 1. Phase jump
- 2747 2. Phase jump followed by a linear frequency change in the main voltage
- 2748 3. Voltage jump (UVRT and OVRT)
- 2749 4. Occurrence of a negative system
- 2750 5. Occurrence of harmonics
- 2751 6. Occurrence of subharmonics
- 2752 7. Change in grid impedance

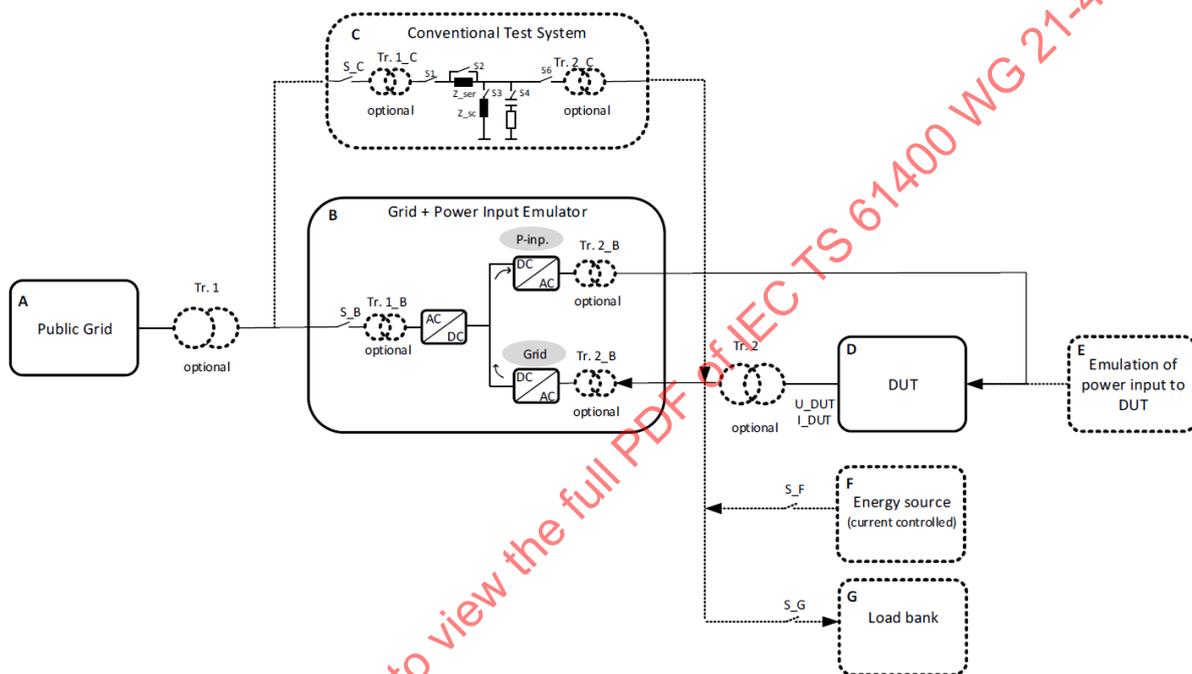
2753 resulting in additional evaluations of the results of tests methods described in the chapter of this TS. In
 2754 these cases, it is assumed, that the grid is voltage controlled and strong.

2755 In addition, the following test is required:

2756 8. Island network formation with current applying regulated voltage source

2757 In this case, it is assumed, that the grid is current controlled and weak.

2758 Figure 40 describes the test setup including necessary extension for testing grid forming
 2759 converter control capabilities. The test setup in described in a way that allows different forms
 2760 of validation (Controller software only, controller in a HiL environment, hardware test) can use
 2761 the same topology.



2762
 2763 **Figure 40 - Test setup extension for testing grid forming converter control capabilities**

2764
 2765 **Table 21 - Description of components shown in Figure 40**

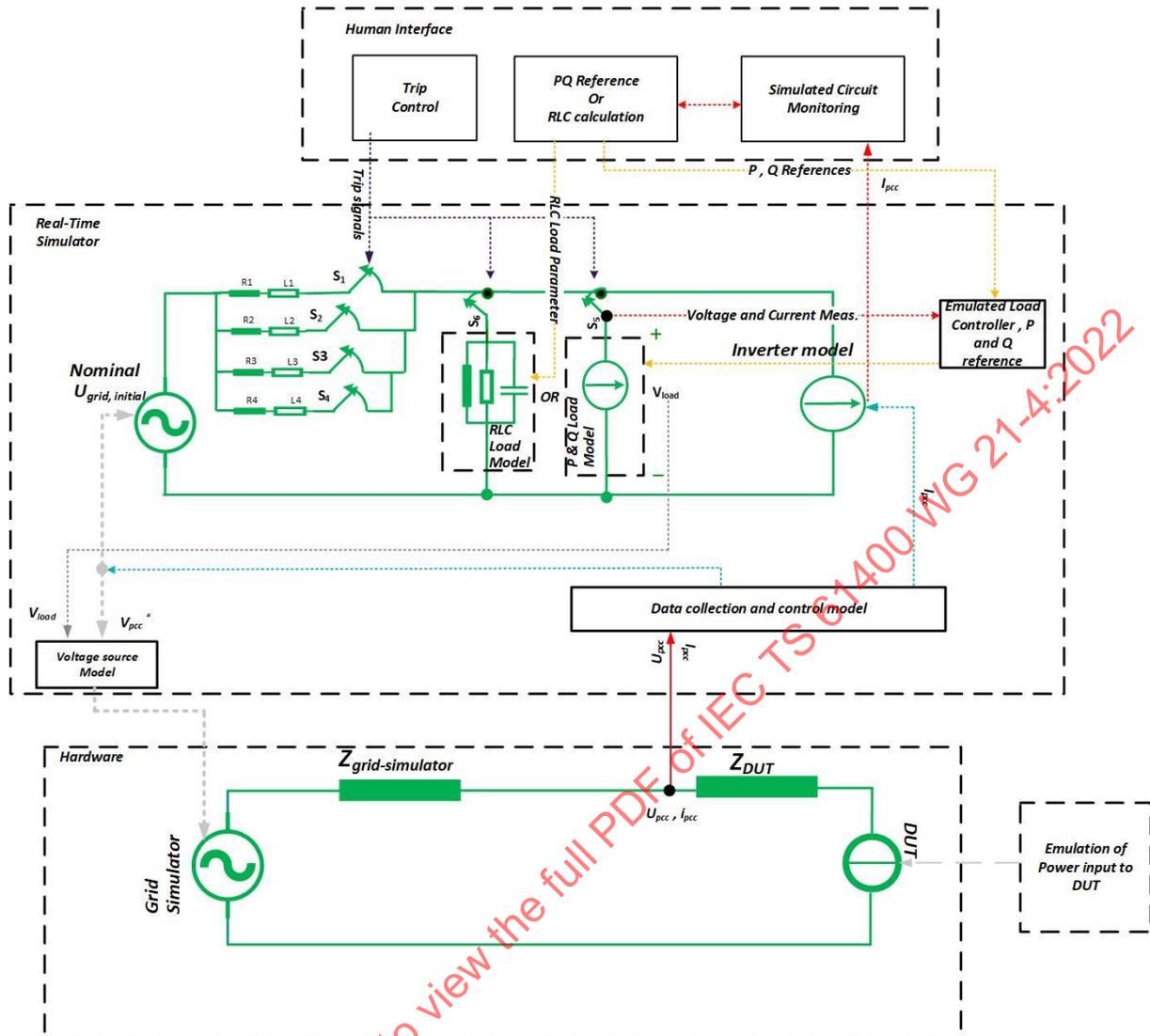
Item	Designation	Description
A	Public grid	Generators, transformers, lines and loads operating at different voltage levels and connected in one network. NOTE: Tr. 1 can be applied to step up or step down the voltage as appropriate.
B	Grid + power input emulator	Grid emulator: Device used for emulating steady state values or dynamic changes of voltage, frequency or impedance. Power input emulator: Device for emulating the power input of the DUT. Depending on the component level, it replaces e.g. the aerodynamics (rotor

		and pitch system) and the generator for testing grid forming on a converter system. NOTE: May or may not include step-up or step-down transformers Tr. 1_B and Tr. 2_B
C	Conventional test system	FRT equipment made up of voltage divider suitable for both UVRT and OVRT testing. NOTE: May or may not include step-up or step-down transformers Tr. 1_C and Tr. 2_C
D	DUT	Device under test (turbine or component level). NOTE: Tr. 2 would be the step-up transformer normally applied for the DUT, if applicable.
E	Emulation of power input to the DUT	Replaces the rotating prime mover which, in the case of a wind turbine, would be the shaft driven by the rotor blades.
F	Energy source	Used for islanding tests, where voltage and frequency are set to deviate from nominal values. NOTE: This might be needed, when the grid + power input emulator is not able to operate as current controlled load.
G	Load bank	Used for islanding tests, where voltage and frequency are set to deviate from nominal values. NOTE: This might be needed, when the grid + power input emulator is not able to operate as current controlled load.

2766
2767
2768

2769 9.5.2 Power Hardware in the loop (PHIL) implementation

2770 A possible power HiL (PHIL) implementation of the hardware setup is shown in Figure 41. Table
2771 21 describes hardware, real-time-simulator and human machine interface of the test setup.



2772

2773

2774

Figure 41 - Power Hardware in the loop (PHIL) implementation

IECNORM.COM : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

2775
2776
2777

Annex A(informative)

Report template

2778

A.1 The final detailed report template will be provided together with the CDV

2779
2780
2781
2782
2783

Information from the project leader to the Annex A: The Annex A is a summary of the defined documentation requirements from chapter 7, 8 and 9. The WG21 wants in this CD to have feedback on the suggested required documentation parts in the main document and will afterwards finalize the informative Annex A, with the same structure as defined in the IEC 61400-21-1.

2784
2785

The Annex A will include suggestions for the reporting of the measurement results. The formatting of the tables and the graphs is exemplary.

2786
2787
2788

The Annex A of this standard will be structured in the same format as the IEC 61400-21-1 and the IEC 61400-27-2, including report templates, tables and time series, of the requested parameters, values, etc. as defined in the documentation subchapters of this standard.

2789
2790
2791

In addition to the suggested test report format, the measured values should be provided in a standardized electronic format, as requested e.g. for the simulation model validation in 61400-27-2.

IECNORM.COM : Click to view the full PDF of IEC TS 61400-21-4:2022

2792

[IECNORM.COM](https://www.iecnorm.com) : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

2793
2794
2795
2796

Annex B (informative)

Subsystems

2797
2798

B.1 Guideline test flow - functional, capability and performance test

2799
2800

This TS provides the measurement and test procedures test which can be used to replace site specific tests as defined in IEC 61400-21-1.

2801
2802
2803

This technical specification is a supplement to the 61400-21-1 and IEC 61400-21-2, and does not replace all parts of these standards, as there are some functions and performance parameters, which only can be validated on the final product and at the project specific site.

2804
2805

The procedures provide the basis for detailed simulation model validations and detailed validation of the electrical characteristics of components and subsystem.

2806
2807

The defined test and measurement procedures can be performed as a combination of functional-, capability-, and performance tests.

2808
2809

The combination of the different tests on subsystem and component level can afterwards, be used to verify the overall performance of the Wind turbine, as shown in Figure 2 and Figure 42

2810
2811

A detailed test overview and overview of the minimum subsystems, necessary for the verification and assessment of the electrical characteristics are shown in Table 22 and Table 23.

2812
2813
2814
2815
2816
2817
2818

If it can be reasoned that the changes that have been implemented pose no significant risk of changing the electrical performance of the unit, then there is no need to perform new tests and measurements on the wind turbine with the changes or DUT. In these cases, the measurement and test results can be adapted to the other wind turbines within the product platform. A detailed guideline can be found in IEC61400-21-1 Annex F. In the cases of minor changes e.g. on the control function, the validation of the performance can be performed as a functional test, including the WT controller and a HiL setup with the necessary control interfaces.

2819
2820
2821

In cases where minor changes in the subsystems requesting a refresh of partial tests and measurements, or if it has been validated and agreed that the test results are not affected by the different test level, a lower system test level than stated would be acceptable.

2822
2823

Table 22 and Table 23, provides as well the overview of the necessary subsystems and components which are necessary for the functional (F), capability (C) and performance test (P).

2824
2825

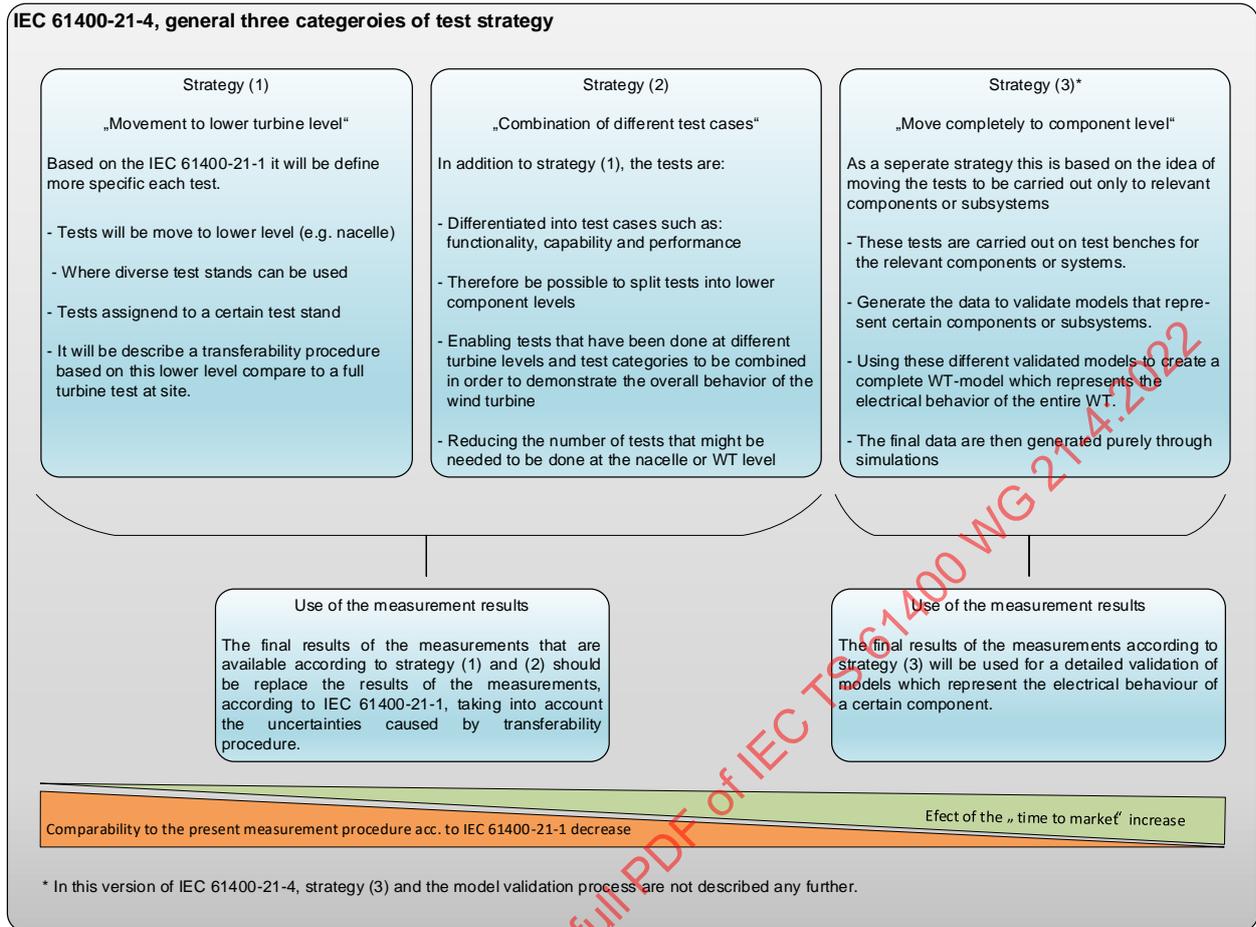
The validation can be performed as a combination of functionality test, capability test and performance test. Where the final validation will be a combination of the different test categories.

2826
2827

The measurement results are finally used to validate theoretical analysis and numerical simulations models as well as electrical performance of the Wind Turbine, subsystems and components.

2828

Figure 42 – gives an overview of the different test categories and strategies.



2829

2830

2831

2832

B.2 Overview of components, subsystems and control functions

2833 Table 22 and Table 23 gives an overview of the major components subsystems and control functions,
2834 against the different measurements and test procedures as defined in this TS. The different columns
2835 defines therefore the minimum requirements for the DUT.

2836 Each column defines therefore as a guidance the necessary parts and subsystems, which
2837 should be as minimum, included in the test system as DUT, to be able validate and perform the
2838 required measurements and tests.

2839 The control functions are listed as functionality, instead of the physical HW (Turbine controller
2840 etc.), as the physical HW implementation of these controller functions can variate from WT type
2841 and manufacture.

2842

Figure 42 – Overview of test strategies

2843
2844

Table 22 – Overview of components, subsystems and control functions according to chapter 8

Test	Chapter Nr.	test bench system	Functionality test	Capability test	Performance test	Converter System	Generator	Additional Cap-banks	Filter	Grid Power Control (active Power)	Grid Power Control (reactive Power)	Generator Power Control (or speed control)	Switch Gear (Circuit breaker / Contactor)	Transformer	Aux. equip.	Grid (FRT) Current Control	Grid Voltage Control	Grid Frequency control	Grid protection functions	Hub	Blades (always emulated)	Pitch system	Pitch controller	Drive train (Incl. Gearbox)
Flicker		Field test *			X																			
Switching operations		Field test *			X																			
Reconnection time		Field test *			X																			
Harmonics, Interharmonics - Higher frequencies		2b			X	P	P	P	P	P	P	P		P										P
Maximum Power		1a			X	P	P	P	P	P	P	P		P	P					P	P	P	P	P
Reactive power characteristic (Q=0)		2a			X	P	P(1,2,3)	P	P	P	P	P			P									
Reactive power capability		2b		X		C	C(1,2,3)	C	C	C	C	C		C										
Voltage dependency of PQ diagram		2b		X		C	C(1,2,3)	C	C	C	C	C		C										
Unbalance factor		2b			X	P	P	P	P			P		P										P
Active power control		2a	X	X		P	P			F,P		F,P								P	P	(P)	F,P	
Active power ramp rate limitation		1a or 2a	X	X		P	P			F,P		F,P								P	(P)	(P)	F,P	
Frequency control		2a	X	X		P	P			F, P		F, P	P					F,P	F,P					
Synthetic inertia		1a		X	X	P,C	P,C			P,C		P,C							F,P	F,P				
Reactive power control		2b	X	X		P	P(1,2,3)	P			F,P									P,C	P,C	P,C	P,C	P,C
UVRT		From 3a- 1 a	X	X	X	P,C	P,C	P	P,C	P,C,F	P,C,F	P,C,F	(P)	P,C	P	P,C,F	P,C,F	P,C,F	(P)	P*,C*	P*,C*	P*,C*	P*,C*	(P*),C*
OVRT		From 3a- 1 a	X	X	X	P,C	P,C	P	P,C	P,C,F	P,C,F	P,C,F	(P)	P,C	P	P,C,F	P,C,F	P,C,F	(P)	P*,C*	P*,C*	P*,C*	P*,C*	(P*),C*
Grid protection		3c	X										F							F				
Rate of change of frequency RoCoF (df/dt)		3c	X										F							F				

2845

2846 P: Performance test C: capability test F: Functional test
 2847 (1,2,3,4): refers to turbine type I, II, III and IV * Can be emulated

Table 23 - Overview of components, subsystems and control functions according to chapter 9

2849

Test	Chapter Nr.	Test bench system	Functionality test	Capability test	Performance test	Converter System	Generator	Additional Cap-banks	Filter	Grid Power Control (active Power)	Grid Power Control (reactive Power)	Generator Power Control (or speed control)	Switch Gear (Circuit breaker / Contactor)	Transformer	Aux. equip.	Grid (FRT) Current Control	Grid Voltage Control	Grid Frequency control	Grid protection functions	Hub	Blades (always emulated)	Pitch system	Pitch controller	Drive train (Incl. Gearbox)	
Flicker control		1b	X		X	P	P	P	P	F,P	F,P			P			F,P							P,C	
Flicker and voltage change during switching operations		2b	X		X	P	P	P	P	F,P	F,P			P			F,P								
Active filter / Sink for harmonics		2b	X		X	P	P(1,2,3)	P	P	F,P	F,P			P			F,P							P(1,2,3)	
Impedance measurements		2b			X	X	1,2,3	X	X	X	X			X	X	X									1, 2, 3
Voltage capability		2b		X		C	C	C	C	C	C			C	C		C								
Frequency capability		2b		X		C	C	C	C	C	C			C	C		C								
Current unbalance		2b		X		C	C	C	C	C	C			C	C		C								
Grid Impedance variations		1b		X		C	C	C	C	C	C			C	C		C					C*	C*	C	
Island operation		1b		X		C	C	C	C	C	C			C	C		C					C*	C*	C	
RoCoF – real df/dt – capability		1b		X		C	C	C	C	C	C			C	C		C					C*	C*	C	
Phase jump		1b		X		C	C	C	C	C	C			C	C		C					C*	C*	C	
Grid forming		1a																							

2850

2851 P: Performance test C: capability test F: Functional test
 2852 (1,2,3,4): refers to turbine type I, II, III and IV * Can be emulated

2853 The control functions are listed as functionality, instead of the physical HW (Turbine controller
2854 etc.), as the physical HW implementation of these controller functions can variate from WT type
2855 and manufacture.

2856

2857

[IECNORM.COM](https://www.iecnorm.com) : Click to view the full PDF of IEC TS 61400 WG 21-4:2022

2858
2859
2860
2861

Annex C (informative)

Replacement of components

2862 C.1 Introduction

2863 The aim of the following chapter is to describe a standardized workflow to avoid complete repeating of
2864 a grid compliance measurement on a wind turbine in field or on a test bench by changing individual
2865 components or releasing new software versions.

2866 C.2 Definition of components

2867 This process is considering both changes to hardware or software of the turbine:

2868 1. Adaption or improvement of software

2869

2870 The software changes includes that one of the turbine controllers, the converter, safety system
2871 or other software of components are updated. The assumption is that a prototype of a product
2872 family has been tested with appropriate software and there is a certificate or equivalent
2873 attestation that the grid compliance is fulfilled.

2874

2875 2. Adaption or improvement of hardware

2876

2877 The hardware includes all relevant hardware components of a turbine. The assumption is that
2878 a prototype was tested with a defined set of components in the field or on test bench. Either at
2879 the same time or later, it is decided that this type of wind turbine will be sold with other
2880 components, for example, from another manufacturer. Also considering parts of a component
2881 being adjusted to increase performance. These component adjustments or manufacturer
2882 change should not result in the automatic loss of measurement results or certificates. Rather,
2883 an analysis should conclude if this adaptation affects the grid compliance properties.

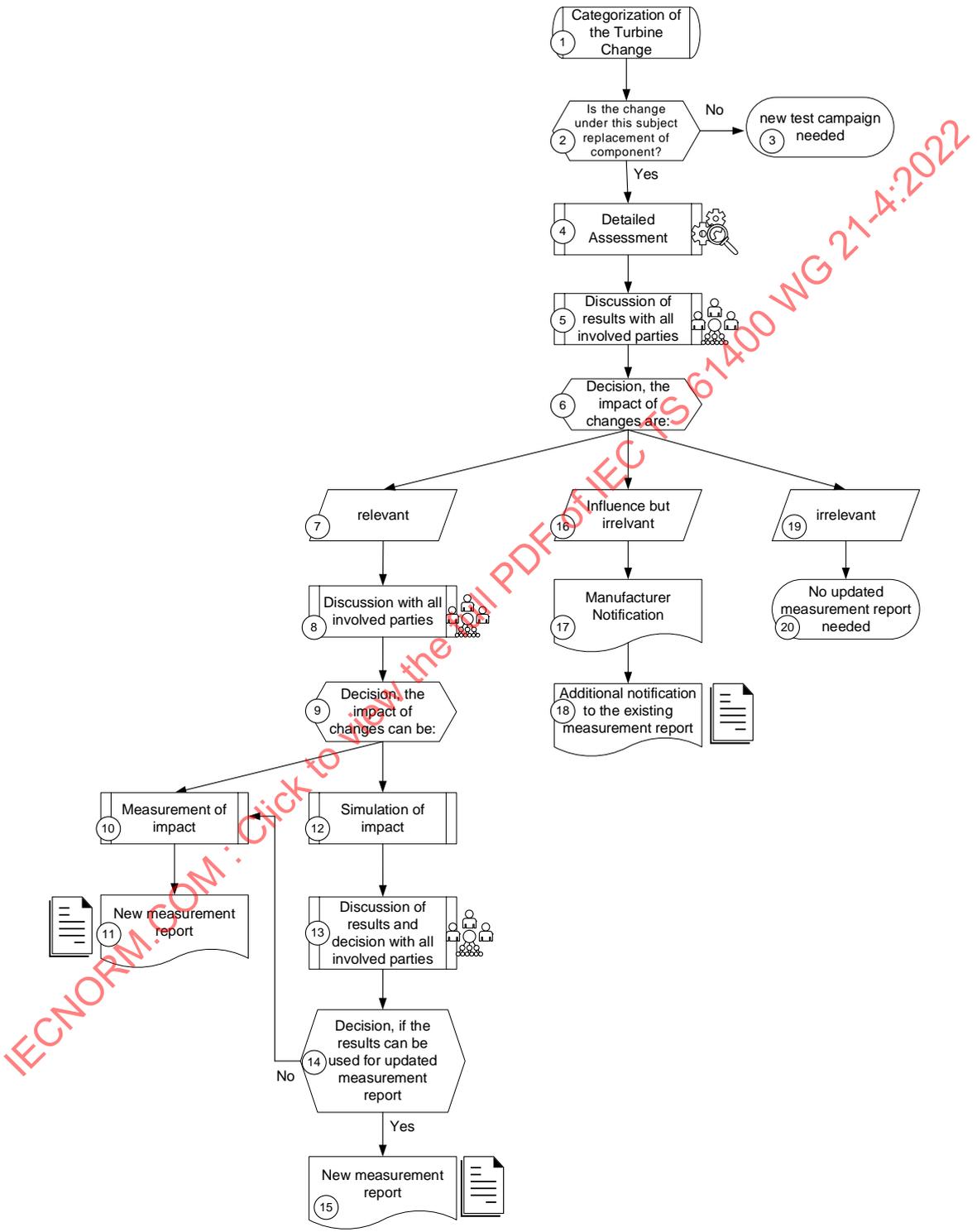
2884

2885

IECNORM.COM : Click to view the full PDF of IEC TS 61400-WG 21-4:2022

2886 **C.3 Workflow replacement of component**

2887 The following Figure 43 shows a standardized workflow for replacement of a hard- and software
 2888 component. A detailed description about the workflow and the definition of each box is stated
 2889 below.



2890

2891

2892 **Figure 43 - Flowchart of the procedure to handle a hardware or software update**

2893

2894 **1) Categorization of the Turbine Change**

2895 A software or hardware component is replaced by the manufacture and the process of reassessment
2896 starts. It has to be checked, if the change is a subject of the described process of replacement of
2897 components. The workflow can be used, if the changed component is listed in Figure 4 and the
2898 change is done at the same product family as the tested prototype (see IEC 61400-21-1: 2019, Annex
2899 F).

2900

2901 **2) Is the change under this subject replacement of component?**

2902 If the change fulfills the criteria in Box 1, the described process of reassessment in Box 4 can be
2903 follow. Otherwise, the change does not fulfill the criteria in Box 1 and a new test campaign is needed,
2904 as describes in Box 3.

2905 **3) New test campaign needed**

2906 A new measurement according to Chapter 7.1 or IEC 61400-21-1 must be done.

2907

2908 **4) Detailed assessment**

2909 A first assessment of the influence on the electrical characteristics is done by the manufacture. The
2910 results of the assessment process shall be summarized in a report. The report includes the following
2911 information:

- 2912 • Description/ Specification of changed parameters or hardware component
- 2913 • Reason for the change of component
- 2914 • Description of the affected properties and functions of the turbine
- 2915 • Which tests according to Table XXX (Annex B) consider the component?
- 2916 • Results of the evaluation

2917

2918 **5) Discussion of results with all involved parties**

2919 The evaluation report is discussed with all involved parties and a decision is made on the impact of
2920 changes. There are three categories:

- 2921 • Relevant: Change has an influence on the electrical characteristics
- 2922 • Influence but irrelevant: Change have an insignificant impact on the electrical characteristics
2923 of the wind turbine, which can be neglected
- 2924 • Irrelevant: Change has no influence on the electrical characteristics of the wind turbine

2925

2926 **6) Decision**

2927 Depending on the categorization in Box 5, three different paths of actions are defined:

- 2928 • Relevant: Box 7 to Box 18
- 2929 • Influence but irrelevant: Box 19 to Box 22
- 2930 • Irrelevant: Box 23 to Box 24

2931

2932 **7) Path: relevant**

2933 If the changes are relevant for the electrical characteristics, then two options for analysis are available:

- 2934 • Measurement of impact (Box 10)
2935 • Simulation of impact (Box 14)

2936 The classification of impact and definition of test cases is based on a discussion with all involved
2937 parties (Box 8 and Box 9). Table 22 and Table 23 in Annex B can serve as the basis for discussion.
2938

2939 **Box 10. Measurement of impact**

2940 The measurement can be divided in two categories:

- 2941 a. A remeasurement of the affected grid compliance characteristics at the upgraded
2942 complete wind turbine in the field according to IEC 61400-21-1 or test bench according to
2943 Chapter 7.1.
2944 b. A remeasurement of the affected grid compliance characteristics on the adjusted or
2945 replaced component on a test bench

2946 For a remeasurement at the upgrades complete turbine in field see IEC 61400-21-1 and on test bench
2947 see Chapter 7.1. A test procedure for a remeasurement on the adjusted or replaced component on a
2948 test bench is described in C.4.

2949 **Box 11. New measurement report**

2950 The results of measurement have to be summarized in a new measurement report. The new
2951 measurement report also includes a comparison between the test results with the reference
2952 component and the changed component.

2953 **Box 12. Simulation**

2954 The grid scenarios for simulation are defined according to the test cases. The simulation is based on a
2955 validated model of the DUT and an adapted model of the DUT. The validated model must be adapted
2956 according to the changes. The simulation must be done with the validated model and the adapted
2957 model. The results of the simulation with the validated model represent the reference. A comparison
2958 must be done with the simulation results.
2959

2960 **Box 13. Discussion of results decision with all involved parties**

2961 The simulation results are discussed with all involved parties and a decision is made on the influence
2962 of changes on the electrical properties, either an additional Notification for the measurement report is
2963 made or a new measurement (Box 10) can be carried out.
2964

2965 **Box 14. decision with all involved parties**

2966 A decision is made on the influence of changes on the electrical properties, either an additional
2967 Notification for the measurement report is made or a new measurement (Box 10) can be carried out.

2968 **Box 15. New measurement report**

2969 The simulation results are included in the existing measurement report as an additional
2970 notification.

2971 **Box 16. Path: Influence but irrelevant**

2972 If the changes have an influence in the electrical characteristics, but modifications are irrelevant
2973 for the grid characteristics, the follow path can be used.

2974 **Box 17. Manufacturer notifications**

2975 The manufacturer prepares a manufacturer notification based on the detailed assessment
2976 report (Box 4).

2977 **Box 18. Additional notification to existing report**

2978 The manufacture notification is included in the existing measurement report as an additional
2979 notification.

2980 **Box 19. Path: Irrelevant**

2981 If the changes are irrelevant, no further action is needed.

2982 **Box 20. No updated measurement report needed**

2983 The existing measurement report is not updated and can be used for other processes.

2984 Note: If a certification procedure exists, the updated measurement report will be passed to the certification body to
2985 update the certificate.

2986 **C.4 Test & measurement procedure**

2987 When measuring a complete turbine in the field, you can simplify the in- and output as illustrated in
2988 Figure 44. The turbine is integrated in a specific environment, such as:

- 2989 • the variable primary energy input
- 2990 • the electrical network which consuming the electrical energy output
- 2991 • the parameters that determine the mode of operation of the DUT in relation to the operating
2992 point.
- 2993 • Eventually reference values like P, Q, U, $\cos \phi$, etc.

2994 Generally, the physical quantities at the input and output of the DUT are measured as shown in (s.
2995 Figure 44.

2996

2997 The network changes or network disturbances shown in the illustration below can, for example,
2998 represent voltage dips or even network preloads. The measurement results are either used for project-
2999 related analyses or evaluated regarding grid codes.

3000

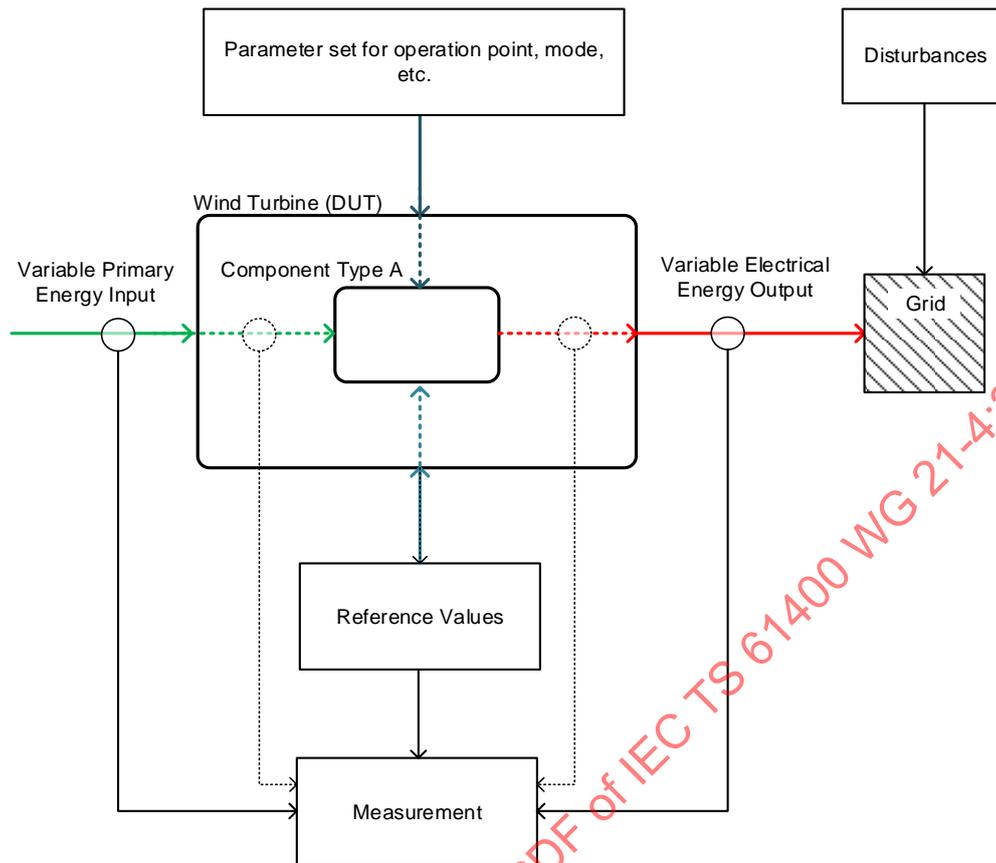


Figure 44 - Illustration of a set-up on a test field, when testing a complete wind turbine with the in- and outputs, the parameter, references, measurements, the grid and disturbances including a certain component type A.

First step:

The first step to show that a component change shows the same electrical behavior is, to make sure that at least the electrical environment is the same within certain limits compare to the related basis measurement (e.g. a field test).

More specifically, should the DUT now represent a single component to be tested on a test bench, the environmental conditions should be adapted to the test in the field.

If a test on a wind turbine in the field is performed first, the boundary conditions as well as the measurement results are present (solid lines). If, at the time of the field measurements, the inputs and outputs as well as, if different, the border conditions (dashed line) are also indicated, this can later be used to measure a modified component on, for example, a test bench. As described, it is always important to adapt the boundary conditions as well as possible to the field measurements.

Second step:

The second is to test the component type A again with some reduced test cases on a test rig and measure the same in and outputs as done during the field tests (s. Figure 45)