Datasheet of Power Quality

EnVentus™

The following document is intended for information purpose only and is subject to changes in content – without prior notification – as a result of product developments. Prior to use, all users are responsible for ensuring that they are referring to the most recent, valid version.

Vestas

Revision history

VERSION:	CHANGE:	DATE	RESPONSIBLE
00	New document	2021-03-30	RMCBA
01	Reactive power control updated acc. to EnVentus reports	2021-05-14	RMCBA
02	Flicker and Harmonics updated for V162-6MW	2021-09-11	RMCBA
03	Update to cover 6.2MW variant	2022-04-27	DICOS
03	Reactive power capability updated with V1xx-6.2MW reports	2022-10-06	DICOS
03	Adjust test results to show full variant cover Introduction update	2022-11-29	DICOS

Table of Contents

Introduction 3
Results 6
8.1 General 6
8.1.1 Observation of active power against wind speed 6
8.2 Power Quality Aspects 6
8.2.1 Voltage fluctuations 6
8.2.2 Continuous operation 6
8.2.3 Switching operations 7
8.2.4 Current harmonics, interharmonics and higher frequency components 8
8.2.5 Harmonic model 11
8.3 Steady state operation 12
8.3.1 Maximum power 12
8.3.2 Reactive power capability 12
8.4 Control performance 14
8.4.1 Active power control (Set-point control) 14
8.4.2 Active power ramp rate limitation 16
8.4.3 Frequency control 18
8.4.5 Reactive power control (Set-point control) 22
8.5 Dynamic performance 25
8.5.2 Undervoltage events / Response to voltage drops 25
8.5.3 Overvoltage events 25
8.6 Grid protection 25
8.6.2 Voltage and frequency protection 25
8.6.4 Reconnection time 26
9 Transferability of results 27
Reference documents 28

Introduction

This report presents datasheets for the EnVentus™. Since this turbine family is electrically a further development of the 4.0/4.2 MW turbine, accredited power quality measurements according to IEC 61400-21 from V136-4.2 MW and V136-3.6 MW have been used as estimates for the per unit performance, where data is not yet available for EnVentus™. In each chapter, an indication from where the results are extracted is given. On the bellow table it can be seen the variants data available for each test group on this version.
The sections in this document have been numbered according to IEC 61400-21-1 [1].

Test Group	Variants
Power Quality	
Voltage Fluctuations	EnVentus™
Continuous Operation	EnVentus™
Switching Operation	EnVentus™
Current harmonics, interharmonics and higher frequency components	EnVentus™
Harmonic model	EnVentus™
Steady State Operation	
Maximum Power	EnVentus™
Reactive Power Capability	EnVentus™
Control performance	
Active Power Control (set-point control)	3.6 MW
Active Power ramp rate limitation	3.6 MW
Frequency Control	V1xx-4.2 MW
Reactive Power Control (set-point control)	EnVentus™
Dynamic Performance	
Undervoltage events / Response to voltage drops	V150-4.2 MW
Overvoltage events	V150-4.2 MW
Grid Protection	
Voltage and frequency protection	V1xx-4.2 MW
Reconnection time	V117-3.6 MW

Wind turbine family

This datasheet covers the variants in the EnVentus™ platform according to below table.

EnVentus™	6.2 MW	6.0 MW	5.6 MW *
V150		X	X
V162	X	X	X

Table 1 Covered variants of EnVentus™.

*) other project-specific and/or derated power versions of the same WTG are also covered.

Wind turbine general data

Wind turbine type designation	See Table 1
Wind turbine manufacturer	Vestas Wind Systems

Table 2 Test turbine(s)

Wind turbine type (horizontal/vertical axis)	Horizontal
Number of blades	3
Rotor diameter (m)	See Table 1
Hub height (m)	--
Blade control (pitch/stall)	Pitch
Speed control (fixed/two-speed/variable)	Variable
Generator type and rating(s) (kW)	PMG up to 6250 kW
Frequency converter type and rating (kVA)	4-Q back-to-back full-scale converter, 6550 kVA
Transformer ratio and rating (kVA)	20 – 36 kV/ 0.720 kV, 7000 kVA / 7300 kVA / 7500 kVA
Identification of wind turbine terminals	Flicker and harmonics: High voltage side of transformer UVRT: Low voltage side of transformer

Table 3 Rated data

Wind turbine nominal data LV-side

Nominal power, P_n (kW)	See Table 1
Nominal wind speed, v_n (m/s)	See [3-7, 19, 20, 29]
Nominal apparent power, S_n (kVA)	6200 kVA @ 5.6 MW 6550 kVA @ 6.0 MW 6770 kVA @ 6.2 MW and 7500kVA
Nominal reactive power, Q_n (kVAr)	+2664(cap) / -1987(ind) kVAr @ 5600 kW and U=1 p.u. +2664(cap) / -1987(ind) kVAr @ 6000 kW and U=1 p.u. +2753(cap) / -2053(ind) kVAr @ 6200 kW and U=1 p.u. and 7500kVA +2158(cap) / -1228(ind) kVAr @ 6200 kW and U=1 p.u. and 7300kVA
Nominal current, I_n (A)	5000 A @ 5.6 MW 5250 A @ 6.0 MW 5440 A @ 6.2 MW
Nominal voltage, U_n (V)	3 x 720 V phase to phase
Nominal frequency, f_n (Hz)	50/60 Hz

Table 4 Nominal data

Type of information	Document name and date
Description of the tested wind turbine, including settings of the relevant control parameters	This document states the power quality aspects of the EnVentus™ turbines.
Author	RMCBA/DICOS
Reviewers	OLHAN DIRIZ GEKAN PCK
Approver	TPDSA

Table 5 Document info

Results

8.1 General

8.1.1 Observation of active power against wind speed

Please refer to the wind turbine performance specifications [3-7, 19, 20, 29].

8.2 Power Quality Aspects

8.2.1 Voltage fluctuations

The voltage fluctuations have been measured in the field at Østerild test center for a V150-6.0 MW turbine.

8.2.2 Continuous operation

Results from EnVentus™ V150-6.0 MW are available in ref. [9] and from V162-6.0 MW in ref. [27] .
Since flicker is a low frequency phenomenon, the results for both 50 Hz and 60 Hz are not expected to vary significantly. The rotor size can impact flicker, therefore the results for both rotor sizes are presented. The difference in power rating should not be expected to affect significantly the performance.

The mode of operation of the turbine was with Reactive Power set point Q = 0.

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100	Max.
30º	0.48	0.66	0.68	0.88	1.40	1.66	1.71	1.65	1.72	1.78	1.47	**1.78**
50º	0.47	0.64	0.63	0.74	1.09	1.25	1.28	1.19	1.23	1.29	1.06	**1.29**
70º	0.46	0.57	0.57	0.58	0.72	0.77	0.79	0.75	0.73	0.75	0.68	**0.79**
85º	0.43	0.51	0.51	0.51	0.56	0.60	0.60	0.63	0.58	0.62	0.59	**0.63**

Table 6: V150-x.x MW Flicker in continuous operation [9]

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100	Max.
30º	0.71	0.74	0.76	0.77	1.03	1.24	1.16	1.17	1.24	1.07	1.17	**1.24**
50º	0.68	0.71	0.70	0.69	0.89	0.98	0.94	0.92	0.97	0.97	0.91	**0.98**
70º	0.62	0.64	0.62	0.61	0.72	0.72	0.69	0.67	0.70	0.68	0.69	**0.72**
85º	0.58	0.59	0.57	0.56	0.64	0.65	0.61	0.60	0.61	0.61	0.67	**0.67**

Table 7: V162-x.x MW Flicker in continuous operation [27]

8.2.3 Switching operations

The operational mode of the wind turbine during the test was: **Reactive set-point control, Q = 0**

a. Start-up at cut-in wind speed

Data acquired	**5**			
Maximum number of switching operations, N_{10m}:	**10**			
Maximum number of switching operations, N_{120m}:	**120**			
Network impedance phase angle, ψ_k [°]:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:	0.01	0.01	0.01	0.02
Voltage change factor, $k_U(\psi_k)$:	0.06	0.05	0.03	0.02

Table 8: V150-x.x MW Switching data based on measurements [9]

Data acquired	**5**			
Maximum number of switching operations, N_{10m}:	**10**			
Maximum number of switching operations, N_{120m}:	**120**			
Network impedance phase angle, ψ_k [°]:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:	0.01	0.01	0.01	0.01
Voltage change factor, $k_U(\psi_k)$:	0.05	0.04	0.03	0.02

Table 9: V162-x.x MW Switching data based on measurements [27]

b. Start-up at rated wind speed

Data acquired	**5**			
Maximum number of switching operations, N_{10m}:	**1**			
Maximum number of switching operations, N_{120m}:	**12**			
Network impedance phase angle, ψ_k [°]:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:	0.04	0.03	0.02	0.02
Voltage change factor, $k_U(\psi_k)$:	0.84	0.59	0.28	0.04

Table 10: V150-x.x MW Switching data based on measurements [9]

Data acquired	**5**			
Maximum number of switching operations, N_{10m}:	**1**			
Maximum number of switching operations, N_{120m}:	**12**			
Network impedance phase angle, ψ_k [°]:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:	0.03	0.03	0.02	0.02
Voltage change factor, $k_U(\psi_k)$:	0.84	0.59	0.27	0.04

Table 11: V162-x.x MW Switching data based on measurements [27]

c. **Service shutdown at rated power**

d.

Data acquired	**5**			
Maximum number of switching operations, N_{10m}:	**1**			
Maximum number of switching operations, N_{120m}:	**12**			
Network impedance phase angle, ψ_k [°]:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:	0.07	0.05	0.03	0.01
Voltage change factor, $k_U(\psi_k)$:	0.84	0.59	0.28	0.04

Table 12: V150-x.x MW Switching data based on measurements [9]

Data acquired	**5**			
Maximum number of switching operations, N_{10m}:	**1**			
Maximum number of switching operations, N_{120m}:	**12**			
Network impedance phase angle, ψ_k [°]:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:	0.07	0.05	0.03	0.01
Voltage change factor, $k_U(\psi_k)$:	0.83	0.59	0.27	0.03

Table 13: V162-x.x MW Switching data based on measurements [27]

8.2.4 Current harmonics, interharmonics and higher frequency components

The emission of current harmonics, interharmonics and higher frequency components from the wind turbine is specified for in percent of I_n for operation of the wind turbine within the power bins 10, 20, … , 100 % of P_n. The operational mode of the wind turbine during the test was: **Reactive set-point control, Q = 0.**
I_n is defined as the current magnitude at U = 1 p.u., Q = 0 and P = P_n for the given power mode.

V150-6.0 MW 50 Hz data is presented below and in ref. [10]. V162-6.0 MW data is presented in ref. [28].

8.2.3.1 Integer harmonics

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100	MAX
H	I_h/I_n (%)											
2	**0.17**	0.14	0.13	0.13	0.14	0.14	0.15	0.15	0.16	0.16	0.16	0.17
3	**0.13**	0.13	0.11	0.11	0.11	0.09	0.08	0.06	0.08	0.07	0.08	0.13
4	0.09	0.15	0.16	**0.17**	0.16	0.14	0.12	0.12	0.12	0.12	0.13	0.17
5	0.15	0.14	0.15	0.15	0.15	**0.17**	0.15	0.13	0.10	0.09	0.09	0.17
6	0.04	0.06	0.07	**0.09**	0.09	0.08	0.07	0.06	0.07	0.08	0.07	0.09
7	**0.15**	0.15	0.12	0.15	0.13	0.11	0.10	0.11	0.10	0.10	0.09	0.15
8	0.06	**0.15**	0.12	0.12	0.11	0.09	0.09	0.10	0.09	0.10	0.10	0.15
9	0.08	0.11	0.12	0.15	**0.16**	0.12	0.07	0.06	0.06	0.06	0.05	0.16
10	0.05	0.10	0.13	**0.17**	0.15	0.14	0.11	0.11	0.11	0.12	0.13	0.17
11	0.28	0.26	0.30	**0.46**	0.34	0.34	0.30	0.25	0.23	0.30	0.32	0.46
12	0.06	**0.15**	0.14	0.14	0.14	0.13	0.09	0.08	0.08	0.09	0.09	0.15
13	0.21	0.35	0.33	0.34	**0.38**	0.35	0.27	0.21	0.19	0.18	0.17	0.38
14	0.03	0.06	0.06	**0.06**	0.06	0.05	0.04	0.04	0.04	0.05	0.06	0.06
15	0.05	0.05	0.06	0.06	**0.06**	0.05	0.04	0.03	0.03	0.03	0.03	0.06
16	0.03	0.04	0.04	0.04	**0.04**	0.04	0.04	0.03	0.03	0.03	0.04	0.04
17	0.08	0.08	0.07	0.09	**0.11**	0.09	0.07	0.07	0.07	0.08	0.08	0.11
18	0.02	0.03	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.04	**0.04**	0.04
19	0.05	0.09	**0.11**	0.08	0.07	0.07	0.07	0.08	0.08	0.09	0.10	0.11
20	0.02	0.04	0.03	0.03	0.04	**0.04**	0.04	0.04	0.04	0.04	0.04	0.04
21	0.02	0.04	0.03	0.03	0.03	0.03	**0.06**	0.06	0.05	0.04	0.05	0.06
22	0.03	0.05	0.05	**0.05**	0.05	0.05	0.04	0.05	0.05	0.05	0.04	0.05
23	0.10	0.19	**0.29**	0.24	0.22	0.16	0.20	0.17	0.16	0.14	0.14	0.29
24	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	**0.04**	0.04
25	0.05	0.13	**0.16**	0.16	0.16	0.15	0.14	0.12	0.12	0.12	0.11	0.16
26	0.01	0.02	0.02	0.02	**0.02**	0.02	0.01	0.02	0.01	0.01	0.01	0.02
27	0.01	0.01	0.01	0.01	0.01	0.01	**0.02**	0.02	0.02	0.02	0.02	0.02
28	0.02	**0.03**	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03
29	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	**0.02**	0.02
30	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.01	0.02	**0.02**	0.02
31	0.01	**0.02**	0.02	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.02
32	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01
33	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.01	**0.01**	0.01
34	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	**0.02**	0.02
35	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.01	**0.01**	0.01	0.01
36	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01
37	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	**0.01**	0.01	0.01	0.01
38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
40	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	**0.01**	0.01
41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
42	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	**0.01**	0.01	0.01	0.01
43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
45	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	**0.01**	0.01
46	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01
47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00
48	0.01	**0.01**	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01	0.01
50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	0.00
THC (%)	0.45	0.56	0.61	**0.71**	0.63	0.58	0.51	0.44	0.45	0.46	0.48	0.71

Table 14 - V1xx-x.x MW 50 Hz measurements [10]

8.2.3.2 Interharmonics

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100	MAX
f (Hz)	I_h/I_n (%)											
75	0.03	0.04	0.12	0.18	0.15	0.16	0.20	0.23	**0.38**	0.29	0.35	0.38
125	0.02	0.03	0.05	0.06	0.05	0.05	0.05	0.06	**0.10**	0.08	0.09	0.10
175	0.04	0.04	0.05	0.05	0.05	0.04	0.04	0.04	**0.06**	0.05	0.06	0.06
225	0.03	0.04	0.05	0.05	0.05	0.04	0.04	0.04	0.06	0.06	**0.06**	0.06
275	0.03	0.04	0.04	0.04	0.05	0.05	0.03	0.03	0.05	0.05	**0.05**	0.05
325	0.03	0.04	0.05	0.05	0.05	0.04	0.03	0.04	0.05	0.05	**0.06**	0.06
375	0.03	0.04	0.05	0.04	**0.05**	0.05	0.03	0.03	0.04	0.03	0.04	0.05
425	0.04	0.05	0.06	**0.06**	0.06	0.05	0.04	0.03	0.04	0.04	0.04	0.06
475	0.04	0.05	0.06	0.06	**0.07**	0.07	0.04	0.04	0.05	0.06	0.06	0.07
525	0.04	0.05	**0.06**	0.06	0.06	0.06	0.04	0.04	0.04	0.04	0.05	0.06
575	0.05	0.06	**0.07**	0.06	0.06	0.06	0.04	0.03	0.04	0.04	0.04	0.07
625	0.04	0.05	**0.06**	0.05	0.05	0.05	0.03	0.03	0.03	0.03	0.04	0.06
675	0.03	0.04	**0.04**	0.04	0.04	0.04	0.02	0.02	0.03	0.03	0.03	0.04
725	0.02	0.03	**0.03**	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.03
775	0.02	0.02	**0.03**	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.03
825	0.01	0.02	**0.02**	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02
875	0.01	0.02	**0.02**	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02
925	0.01	0.02	**0.02**	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02
975	0.01	0.02	0.02	0.02	0.02	0.02	**0.02**	0.02	0.02	0.02	0.02	0.02
1025	0.01	0.02	0.02	0.02	0.02	0.02	**0.03**	0.02	0.02	0.02	0.02	0.03
1075	0.02	0.03	0.03	**0.03**	0.03	0.02	0.03	0.02	0.03	0.03	0.02	0.03
1125	0.02	0.03	0.03	**0.03**	0.03	0.02	0.02	0.02	0.02	0.03	0.02	0.03
1175	0.02	0.03	**0.03**	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03
1225	0.02	0.02	0.02	**0.03**	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03
1275	0.01	0.02	0.02	**0.02**	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02
1325	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01	0.01	0.01
1375	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01
1425	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01
1475	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01
1525	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01	0.01	0.01
1575	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.01	**0.01**	0.01	0.01	0.01
1625	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01	0.01
1675	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	**0.01**	0.01
1725	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	**0.01**	0.01
1775	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	**0.01**	0.01
1825	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.01**	0.00	0.01	0.01
1875	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.01**	0.00	0.01	0.01
1925	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.01**	0.00	0.01	0.01
1975	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	**0.01**	0.01

Table 15 - V1xx-x.x MW 50 Hz measurements [10]

8.2.3.3 Higher frequency components

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100	MAX
f (kHz)	I_h/I_n (%)											
2.1	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	**0.02**	0.02	0.02
2.3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	**0.02**	0.02	0.02
2.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	**0.02**	0.02	0.02
2.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	**0.02**	0.02	0.02
2.9	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	**0.02**	0.02	0.02
3.1	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	**0.02**	0.01	0.02
3.3	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	**0.02**	0.01	0.02
3.5	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	**0.02**	0.01	0.02
3.7	**0.02**	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02
3.9	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	**0.07**	0.07
4.1	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	**0.05**	0.05
4.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
4.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
4.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
4.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
5.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
5.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
5.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
5.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
5.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
6.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
6.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
6.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
6.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
6.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
7.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
7.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
7.5	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	**0.01**	0.01	0.01
7.7	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01	**0.01**	0.01	0.01
7.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01
8.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01
8.3	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**	0.01	0.01
8.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
8.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01
8.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	**0.01**	0.01	0.01

Table 16 - V1xx-x.x MW 50 Hz measurements [10]

8.2.5 Harmonic model

The estimated harmonic model can be found in [17].

8.3 Steady state operation

8.3.1 Maximum power

Data is taken from a V150-6.0 MW 50 Hz turbine at Østerild test center.

	Max measured 600 s average	Max measured 60 s average	Max measured 0.2 s average
P (MV side) in kW	5907	6053	6106
P (MV side) in p.u.	0.985	1.009	1.018

Table 17 Based on measurements [11]

8.3.2 Reactive power capability

Reactive power capability can be found in the Performance Specification for the specific turbine variant [3-7, 19, 20, 29].
Measurements are taken in a V1xx-6.0 MW 50 Hz nacelle, a V1xx-5.6 MW 50 Hz, a V1xx-6.0 MW 60 Hz, a V1xx-5.6 MW 60 Hz, a V1xx-6.2 MW 50Hz and a V1xx-6.2 MW 60Hz.
Only values for V1xx-6.0 MW, 50 Hz with nominal voltage are presented as exemplification. All other variants and voltage levels values can be consulted in the official reports below:

- V1xx-6.0 MW 50 Hz [23]
- V1xx-5.6 MW 50 Hz [24]
- V1xx-6.0 MW 60 Hz [25]
- V1xx-5.6 MW 60 Hz [26]
- V1xx-6.2 MW 50 Hz [30]
- V1xx-6.2 MW 60 Hz [31]

Pn (%)	P (kW)	Q (kvar)	cos(φ)	Upos (p.u.)
0	-72	3384	-0.021 CAP	0.999
10	603	3385	0.176 CAP	0.998
20	1201	3384	0.334 CAP	0.999
30	1769	3383	0.463 CAP	1.000
40	2342	3383	0.569 CAP	0.999
50	2933	3382	0.655 CAP	0.999
60	3530	3381	0.722 CAP	0.999
70	4125	3379	0.774 CAP	0.999
80	4724	3380	0.813 CAP	0.999
90	5370	3373	0.847 CAP	1.001
100	5969	2642	0.914 CAP	0.998

Table 18 – Overexcited Reactive Power capability at LV side [23]

Pn (%)	P (kW)	Q (kvar)	cos(φ)	Upos (p.u.)
0	-77	-2922	-0.026 IND	0.998
10	596	-2923	0.200 IND	0.998
20	1189	-2924	0.377 IND	0.998
30	1762	-2924	0.516 IND	0.999
40	2335	-2924	0.624 IND	0.999
50	2934	-2924	0.708 IND	0.999
60	3522	-2923	0.770 IND	0.999
70	4118	-2922	0.816 IND	0.997
80	4713	-2920	0.850 IND	0.998
90	5370	-2921	0.878 IND	0.995
100	5965	-1986	0.949 IND	1.001

Table 19 – Underexcited Reactive Power capability at LV side [23**]**

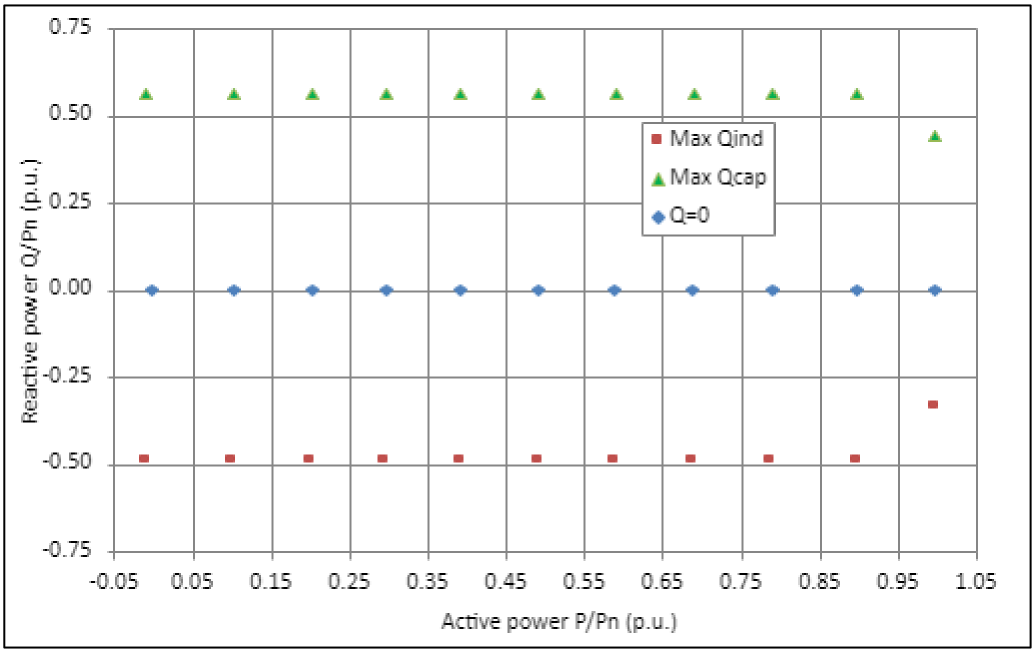

Figure 1: Reactive power capability at LV side with U=1pu [23]

8.4 Control performance

8.4.1 Active power control (Set-point control)

The active power control has been tested on a 3.6 MW nacelle. The mechanical setup and wind profiles have been emulated. Since the power control is mainly determined by the control systems, the per unit values can be reused for EnVentus™.

The active power control (set-point control) results of 3.6 MW were obtained by the following two tests:

Test A: Settling time [12]

The test was executed with two cases:

i. Transition from P=1 p.u. to 0.3 p.u. Results of the settling time are shown below.

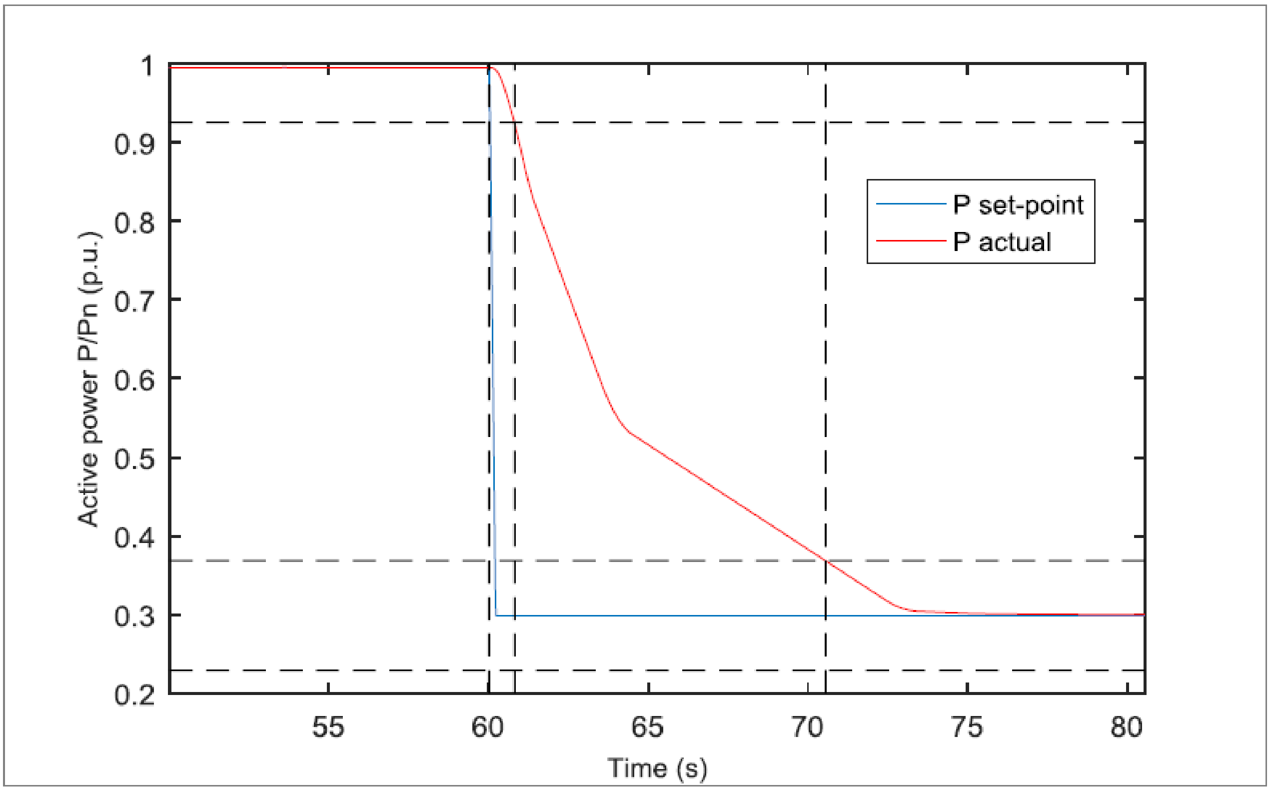

Figure 2: P set-point and actual active power during the test (LV side) [12]

Time of set-point value change (s)	60.01
Time at which the actual value continuously stays within the tolerance band (s)	70.55
Settling time (s)	10.54

Table 20: Results during active power set-point control test (LV side). [12]

<u>Test B</u>: Settling accuracy

The test was executed with active power value reduction from 1.00 p.u. to 0.20 p.u. with steps of 0.20 p.u. The results are shown below.

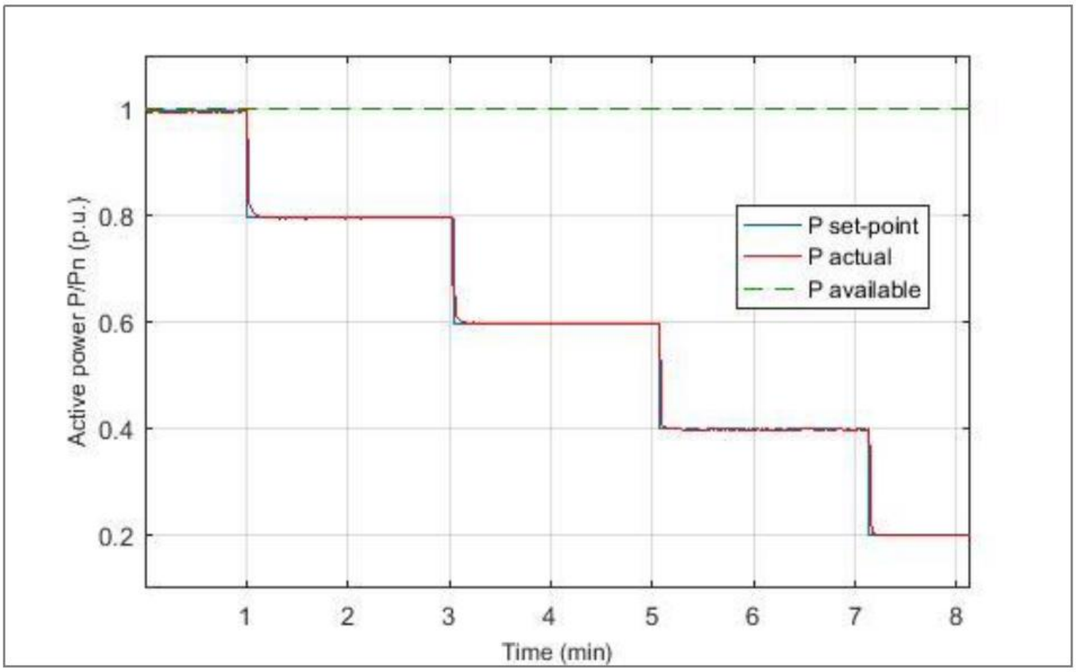

Figure 3: Time-series of active power set-point values, available power and measured active power output (LV side) [12]

Active power step P/P_N [%]	**Set-point value**		**Actual Value**		**Max Value {Actual - Set-point}**	
	[kW]	P/P_N [p.u.]	[kW]	P/P_N [p.u.]	[kW]	P/Pn (p.u.)
100	3582	0.995	3580	0.995	-2	0.000
80	2866	0.796	2863	0.795	-2	-0.001
60	2150	0.597	2148	0.597	-2	-0.001
40	1433	0.398	1433	0.398	0	0.000
20	717	0.199	721	0.200	4	0.001

Table 21: Results during active power set-point control test (LV side).

8.4.2 Active power ramp rate limitation

The estimated performance for EnVentus™ is derived from the test results of 3.6 MW nacelle.

Test A: Normal Start-up

Parameters for active power were set to:

- Operational Mode: Normal. DK
- Ramp Rate Gradient (%/min): Default Ramp Rate Type 1, 120%/min (2%/s)

	Requested set-point value $P_{set\text{-}point}$ (p.u.)	Measured active power (0.2 s average value) P_{act} (p.u)	Time t(s)	Calculated active power gradient ΔP/Δt (p.u./s)
Point 1	0.000	0.002	83.50	
Point 2	1.000	0.996	155.00	0.014

Table 22: Results during active power ramp rate limitation test (LV side) [12]

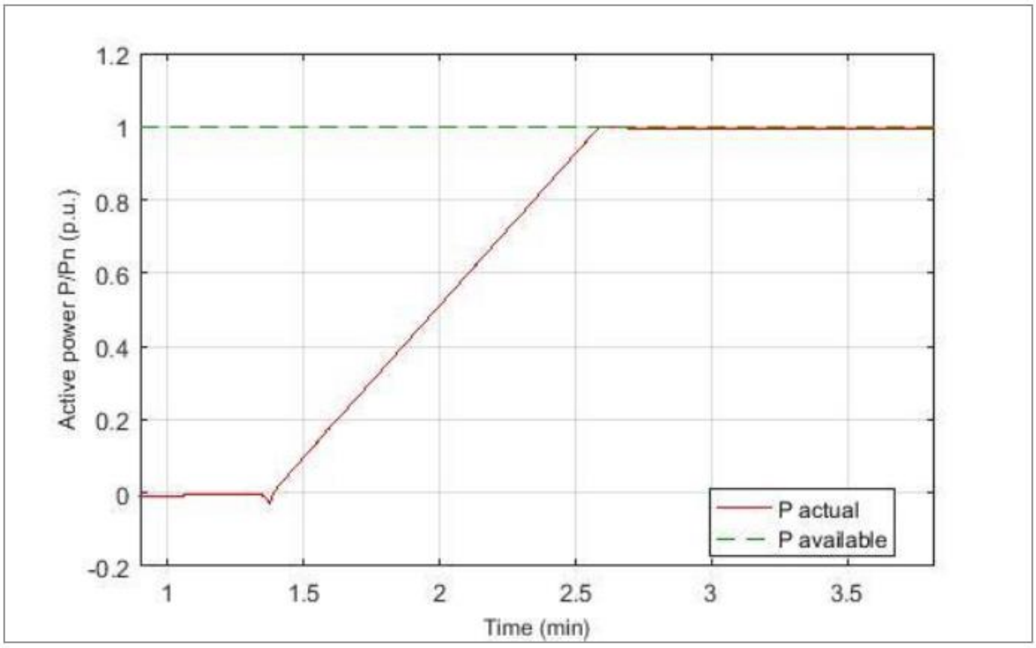

Figure 4 Time-series of available and measured active power output (LV side) [12]

Test B: Normal Stop

Parameters for active power were set to:

- Operational Mode: Normal. DK
- Ramp Rate Gradient (%/min): N/A

	Requested set-point value $P_{set\text{-}point}$ (p.u.)	Measured active power (0.2 s average value) P_{act} (p.u)	Time t(s)	Calculated active power gradiente ΔP/Δt (p.u./s)
Point 1	1.000	0.996	43.70	
Point 2	0.000	-0.002	53.64	-0.100

Table 23: Results during active power ramp rate limitation test (LV side) [12]

RESTRICTED

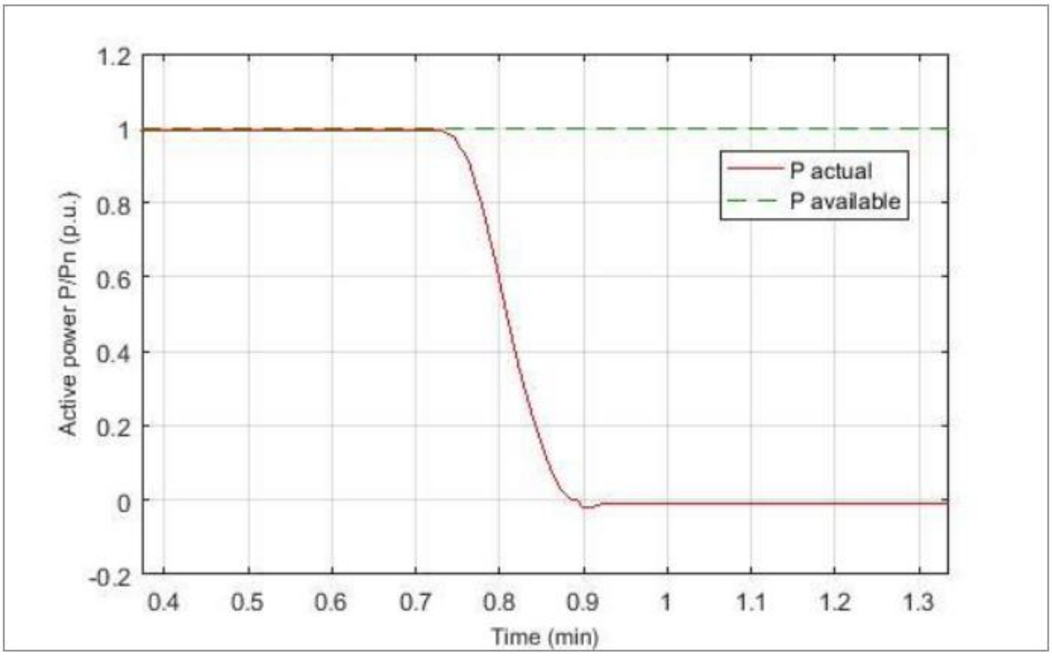

Figure 5: Time-series of available and measured active power output (LV side) [12]

Test C: Normal operation

Parameters for active power were set to:

- Operational Mode: Normal. DK
- Ramp Rate Gradient (%/min): Default Ramp Rate Type 1, 120%/min (2%/s)

	Requested set-point value $P_{set-point}$ (p.u.)	**Measured active power (0.2 s average value) P_{act} (p.u)**	**Time t(s)**	**Calculated active power gradient ΔP/Δt (p.u./sec)**
Point 1	0.800	0.791	199.84	
Point 2	0.100	0.105	234.30	-0.020
Point 3	0.100	0.103	326.80	
Point 4	0.800	0.808	363.34	0.019

Table 24 Results during active power ramp rate limitation test (LV side) [12]

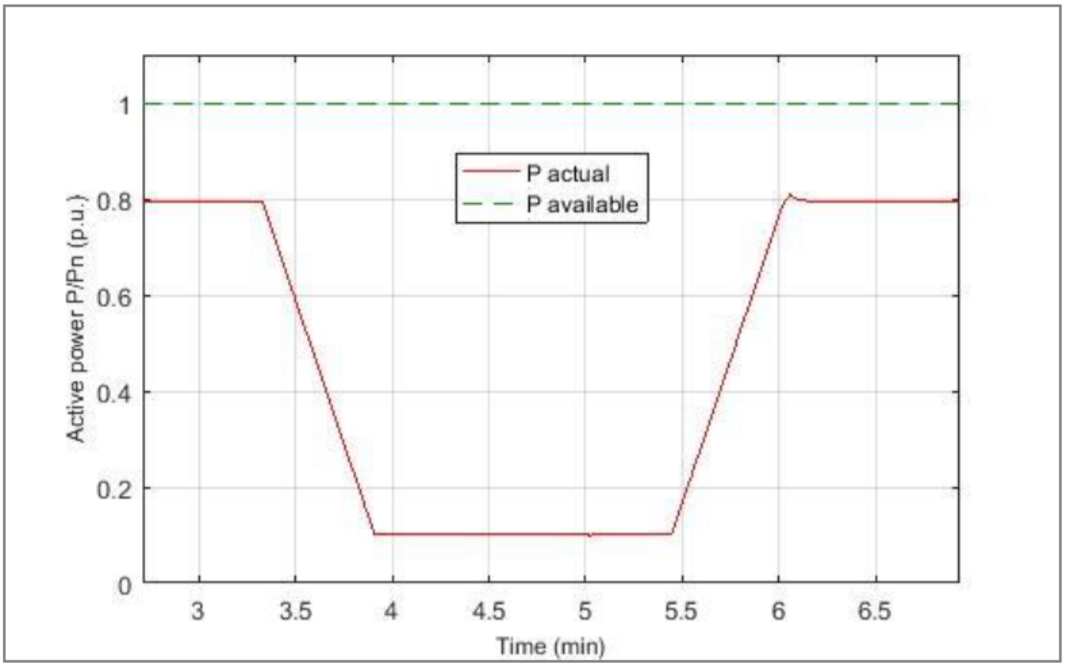

Figure 6 Time-series of active power set-point values, available power and measured active power output (LV side) [12]

8.4.3 Frequency control

The estimated performance for EnVentus™ is derived from the test results of a V1xx-4.2 MW nacelle. [18]
The wind turbine operated during the test with Q=0.
The results for each power level test scenario are depicted below:

A. Test at P>0.8P$_n$

Step of the measurement	Measured grid frequency	Frequency reference	Measured active power [pu]	Active Power Gradient (p.u./Hz)
First measurement point	50.00	50.00	0.979	--
Step Start Control	--	50.20	--	--
Step fstep 1	50.30	50.30	0.941	--
Step fstep 2	51.00	51.00	0.667	-0.392
Step fstep 3	52.00	52.00	0.274	-0.393
Step max	53.00	53.00	0.099	--
Step f < fstep 3	51.50	51.50	0.470	--
Step f < fstep 2	50.50	50.50	0.861	-0.391
Final Step	50.00	50.00	0.980	--
Step release control	--	50.20	--	--
Average gradient for active power (%Pref/Hz)				-39.21%

Table 25: Frequency, active power and active power gradient for each test step [18].

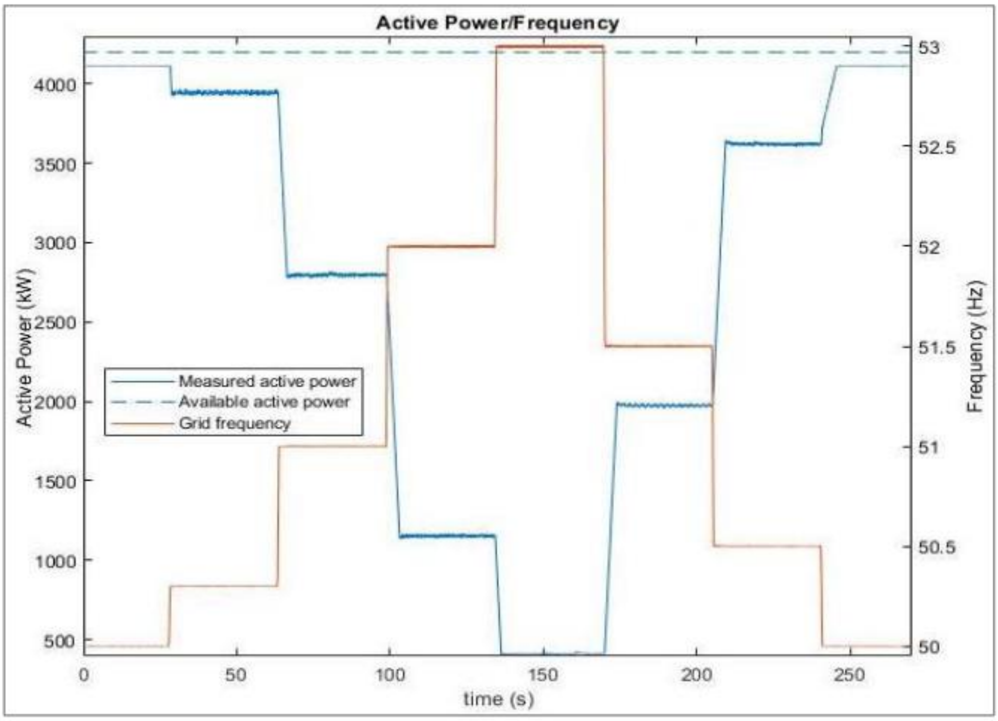

Figure 7: Time series of available power, measured active power and set point value of the grid frequency.

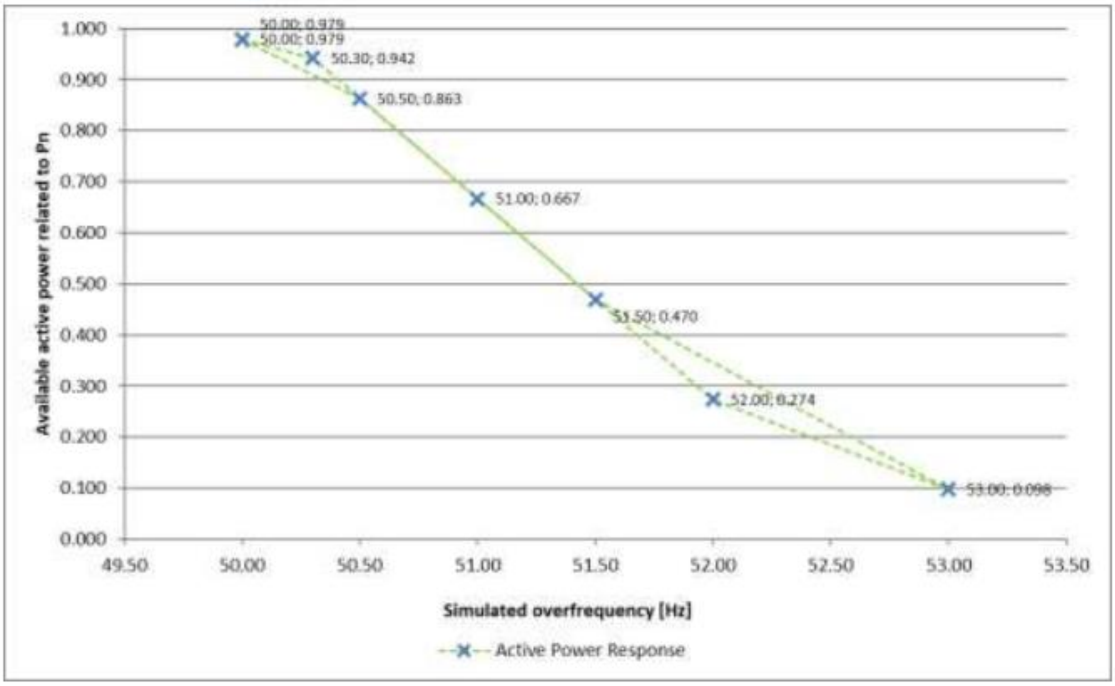

Figure 8: Measured active power over frequency change.

B. Test at $0.25P_n < P < 0.5P_n$

Step of the measurement	Measured grid frequency	Frequency reference	Measured active power [pu]	Active Power Gradient (p.u./Hz)
First measurement point	50.00	50.00	0.392	--
Step Start Control	--	50.20	--	--
Step fstep 1	50.30	50.30	0.376	--
Step fstep 2	51.00	51.00	0.267	-0.155
Step fstep 3	52.00	52.00	0.111	-0.156
Step max	53.00	53.00	0.099	--
Step f < fstep 3	51.50	51.50	0.189	--
Step f < fstep 2	50.50	50.50	0.345	-0.156
Final Step	50.00	50.00	0.392	--
Step release control	--	50.20	--	--
Average gradient for active power (%Pref/Hz)				-38.97%

Table 26: Frequency, active power and active power gradient for each test step.

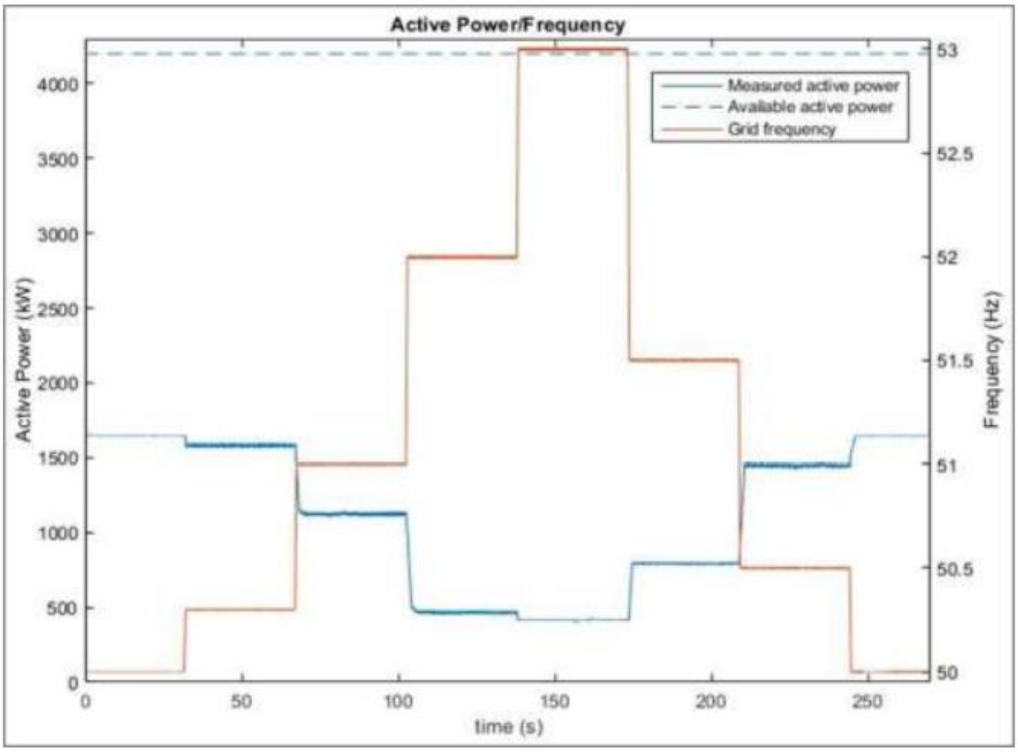

Figure 9: Time series of available power, measured active power and set point value of the grid frequency.

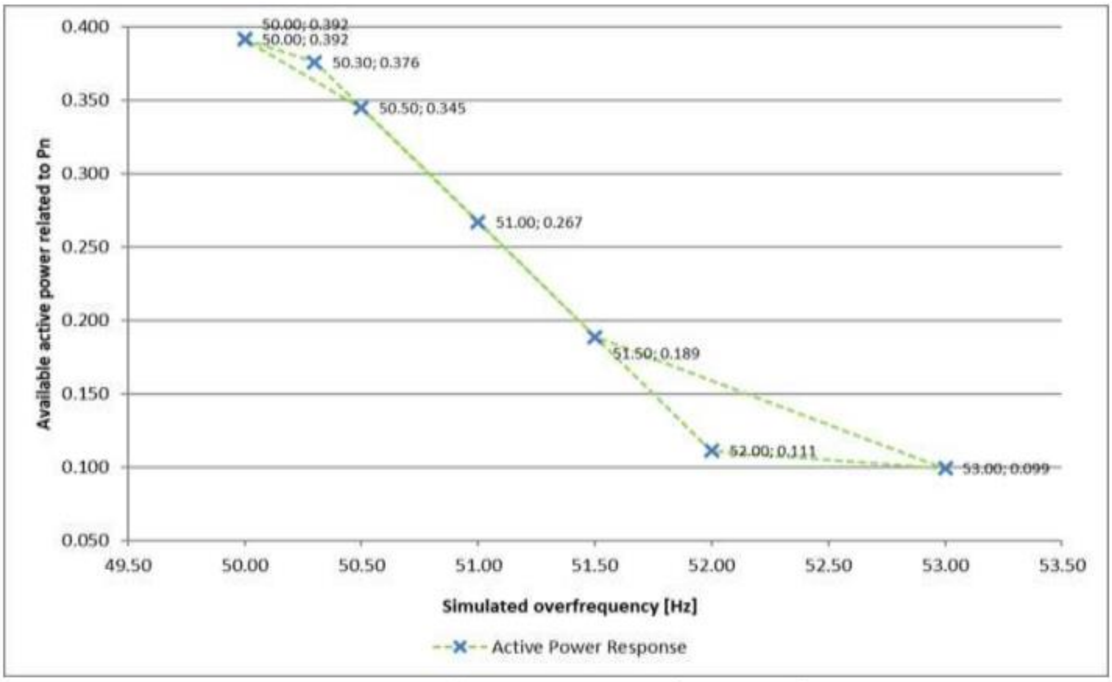

Figure 10: Measured active power over frequency change.

8.4.5 Reactive power control (Set-point control)

The active power control has been tested on a EnVentus™ nacelle configured to 6.0 MW at LORC test center.

8.4.5.2.1 Settling accuracy (IEC)

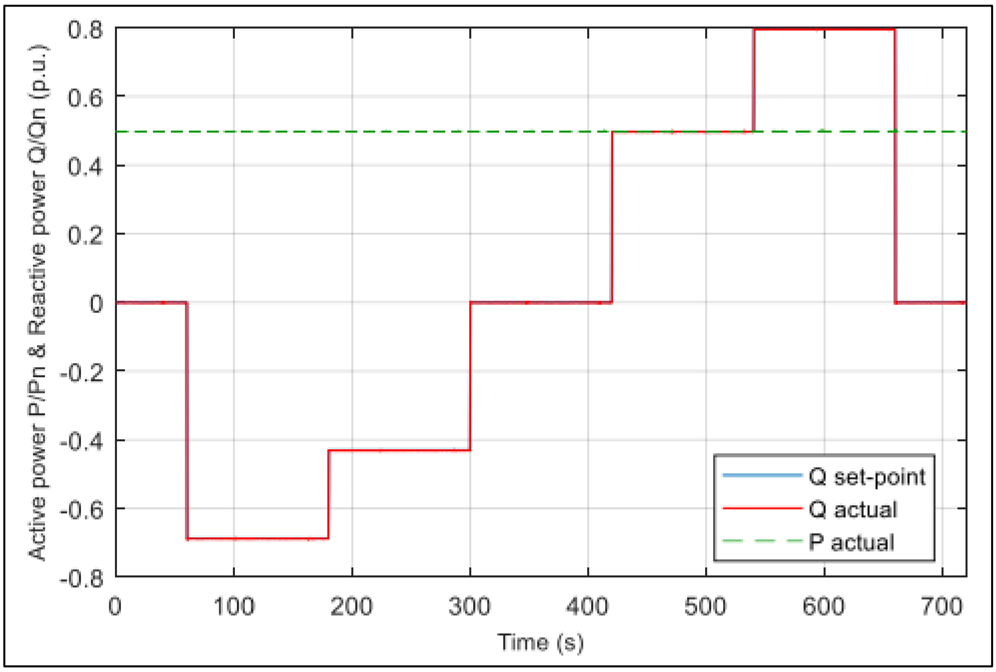

Figure 11 Test for reactive power accuracy (LV side) [14]

8.4.5.2.2 Dynamic response (IEC)

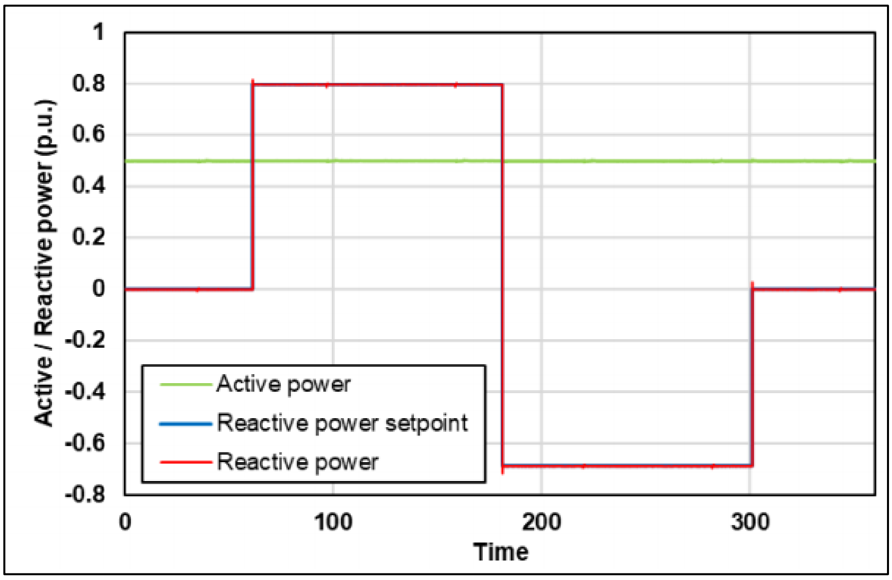

Figure 12: Reactive power measured and set-point during setting accuracy test (LV side).

Q set-point (p.u.)	0 to 0.8 (overexcited)	0.8 (overexcited) to 0.8 (underexcited)	0.8 (underexcited) to 0
Settling time (s)	0.12	0.14	0.12
Rise time (s)	0.02	0.04	0.02
Reaction time (s)	0.10	0.10	0.10

Table 27:Test for dynamic response (LV side).

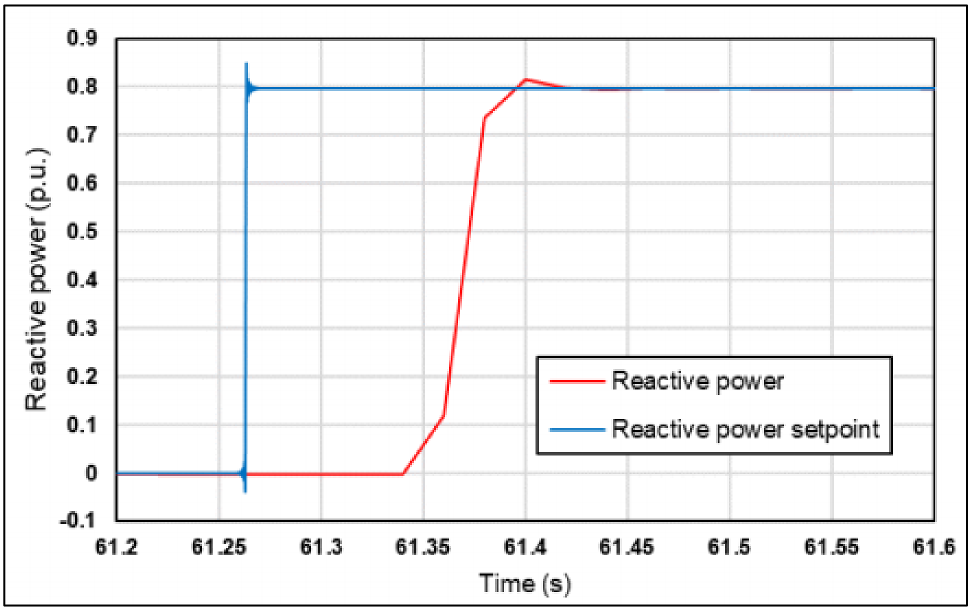

Figure 13: Test for dynamic response - Overexcited step (LV side) [14]

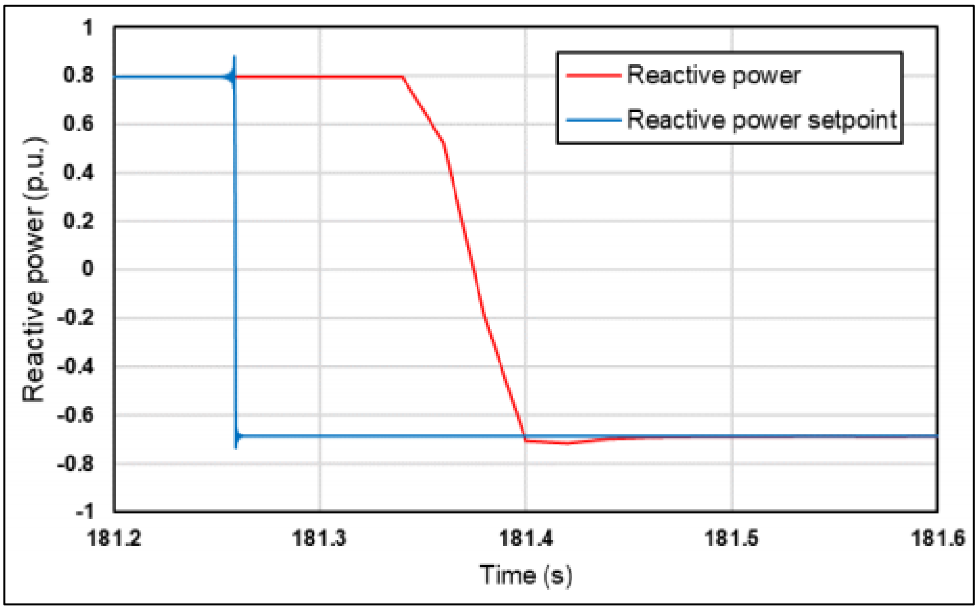

Figure 14: Test for dynamic response - Underexcited step (LV side) [14]

8.4.5.3 Static error/dynamic response (IEC)

Reactive power step Q/Q_N [p.u.]	Voltage	Set-point value		Actual Value		Static error {Actual Value - Set-point}	
	U [p.u.]	[kVAr]	Q/Q_N [p.u.]	[kVAr]	Q/Q_N [p.u.]	[kVAr]	Q/Q_N [p.u.]
-0.8	0.950	-2336	-0.796	-2341	-0.798	-5	-0.002
-0.5	0.967	-1461	-0.498	-1466	-0.500	-5	-0.002
0	0.997	0	0.000	-6	-0.002	-5	-0.002
0.5	1.028	1692	0.498	1690	0.497	-2	-0.001
0.8	1.046	2707	0.796	2706	0.796	-1	0.000

Table 28: Test for accuracy (LV side).

Note: Qn is 2933 kVAr for underexcited and 3400 kVAr for overexcited reactive power

8.5 Dynamic performance

8.5.2 Undervoltage events / Response to voltage drops

The UVRT voltage profile of EnVentus™ can be found in the General description [2].
FRT reports are too detailed to be included in this document but are available upon request. A UVRT report from a V150-4.2 MW WTG is available in reference [21].

8.5.3 Overvoltage events

The OVRT capability of EnVentus™ can be found in the General description [2].
OVRT report from V150-4.2 MW is available in reference [22].

8.6 Grid protection

8.6.2 Voltage and frequency protection

The grid protection settings can be found in the General description [2].
The performance has been measured for the converter control board at a Hardware In the Loop test wall for the V1xx-4.2 MW.

	Reference value of the grid protection device		**Measured value**	
	Protective level [p.u]	**Release time [s]**	**Protective level [p.u]**	**Release time [s]**
Overvoltage HighVolt U>	1.13	60	1.13	60.20
Overvoltage ExtrHighVolt U>>	1.16	60	1.16	60.30
Overvoltage ExtrExtrHighVolt U>>>	1.25	2	1.25	2.00
Overvoltage ExtrExtrExtrHighVolt U>>>	1.36	0.15	1.36	0.16
Undervoltage LowVolt U<	0.87	60	0.865	60.1
Undervoltage ExtrLowVolt U<<	0.85	12	0.845	12.01
Undervoltage ExtrExtrLowVolt U<<<	0.80	4.8	0.795	4.83

Table 29: Grid voltage protections [15]

	Reference value of the grid protection device		Measured value	
	Protective level [Hz]	Release time [s]	Protective level [Hz]	Release time [s]
Overfrequency HighFreq2 f>	53	10	53	10.09
Underfrequency LowFreq3 f<	47	30	46.95	30.17
Overfrequency HighFreq1 f>>	53.5	0.2	53.55	0.22
Underfrequency LowFreq2 f<<	46.5	0.4	46.45	0.43
Underfrequency LowFreq1 f<<<	46	0.2	45.95	0.24

Table 30: Grid frequency protections [15]

8.6.4 Reconnection time

Reconnection has been tested on a V117-3.6 MW turbine at Lem Kær test center.

Loss of grid time in s	Measured loss of grid time in s	Reconnection time in s
10	10.9	2648.7
60	60.4	1768.7
600	600.3	1406.6

Table 31: Evaluation of reconnection time [16]

Mean gradient in % of P_n per minute	Maximum gradient in % of P_n per minute	Defined gradient in % of P_n per minute
9.10	9.86	9.00

Table 32: Evaluation of active power gradient after loss of grid [16]

9 Transferability of results

This power quality datasheet assesses the estimated performance of the EnVentus™ in terms of the power quality aspects. The assessment is based on test results from field measurements of a V117 3.6 MW 50 Hz, V136 3.6 MW 50 Hz and a V150-4.2 MW 50 Hz wind turbine, where data from EnVentus™ turbines is not available. The changes between the wind turbines are not expected to have significant influence in these analyses, so the results are used to estimate the performance. More analytically:

Harmonic injection:
The small differences in the electrical circuit of the turbine models, to allow the operation at higher power, are not expected to cause significant deviations related to the harmonic emission in a per unit basis. In effect the changes made should, in theory, slightly improve the current emissions at higher frequencies, although this effect cannot be guaranteed and must be evaluated with field measurements. A change in the aerodynamics, like a bigger rotor, does not affect the harmonics.

Voltage fluctuations - Flicker:
The voltage fluctuations have been measured in the field for a V150-4.2 MW 50 Hz turbine. Flicker is to some extent affected by the rotor geometry, and although the effect is rather limited for type 4 wind turbines, a deviation between V150-4.2 MW and EnVentus™ model is expected. Flicker must be tested in the field as the rotor size, speed and site characteristics affect the performance.
The usage of flicker measurements from a 50 Hz field measurement for a 60 Hz wind turbine is valid since the flicker is a phenomenon with a frequency well below the grid frequency.

Steady State Operation
The maximum power is mainly determined by the power controlling software which has not been changed between the 3.6 MW and the EnVentus™. The per unit values can therefore be reused.

Control performance
The active power control and ramp rate has been tested on a 3.6 MW wind turbine. Since the power control is mainly determined by the control systems, the per unit values can be reused for EnVentus™.
The same reasoning can be applied to the frequency control and reactive power control of the wind turbines.

Dynamic performance
The dynamic performance is also dependent on the control software, so the under/over voltage ride-through, and grid protections can be reused from the 3.6 MW/ 4.2 MW models.

Reference documents

Ref	Number	Classification	Name
1	-	-	IEC 61400-21-1:2019 Ed1
2	0081-5017	T05	General Description EnVentus™ 5 MW
3	0081-5085	T05	Performance Specification V150-5.0 MW
4	0081-5081	T05	Performance Specification V150-5.4 MW
5	0081-5059	T05	Performance Specification V150-5.6 MW
6	0081-5101	T05	Performance Specification V162-5.4 MW
7	0081-5098	T05	Performance Specification V162-5.6 MW
19	0098-0749	T05	Performance Specification V150-6.0 MW
20	0098-0840	T05	Performance Specification V162-6.0 MW
29	0107-3707	T05	Performance Specification V162-6.2 MW

Table 33 Reference Standards, General Description and Performance Specifications

Ref	Number	Classification	Name	Tested turbines	Test site
9	0105-6478	T05	Flicker and switching operations	V150-6.0 MW 50 Hz	Østerild test center, Turbine test
10	0104-7761	T05	Harmonic measurements	V150-6.0 MW 50 Hz	Østerild test center, Turbine test
11	0105-6494	T05	Maximum Power	V150-6.0 MW 50 Hz	Østerild test center, Turbine test
12	0065-7460	T05	Active Power setpoint	V117-3.6 MW 50 Hz	LORC test center, Nacelle test
13	0070-4525	T04	Active Power setpoint (Internal)	V117-3.6 MW 50 Hz	LORC test center, Nacelle test
14	0091-8806	T05	Reactive power control	V1xx-6.0 MW 50 Hz	LORC test center, Nacelle test
15	0085-2049	T05	Grid protections	V1xx -4.2MW 50 Hz	Converter test wall (HIL), Controller test
16	0069-8793	T05	Ramp rate and reconnection time after grid fault	V117-3.6 MW 50 Hz	Lem Kær test center, Turbine test
17	0105-3390	T05	Harmonic Model EnVentus Mk0	V150/V162-5.6/6.0 MW 50 Hz	Based on measurements from Østerild test center, Turbine test
18	0088-0816	T05	Frequency Control	V1xx-4.2 MW 50 Hz	LORC test center, Nacelle test
21	0088-0775	T05	UVRT according to IEC61400-21-1	V150-4.2 MW 50 Hz	LORC test center, Nacelle test
22	0088-0772	T05	OVRT according to IEC61400-21-1	V150-4.2 MW 50 Hz	LORC test center, Nacelle test
23	0105-3977	T05	Reactive power capabilities	V1xx-6.0 MW 50 Hz	LORC test center, Nacelle test
24	0091-8788	T05	Reactive power capabilities	V1xx-5.6 MW 50 Hz	LORC test center, Nacelle test
25	0105-3982	T05	Reactive power capabilities	V1xx-6.0 MW 60 Hz	LORC test center, Nacelle test

26	0105-4722	T05	Reactive power capabilities	V1xx-5.6 MW 60 Hz	LORC test center, Nacelle test
27	0107-9318	T05	Flicker and switching operations	V162-6.0 MW 50 Hz	Østerild test center, Turbine test
28	0107-9376	T05	Harmonics	V162-6.0 MW 50 Hz	Østerild test center, Turbine test
30	0129-5531	T05	Reactive power capabilities	V1xx-6.2 MW 50 Hz	OLH Vestas Test Center, Test Bench
31	0129-5536	T05	Reactive power capabilities	V1xx-6.2 MW 60 Hz	OLH Vestas Test Center, Test Bench

Table 34 Reference measurements reports