WIND POWER RESEARCH IN FOCUS 2022

Frequency regulation and system services for FFR from existing wind power

Mats Goldberg

2022-10-24

Frequency regulation and system services for FFR from existing wind power

- This research project has been financed by the Swedish Energy Agency

  Thanks Energimyndigheten

- Part 1 (2020):
  Demonstrate the potential of wind power, on national level, to supply FFR by adapting the controller during variable speed operation and estimate energy yield losses.

- Part 2 (2022-23):
  Quantify impact on revenue and fatigue life and disseminate conclusions to stake holders and public debate.

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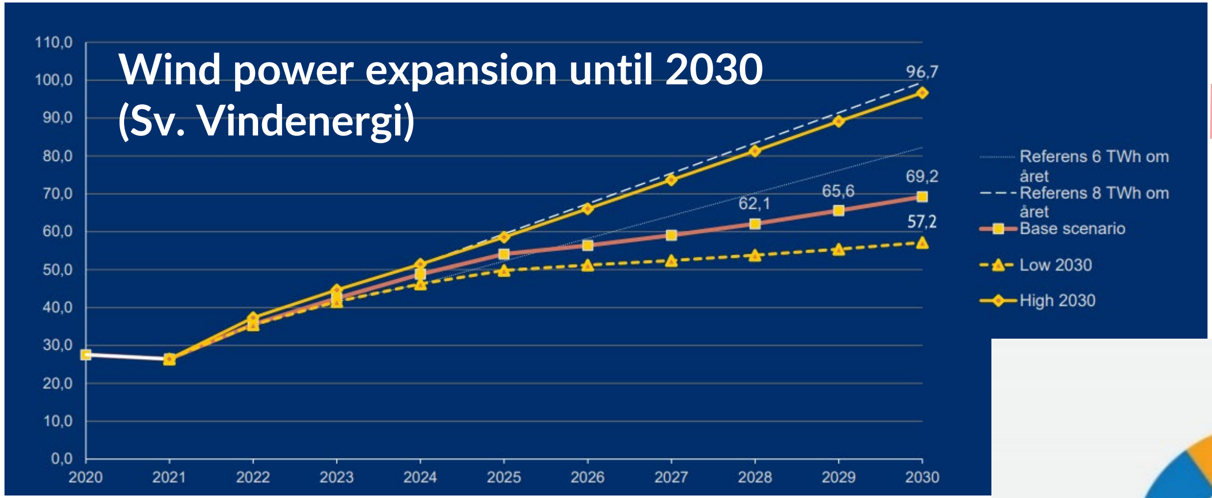
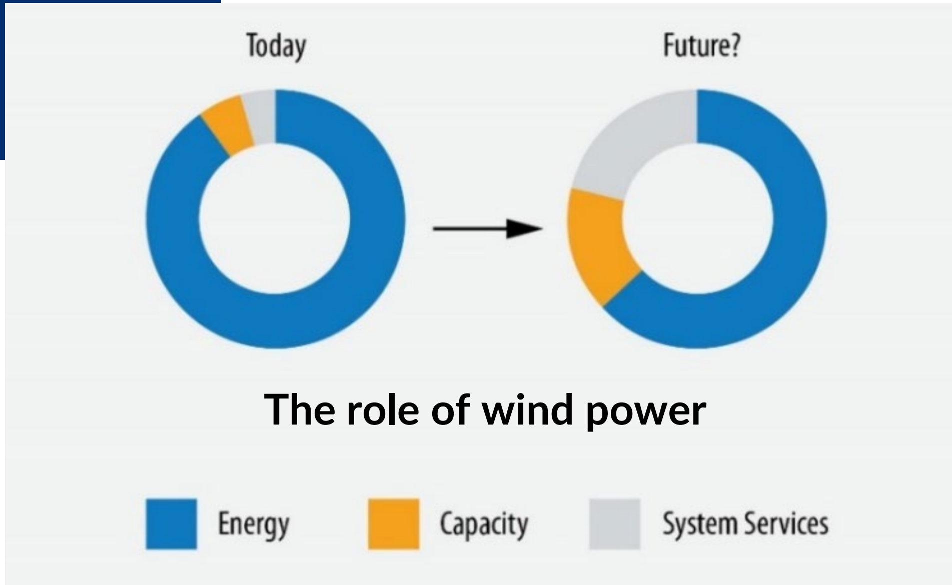
Wind power needs to help support the grid

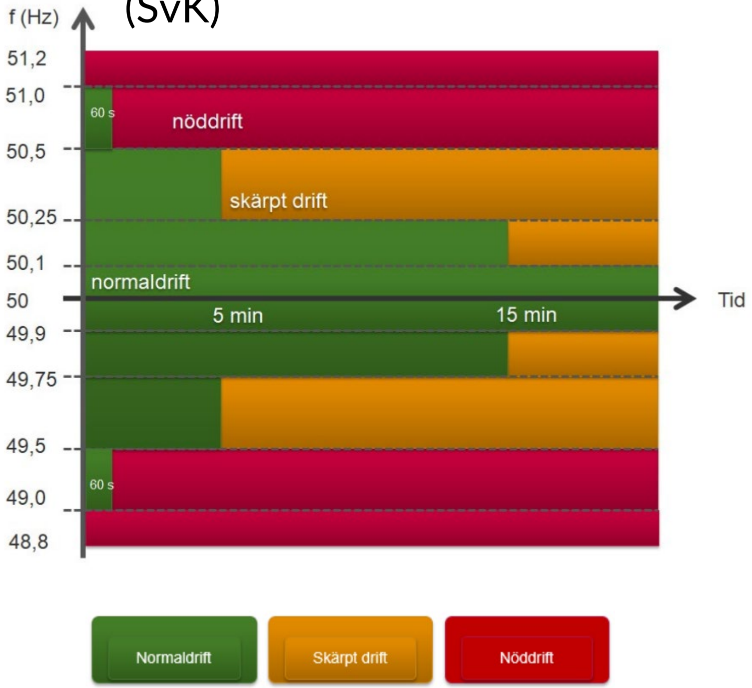




Dykes, K., et.al. (2019). *Results of IEA Wind TCP Workshop on a Grand Vision for Wind Energy Technology*. IEA.

FFR - Securing frequency stability when kinetic energy is low

System operating conditions (SvK)



"The main objective for FCR-D upwards is to secure frequency stability, i.e. that the power system **frequency does not decrease below 49.0 Hz**. The largest reference incident in the Nordic power system is a trip of the nuclear power plant Oskarshamn 3 at 1450 MW. "

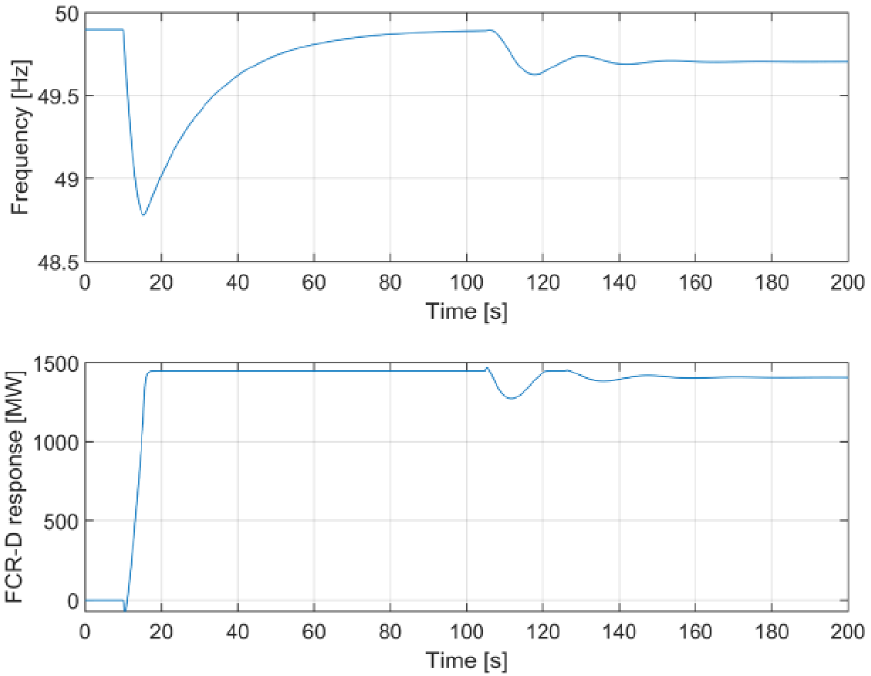
"... **FFR to complement the FCR-D upwards when the kinetic energy is low.**"

N. Modig et al, "FFR Design of Requirements – External document", Version 1.0, ENTSOE, Februrary 2020.

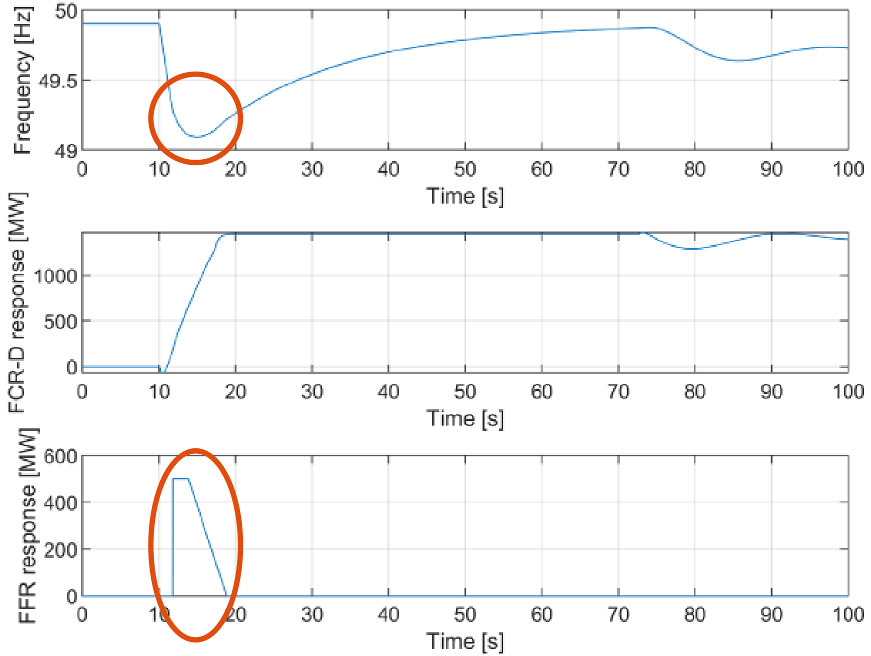
FFR - Securing frequency stability when kinetic energy is low

1450 MW disturbance in a system of
100 GW kinetic energy

wo FFR

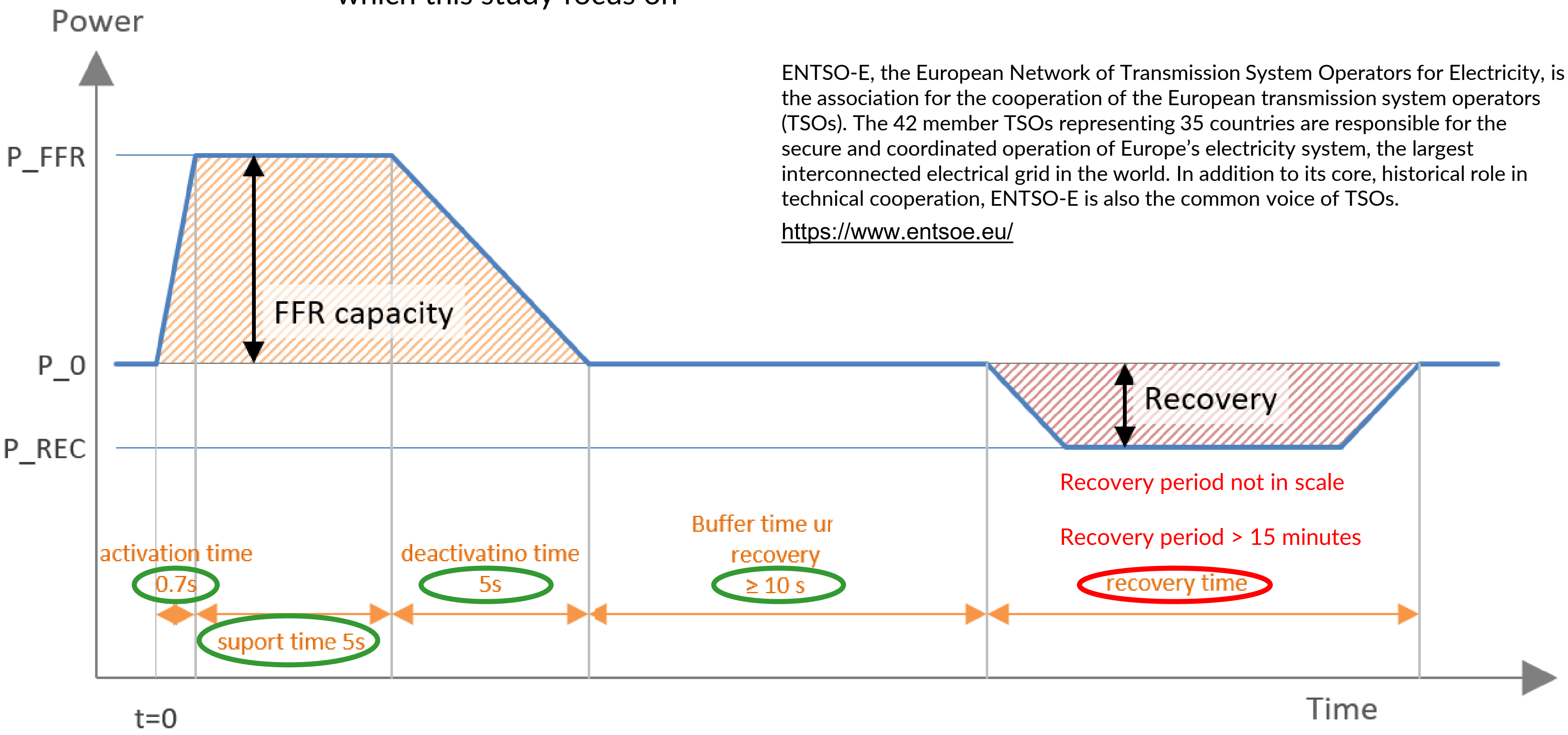


wtih FFR



Technical requirements for Fast Frequency Reserve defined by ENTSO-E

Wind turbines are perfect for Fast Frequency Reserve (FFR) support which this study focus on



ENTSO-E, the European Network of Transmission System Operators for Electricity, is the association for the cooperation of the European transmission system operators (TSOs). The 42 member TSOs representing 35 countries are responsible for the secure and coordinated operation of Europe's electricity system, the largest interconnected electrical grid in the world. In addition to its core, historical role in technical cooperation, ENTSO-E is also the common voice of TSOs.

https://www.entsoe.eu/

Energy storage by wind turbine inertia

A rotating wind turbine has a certain amount of energy (T) stored in the inertia (J) of the turbine.

This energy storage is depending on the angular velocity (ω).

By decreasing the angular velocity, i.e. the rotor speed, this energy can be transformed into mechanical power (P).

$$P = M\,\omega = \frac{\delta T}{\delta t}$$

$$T = \frac{1}{2} J\,\omega^2$$

Energy ~ Rotor speed^2

Stored energy from wind turbine rotational inertia		
Total number of turbines	4120	
Total capacity	9061	MW
Average capacity	2.2	MW
Average turbine inertia	1.0E+07	kgm2
Average angular velocity	1.0	rad/s
Average rotating energy	5.0E+06	J
Total rotating energy	**2.1E+10**	**J**

This is almost 10 % of the existing inertia in Sweden.
However it is not connected to the grid by "stiff" synchronous generators.
Turbine control is needed to utilize it.

IEA 3.4 – 130 wind turbine model in FAST and VIDYN

Within the project, we have created a model in the aeroelastic codes FAST and VIDYN of the public IEA 3.4 – 130 wind turbine.
The turbine control is based on the NREL DISCON concept.

IEA Wind Task 37 on Systems Engineering in Wind Energy
WP2.1 Reference Wind Turbines

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May 23, 2019

Abstract

This report describes two wind turbine models developed within the second work package (WP2) of IEA Wind Task 37 on Wind Energy Systems Engineering: Integrated RD&D. The wind turbine models can be used as references for future research projects on wind energy, representing a modern land-based wind turbine and a latest generation offshore wind turbine. The land-based design is a class IIIA geared configuration with a rated electrical power of 3.4-MW, a rotor diameter of 130 m, and a hub height of 110 m. The offshore design is a class IA configuration with a rated electrical power of 10.0 MW, a rotor diameter of 198 m, and a hub height of 119 m. The offshore turbine employs a direct-drive generator.

4 3.4-MW Land-Based Wind Turbine

Cp-Max was the tool mostly used in the development activities of the land-based wind turbine. Here, the design work aimed at developing a class 3A land-based wind turbine model with a rated electrical power of 3.37 MW, a rated aerodynamic power of 3.6 MW, a rotor diameter of 130 m and a hub height of 110 m. These values were selected by the project partners with the expectation that they will establish as standards within the land-based wind energy market. The optimization was run for minimum COE, estimated by a cost model developed at NREL [29].

4.1 Design Process

The wind turbine was designed against a set of critical design load cases (DLCs), selected to be run within the structural optimization loop of Cp-Max, including standard operating conditions in normal turbulence (1.1), operation under extreme turbulence (1.3), shut down cases in turbulent wind (2.1), and steady wind with gusts (2.3), as well as storm conditions (6.1, 6.2, 6.3) [17]. DLC 1.1 and DLC 1.3 were realized with three turbulent seeds, while the others with one, for a total of 151 dynamic simulations.

The aerodynamic design included 24 optimization variables describing twist at eight stations, chord at nine stations, and the position of the seven airfoils along blade span. The structural design was based on 50 variables parameterizing the skin, the two spar caps, the two webs, and the leading-edge (LE) and trailing-edge (TE) reinforcements at nine stations along blade span, as well as the diameter and wall thickness of ten tower sectors. In this reference design, the mechanical properties of the composites were kept fixed, while sweep curvature, angles in the composite fibers, and offset in the spar cap positions were all set to zero. After a total computational time of approximately 100 hours running on a workstation equipped with 56 logical processors, Cp-Max converged to the solution that is presented here.

The main wind turbine characteristics are summarized in Table 2. Notably, the table reports the values of initial capital cost (ICC) and COE that drove the optimization. The next section presents all the details of the design in terms of rotor aerodynamics, rotor structure, hub, drivetrain, nacelle, tower, and controller.

Table 2: Summary of the configuration of the land-based wind turbine.

Data	Value	Data	Value
Wind class	IEC 3A	Rated electrical power	3.37 MW
Rated aerodynamic power	3.60 MW	DT & Gen. efficiency	93.6%
Hub height	110.0 m	Rotor diameter	130.0 m
Cut-in	4 m/s	Cut-out	25 m/s
Rotor cone angle	3.0 deg	Nacelle uptilt angle	5.0 deg
Rotor solidity	4.09%	Max V_{tip}	80.0 m/s
Blade mass	16,441 kg	Tower mass	553 ton
Blade cost	120.9 k$	Tower cost	829.7 k$
Aerodynamic AEP	14.99 GWh	Electrical AEP	13.94 GWh
ICC	4,142.1 k$	COE	44.18 $/MWh

May 2019

IEA Wind TCP Task 37

Systems Engineering in Wind Energy - WP2.1 Reference Wind Turbines

Technical Report

iea wind

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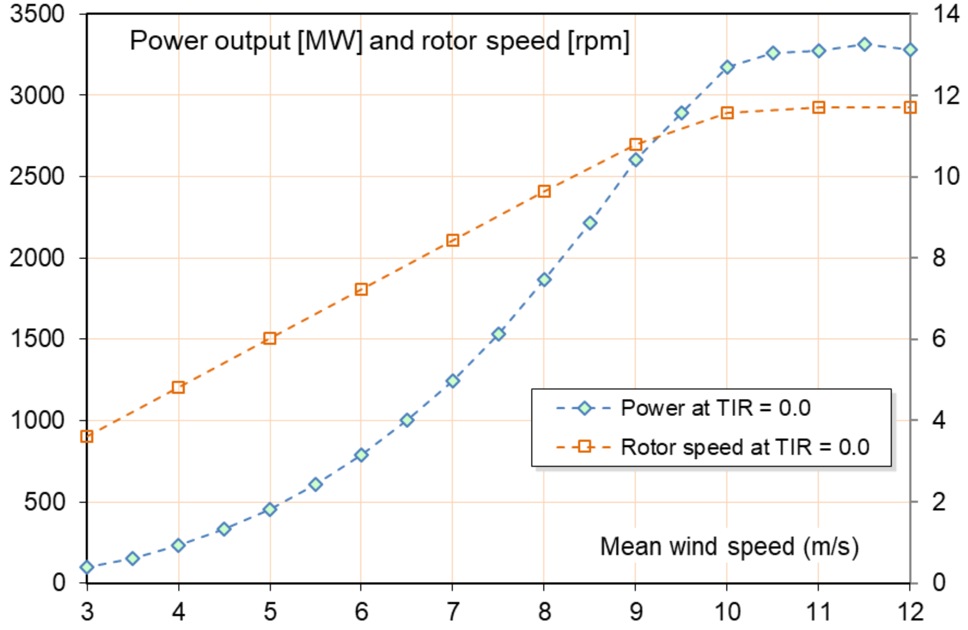
Power curve depending on rotor speed concept

Base line, TIR = 0.0
This is how the turbine is designed to operate

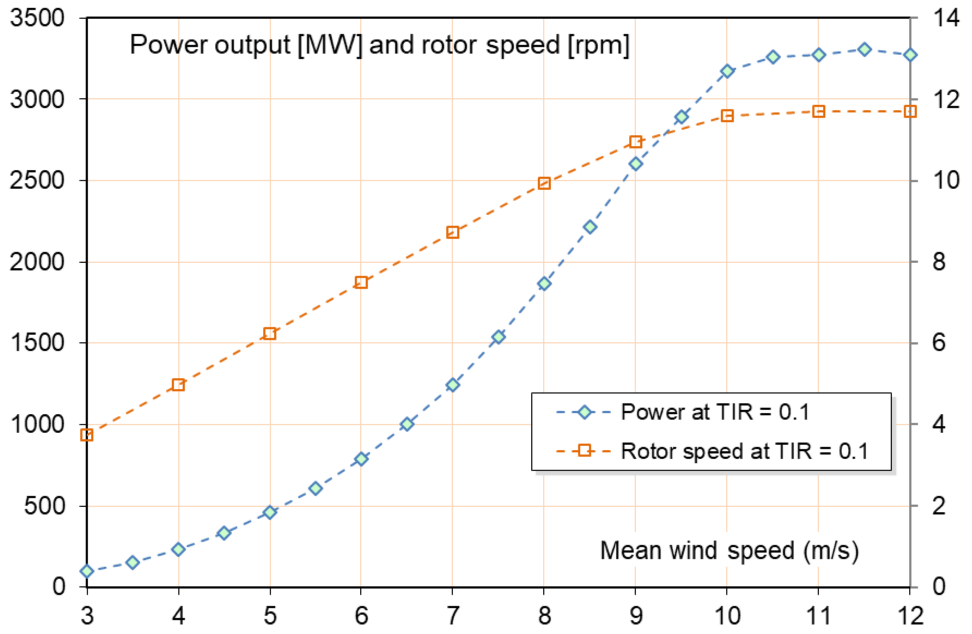


Input wind conditions		
Average wind speed	7.5	m/s

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.716**	**GWh/år**
Capacity factor	42.7%	

Power curve depending on rotor speed concept

Increased rotor speed by TIR = 0.1



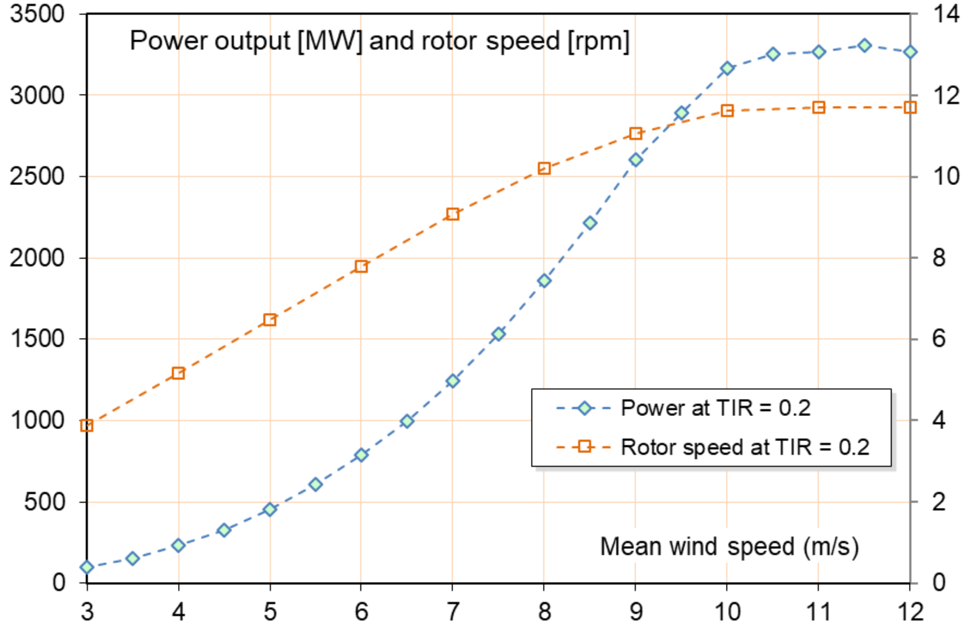
Input wind conditions		
Average wind speed	7.5	m/s

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.710**	**GWh/år**
Capacity factor	42.7%	

Power curve depending on rotor speed concept

Increased rotor speed by TIR = 0.2

Input wind conditions		
Average wind speed	7.5	m/s



Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.685**	**GWh/år**
Capacity factor	42.6%	

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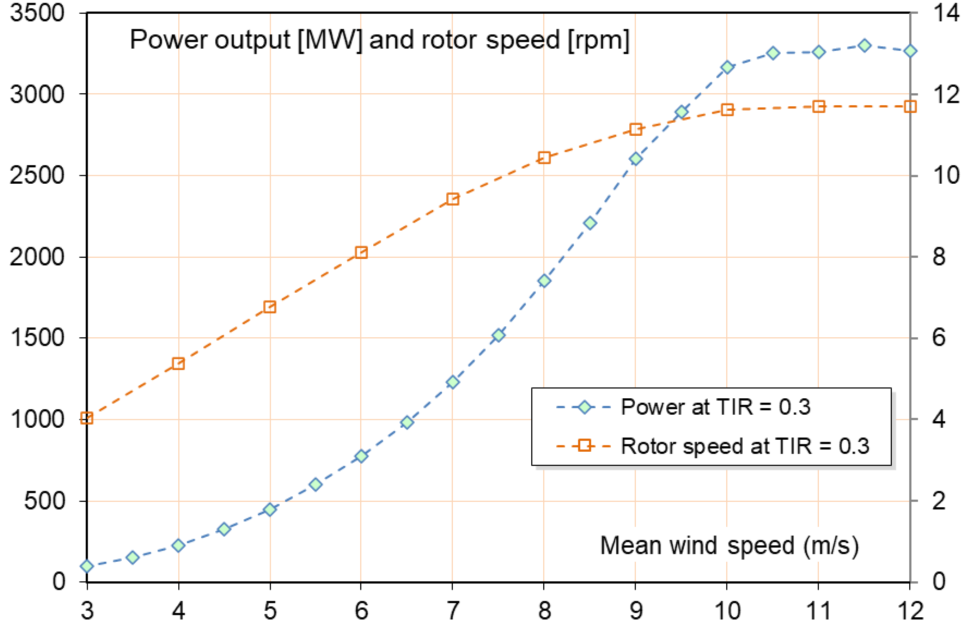
Power curve depending on rotor speed concept

Increased rotor speed by TIR = 0.3



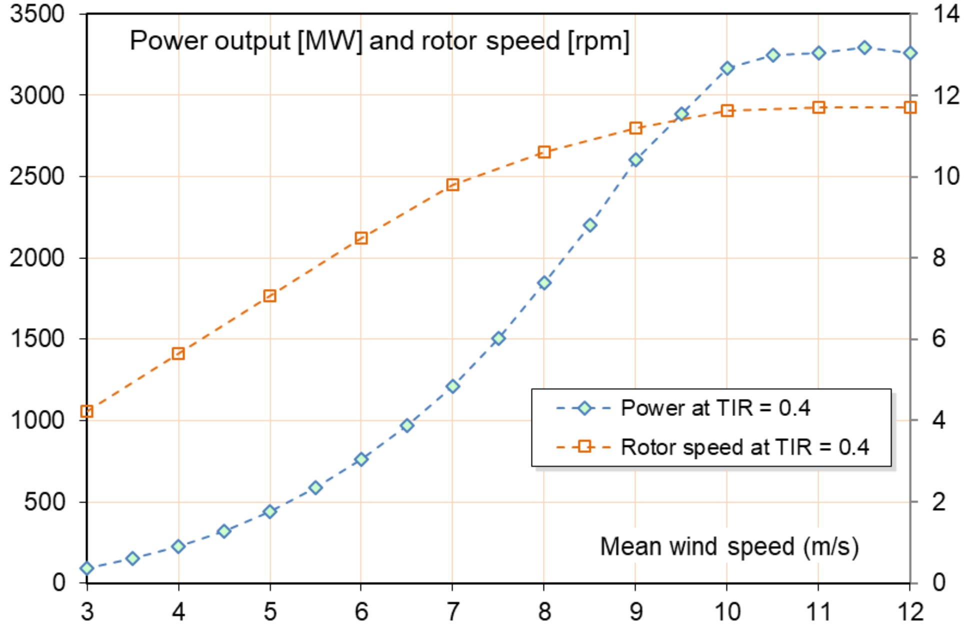
Input wind conditions		
Average wind speed	7.5	m/s

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.646**	**GWh/år**
Capacity factor	42.5%	

Power curve depending on rotor speed concept

Increased rotor speed by TIR = 0.4

Input wind conditions		
Average wind speed	7.5	m/s

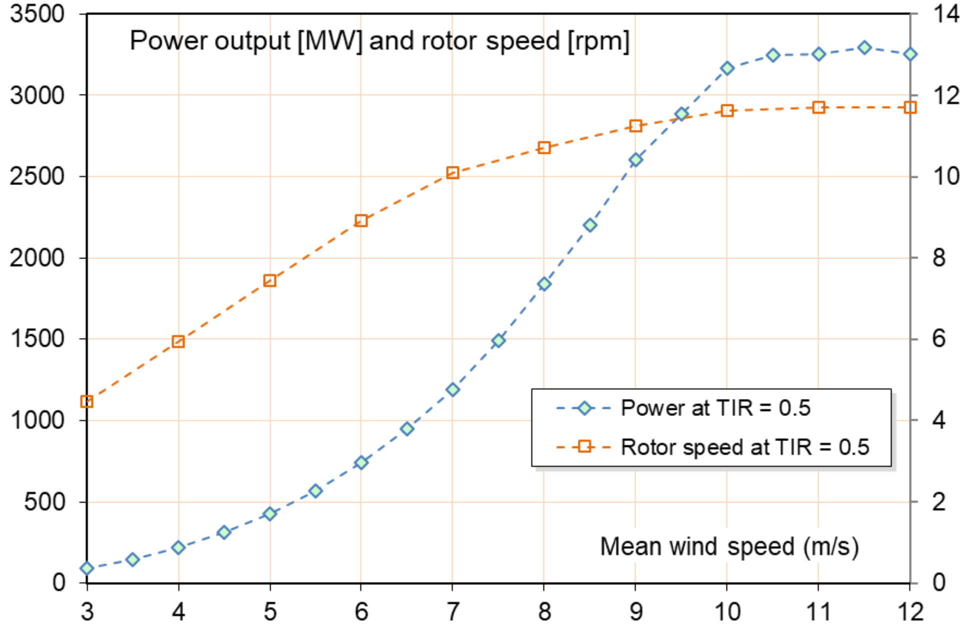


Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.593**	**GWh/år**
Capacity factor	42.3%	

Power curve depending on rotor speed concept

Increased rotor speed by TIR = 0.5

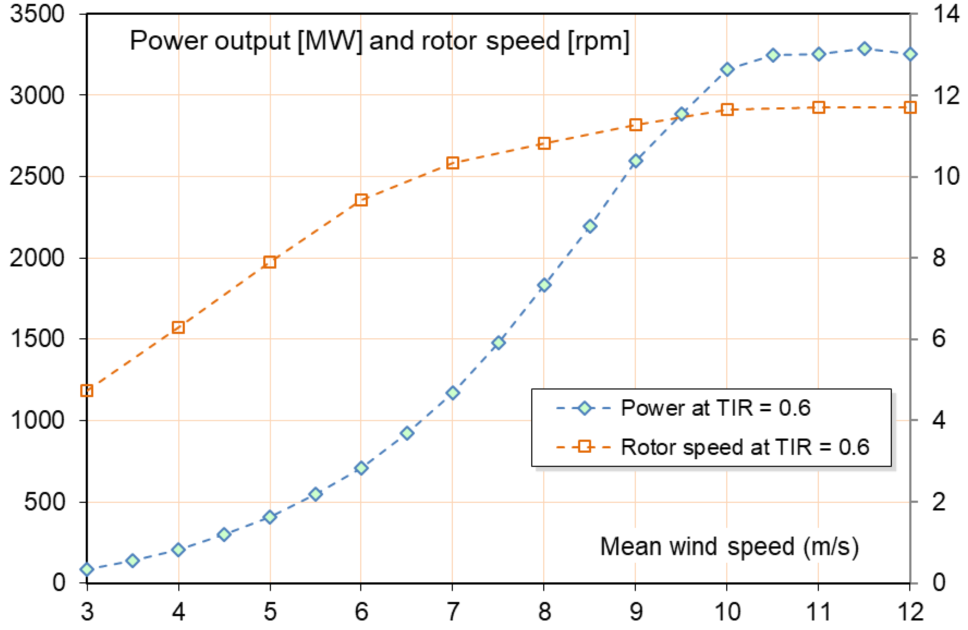
Input wind conditions		
Average wind speed	7.5	m/s



Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.527**	**GWh/år**
Capacity factor	42.1%	

Power curve depending on rotor speed concept

Increased rotor speed by TIR = 0.6



Input wind conditions		
Average wind speed	7.5	m/s

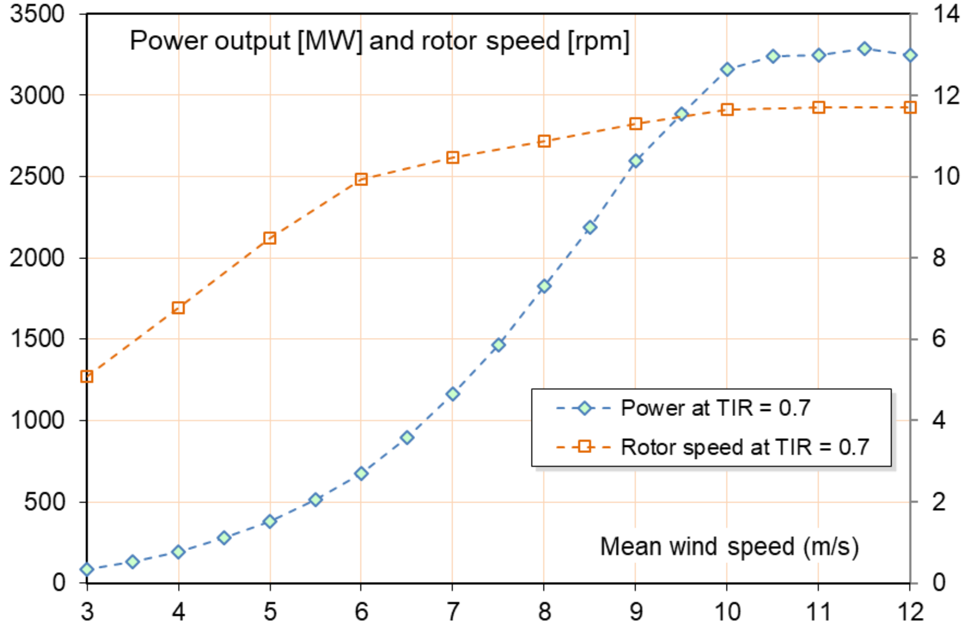
Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.451**	**GWh/år**
Capacity factor	41.8%	

Power curve depending on rotor speed concept

Increased rotor speed by TIR = 0.7

Input wind conditions		
Average wind speed	7.5	m/s

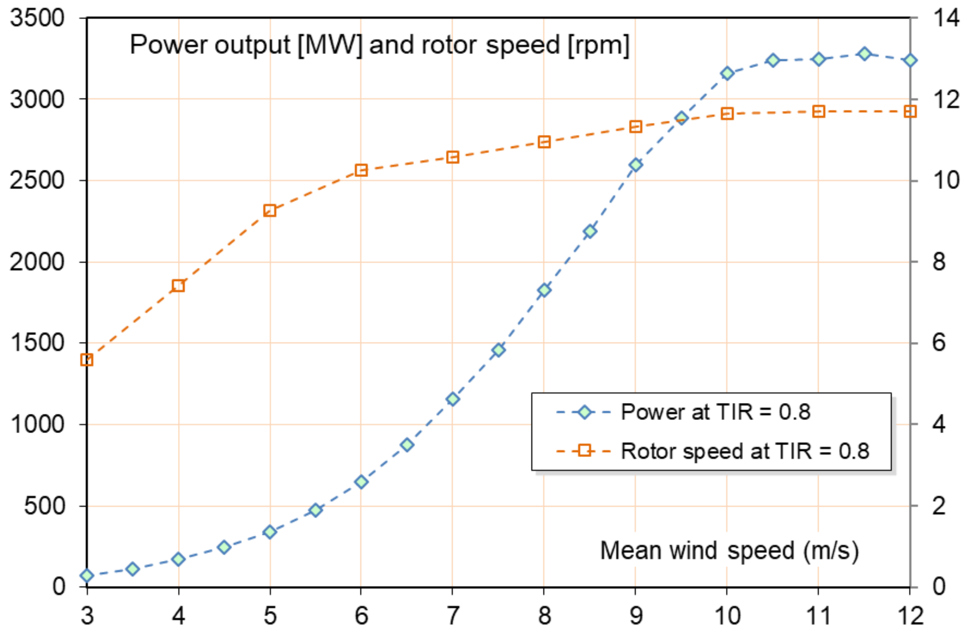
Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.363**	**GWh/år**
Capacity factor	41.5%	



Power curve depending on rotor speed concept

Increased rotor speed by TIR = 0.8

Input wind conditions		
Average wind speed	7.5	m/s

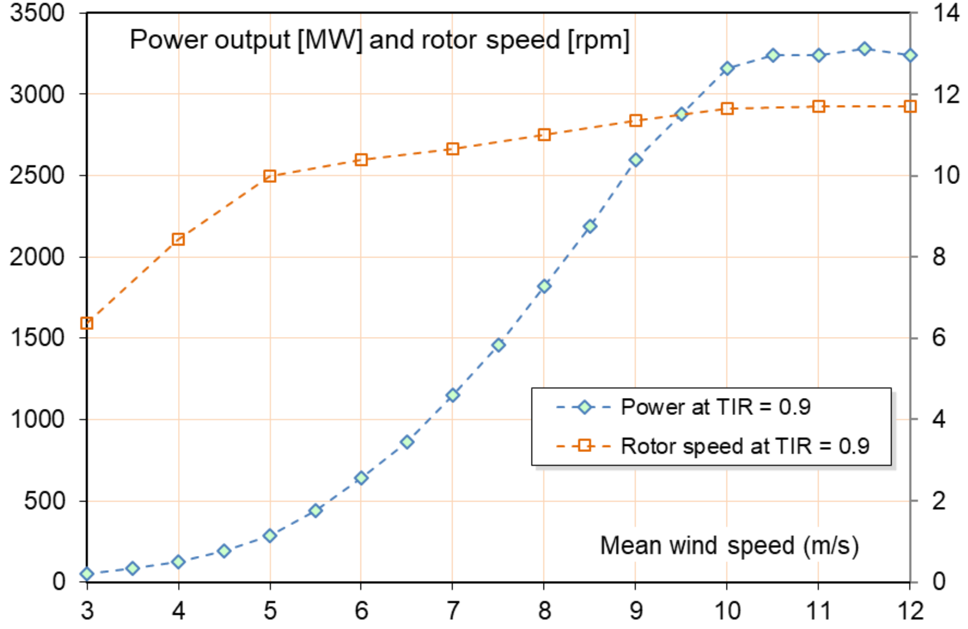


Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.269**	**GWh/år**
Capacity factor	41.2%	

Power curve depending on rotor speed concept

Increased rotor speed by TIR = 0.9

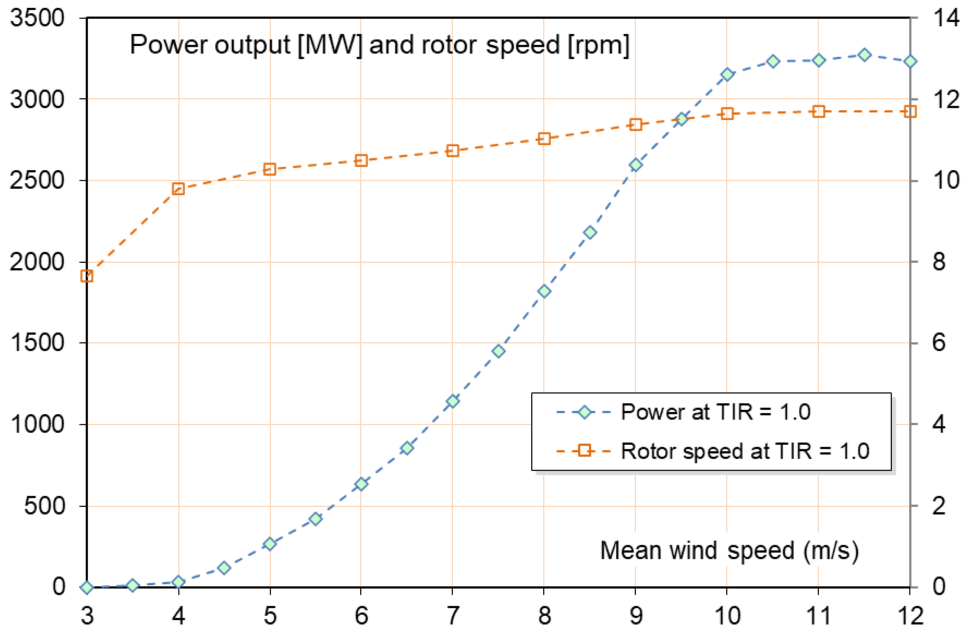
Input wind conditions		
Average wind speed	7.5	m/s



Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.160**	**GWh/år**
Capacity factor	40.8%	

Power curve depending on rotor speed concept

Increased rotor speed by TIR = 1.0



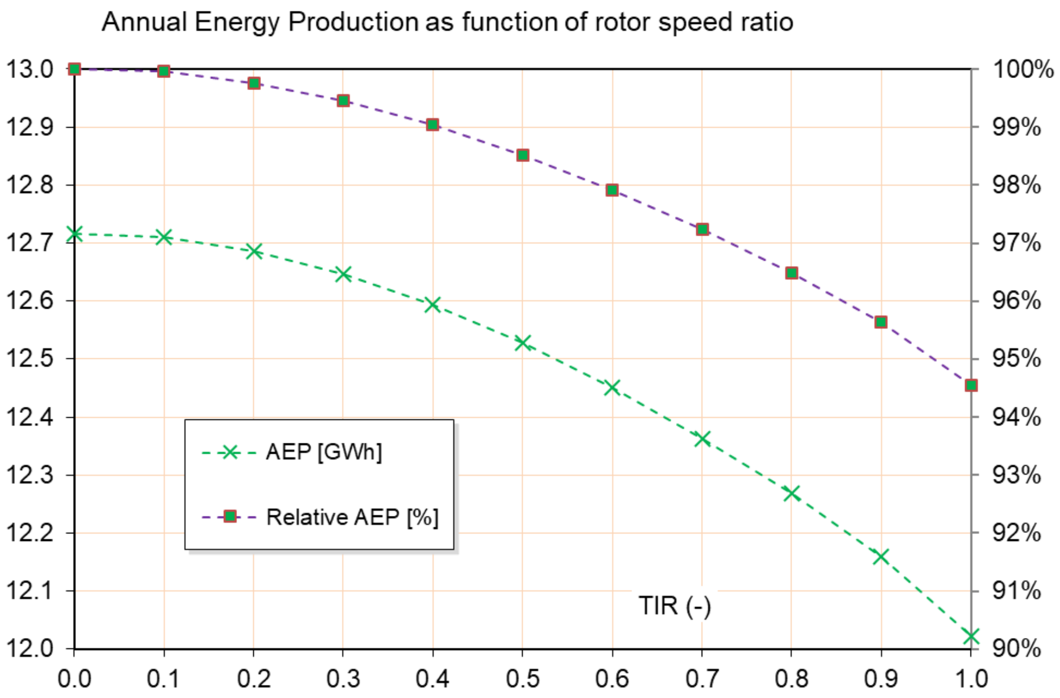
Input wind conditions		
Average wind speed	7.5	m/s

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.022**	**GWh/år**
Capacity factor	40.4%	

Annual energy production depending on rotor speed concept

By plotting the actual and normalized power production, the impact of the rotor speed increase is shown.

This is the cost to pay for to get the FFR reserve!



Summary of reduced production caused by TIR > 0		
TIR	AEP [GWh]	Relative AEP [%]
0.0	12.716	100.00%
0.1	12.710	99.96%
0.2	12.685	99.76%
0.3	12.646	99.45%
0.4	12.593	99.04%
0.5	12.527	98.52%
0.6	12.451	97.92%
0.7	12.363	97.23%
0.8	12.269	96.49%
0.9	12.160	95.63%
1.0	12.022	94.54%

Implementation and verification of FFR control

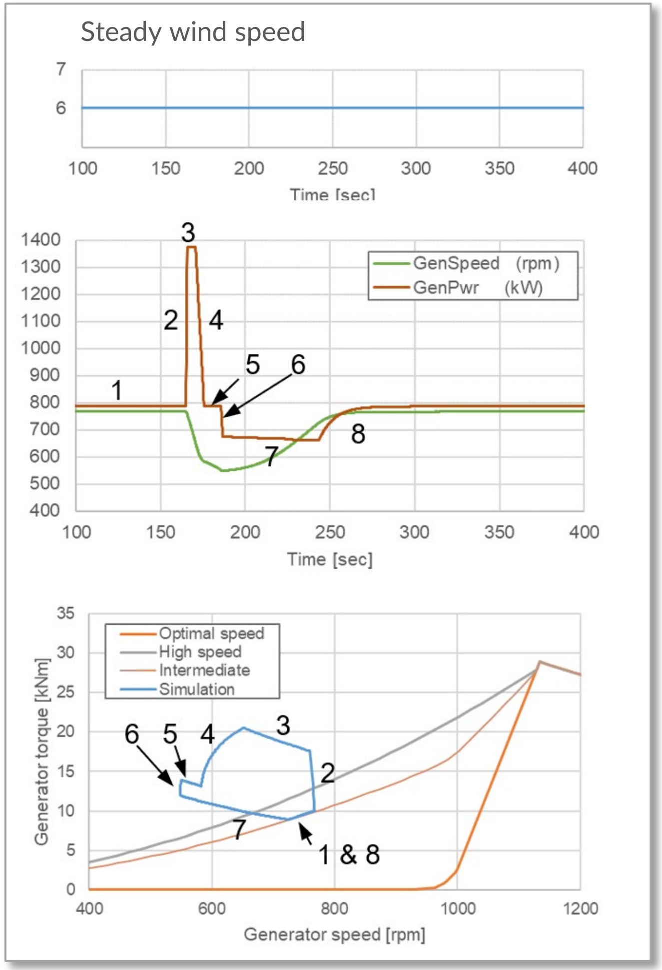
Implementation of the control algorithms for rapid FFR power during 5 seconds.

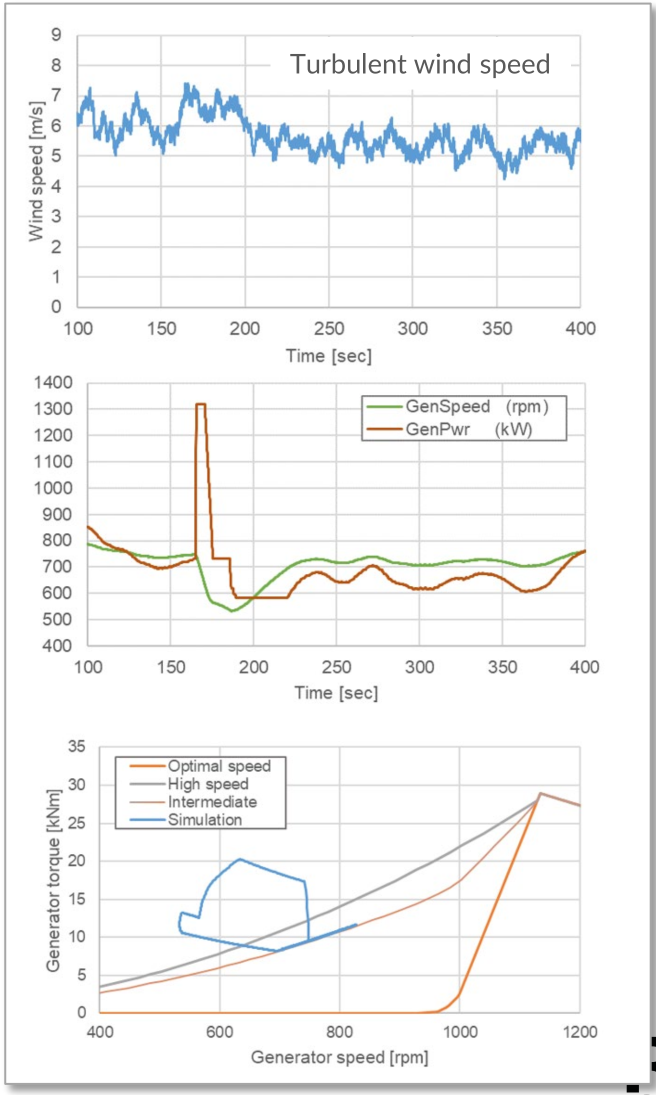
An example is executed.

The sequences are shown in

1. Time domain
2. Torque-Speed diagram

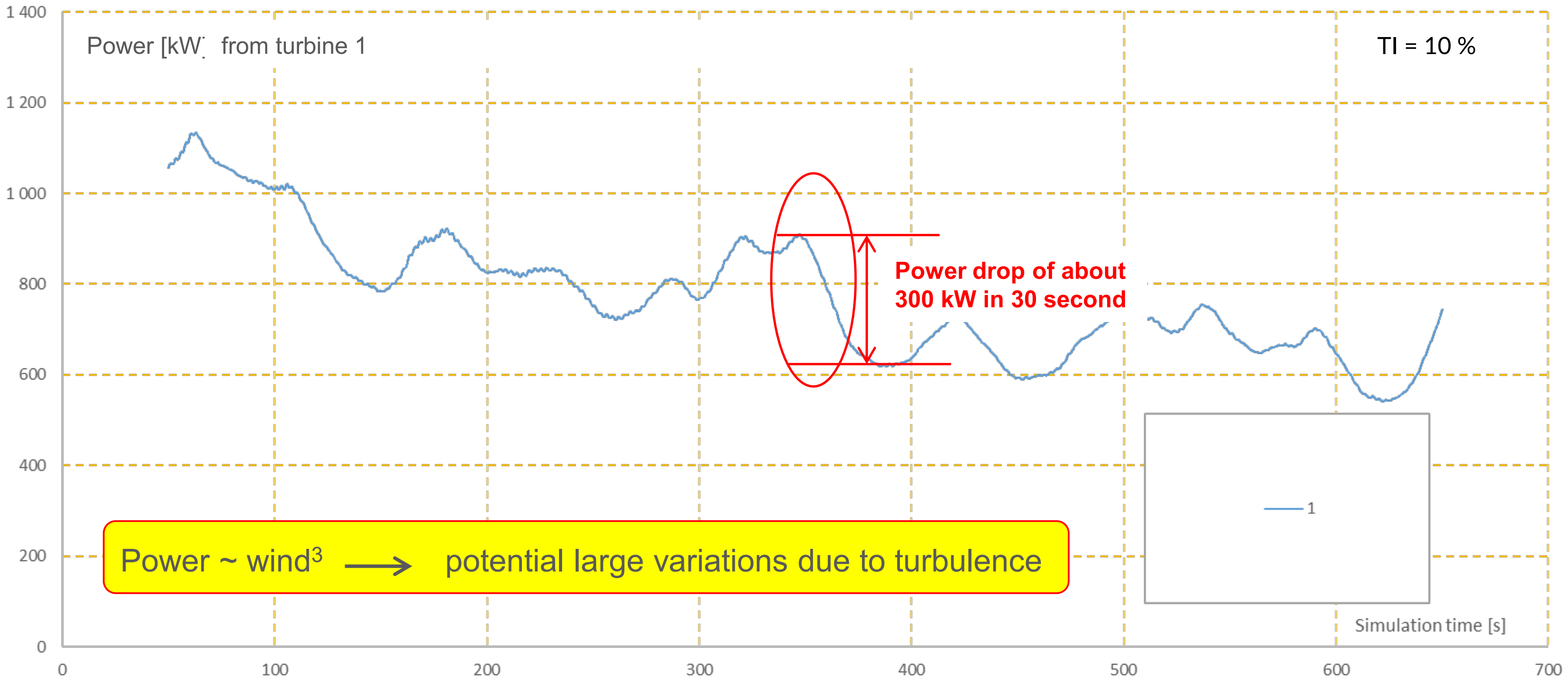
for both steady and turbulent wind speed.





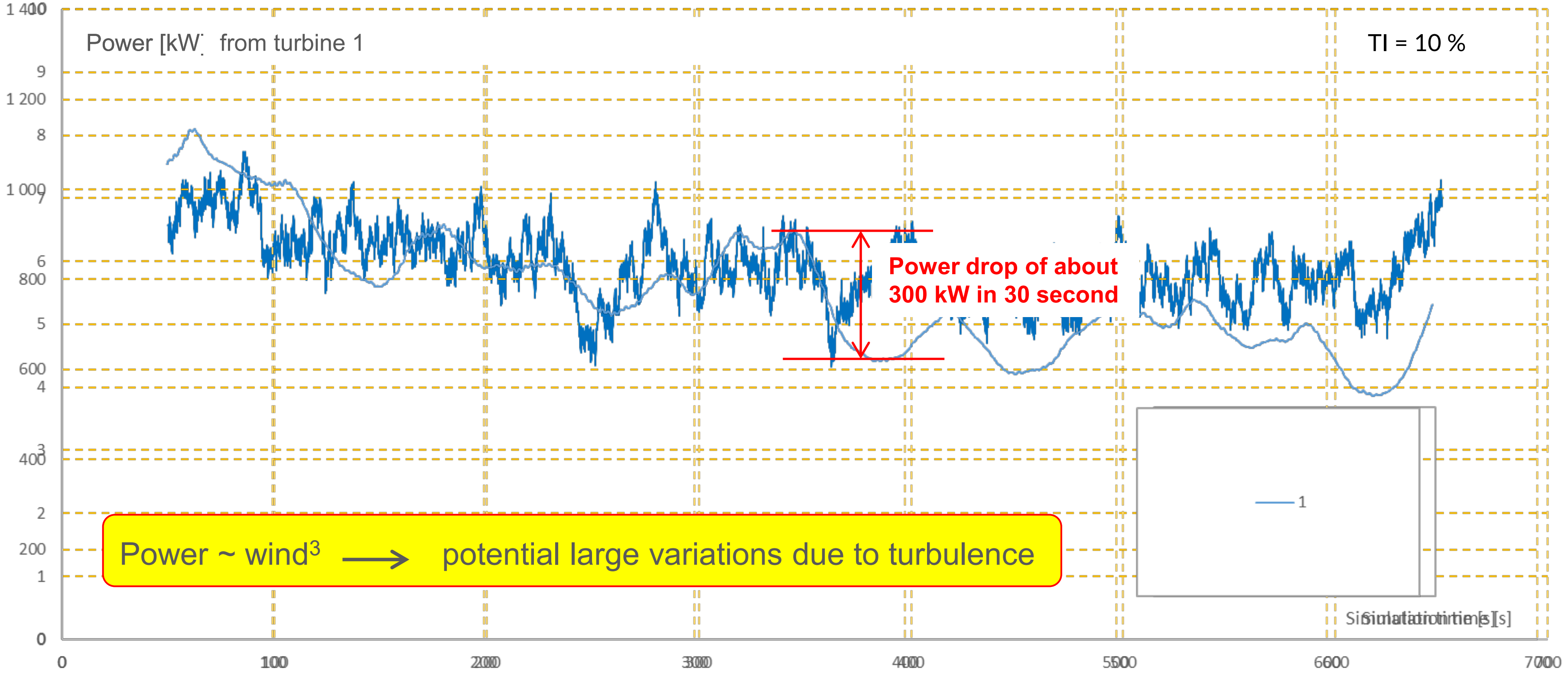
Power output in mean wind speed 6 m/s

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 10 minutes in turbulent wind



Power output in mean wind speed 6 m/s

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 10 minutes in turbulent wind



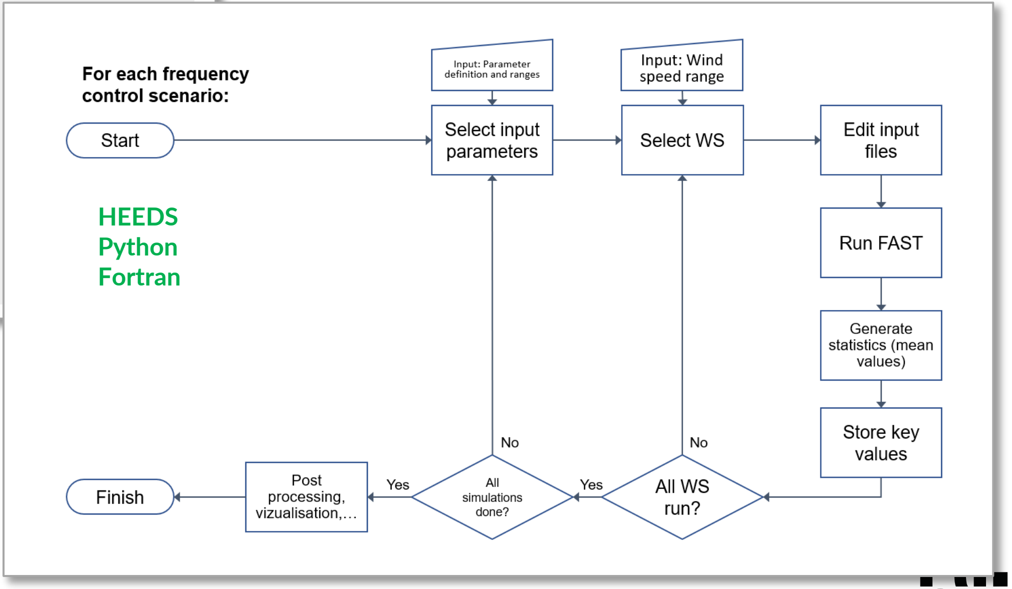
It is not possible to run a turbine at constant power for longer times in low wind speeds

Simulation set up, to cover quite many cases

In order to operate at higher rotor speeds the generator control system was changed. Further an option to apply arbitrary FFR power according to ENTSO-E requirements was added.

					Sum
Simulation combinations	**12**	**10**	**9**	**11**	**11880**
To vary:	Mean wind speed	Turbulence seed	FFR power level	High rotor speed ratio	
	3	xxx01	0	0.0	
	4	xxx02	100	0.1	
	5	xxx03	200	0.2	
	6	xxx04	300	0.3	
	7	xxx05	400	0.4	
	8	xxx06	500	0.5	
	9	xxx07	600	0.6	
	10	xxx08	700	0.7	
	11	xxx09	800	0.8	
	12	xxx10		0.9	
	13			1.0	
	14			TIR, for TrqIntRatio	

Operation as of today, power production only at optimal rotor speed



In total almost 12 000 simulations were executed to cover all combinations of wind speeds (below rated), turbulence cases, FFR power and rotor speed increase at normal operation.

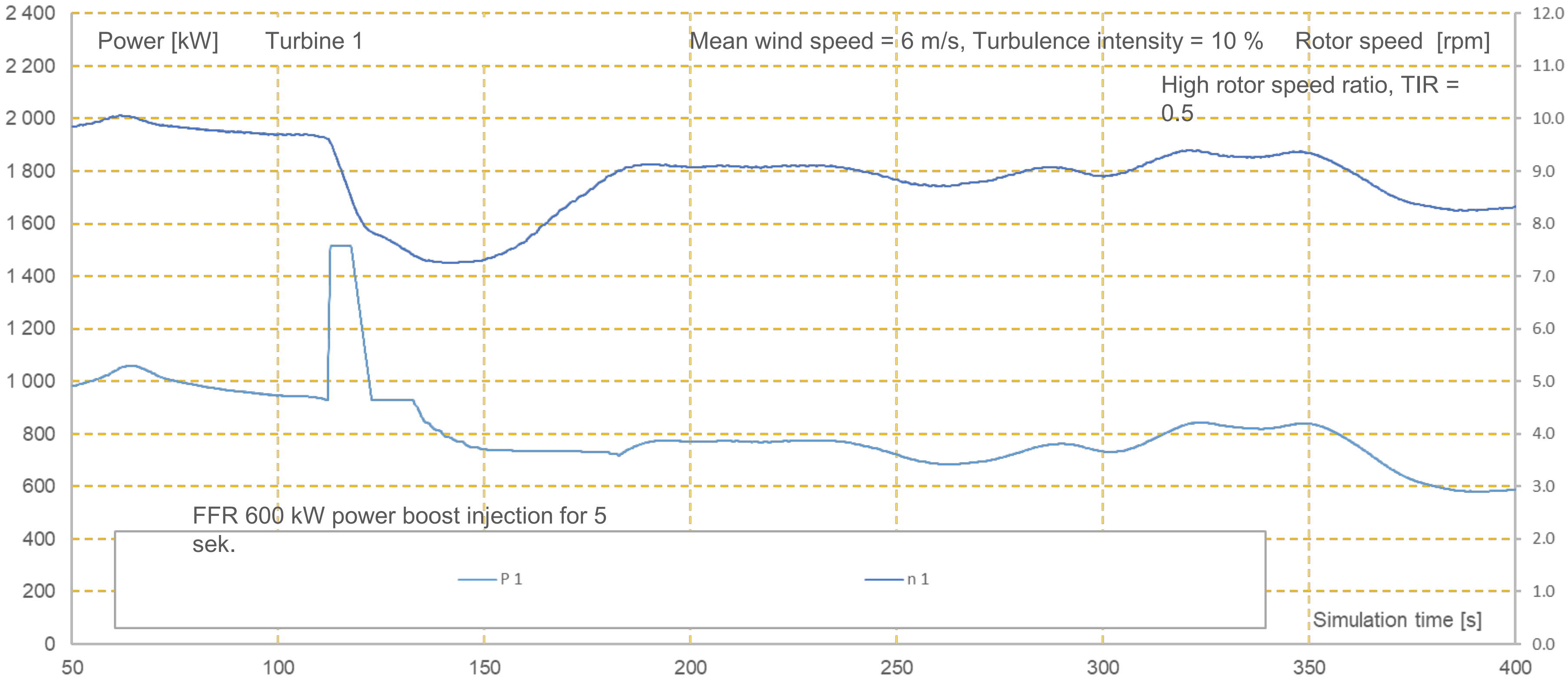
One example: FFR of 600 kW power boost at 6 m/s

The example is specified below:

					Sum
Simulation combinations	**12**	**10**	**9**	**11**	**11880**
To vary:	Mean wind speed	Turbulence seed	FFR power level	High rotor speed ratio	
	3	xxx01	0	0.0	
	4	xxx02	100	0.1	
	5	xxx03	200	0.2	
	6	xxx04	300	0.3	
	7	xxx05	400	0.4	
	8	xxx06	500	0.5	
	9	xxx07	600	0.6	
	10	xxx08	700	0.7	
	11	xxx09	800	0.8	
	12	xxx10		0.9	
	13			1.0	
	14				

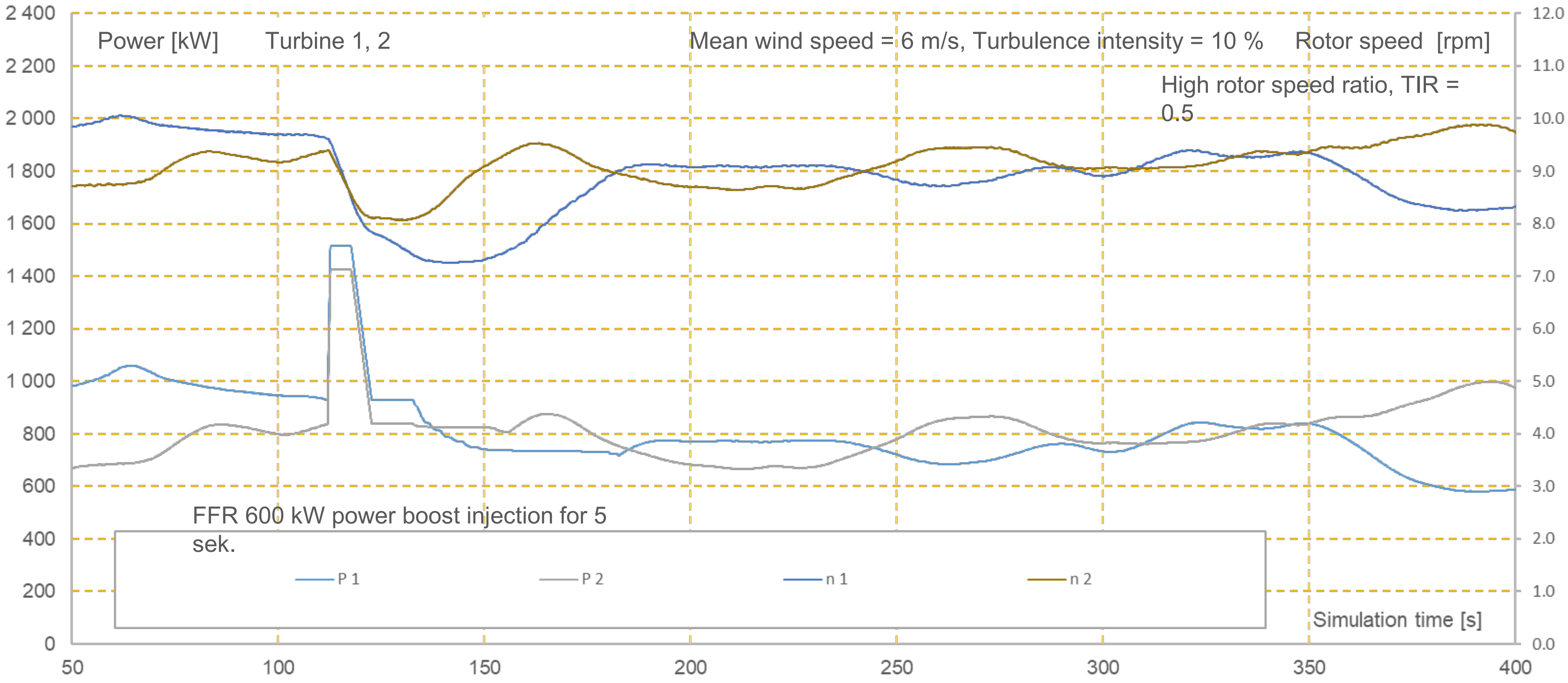
Power and rotor speed during FFR 600 kW power boost

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



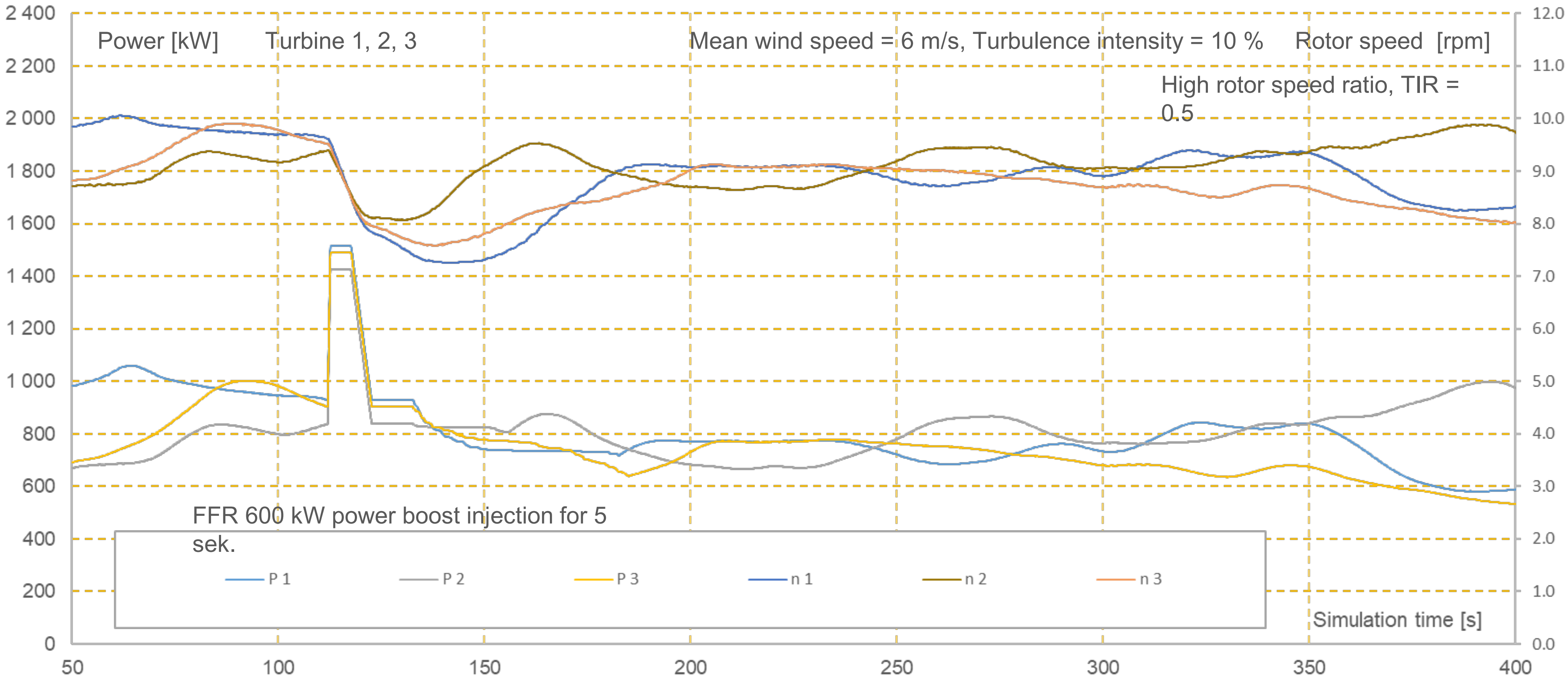
Power and rotor speed during FFR 600 kW power boost

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



Power and rotor speed during FFR 600 kW power boost

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



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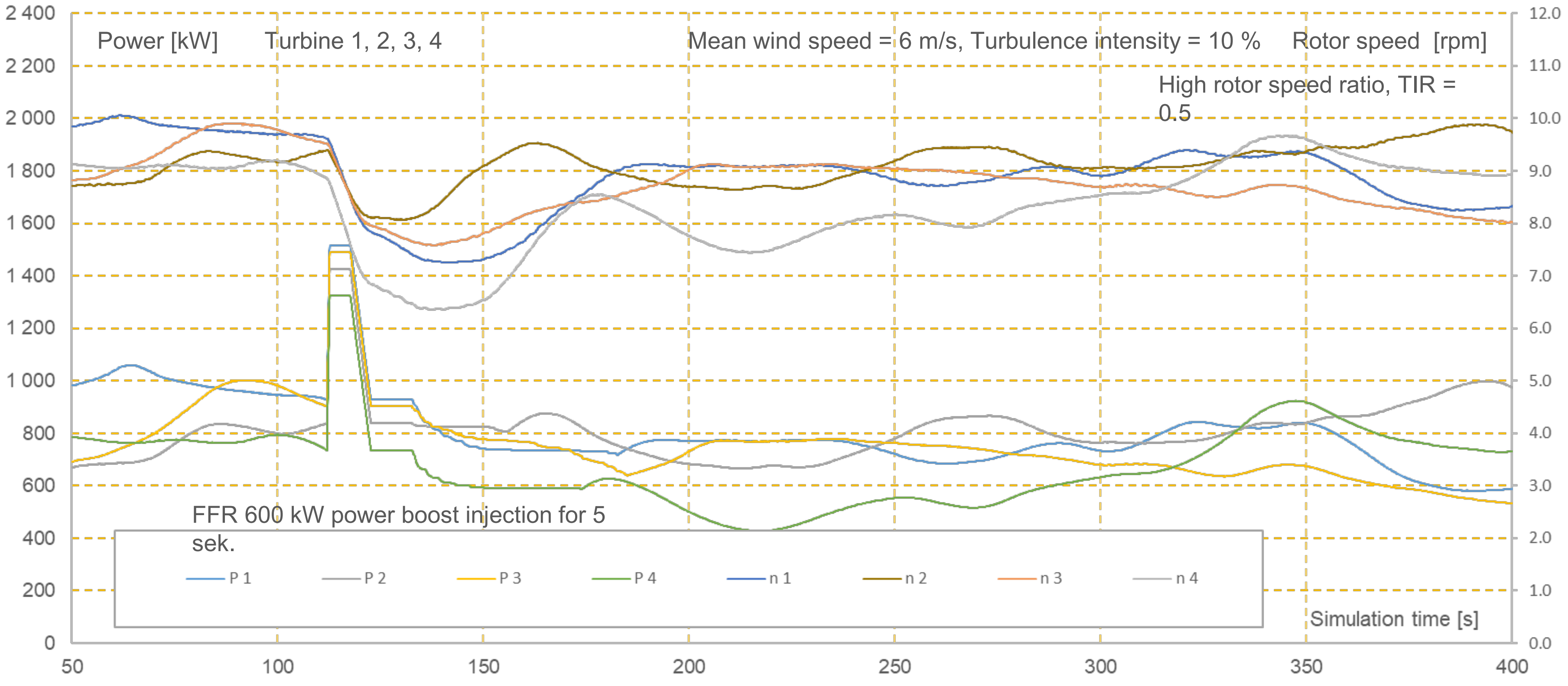
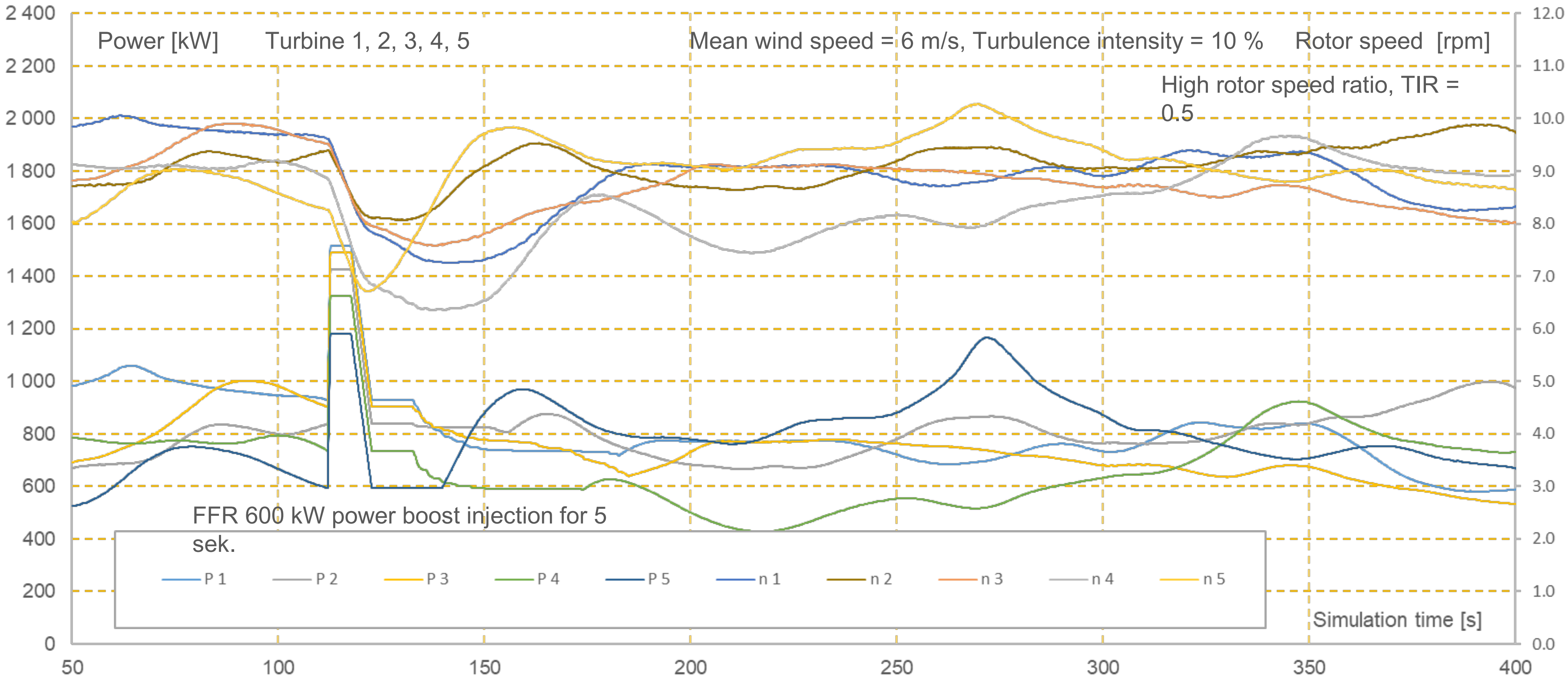
Power and rotor speed during FFR 600 kW power boost

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



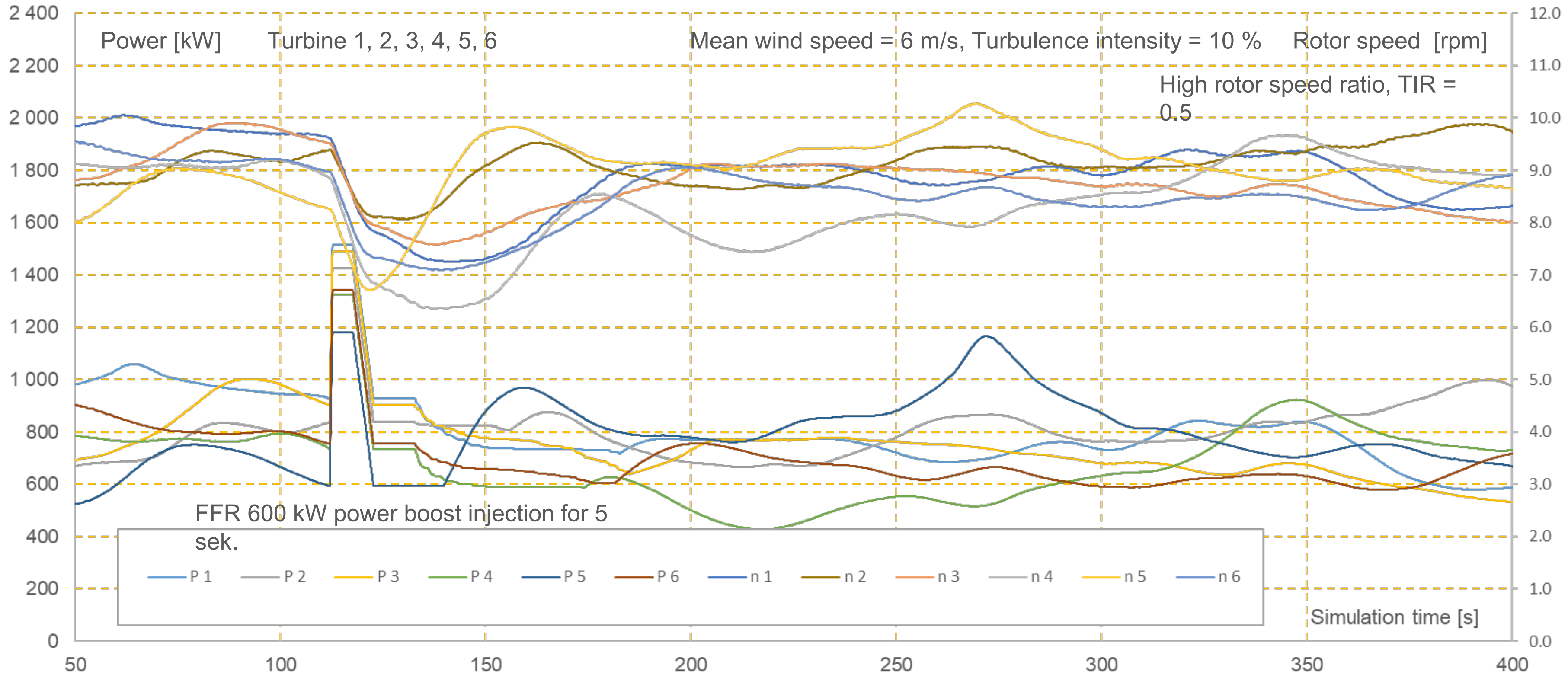
Power and rotor speed during FFR 600 kW power boost

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



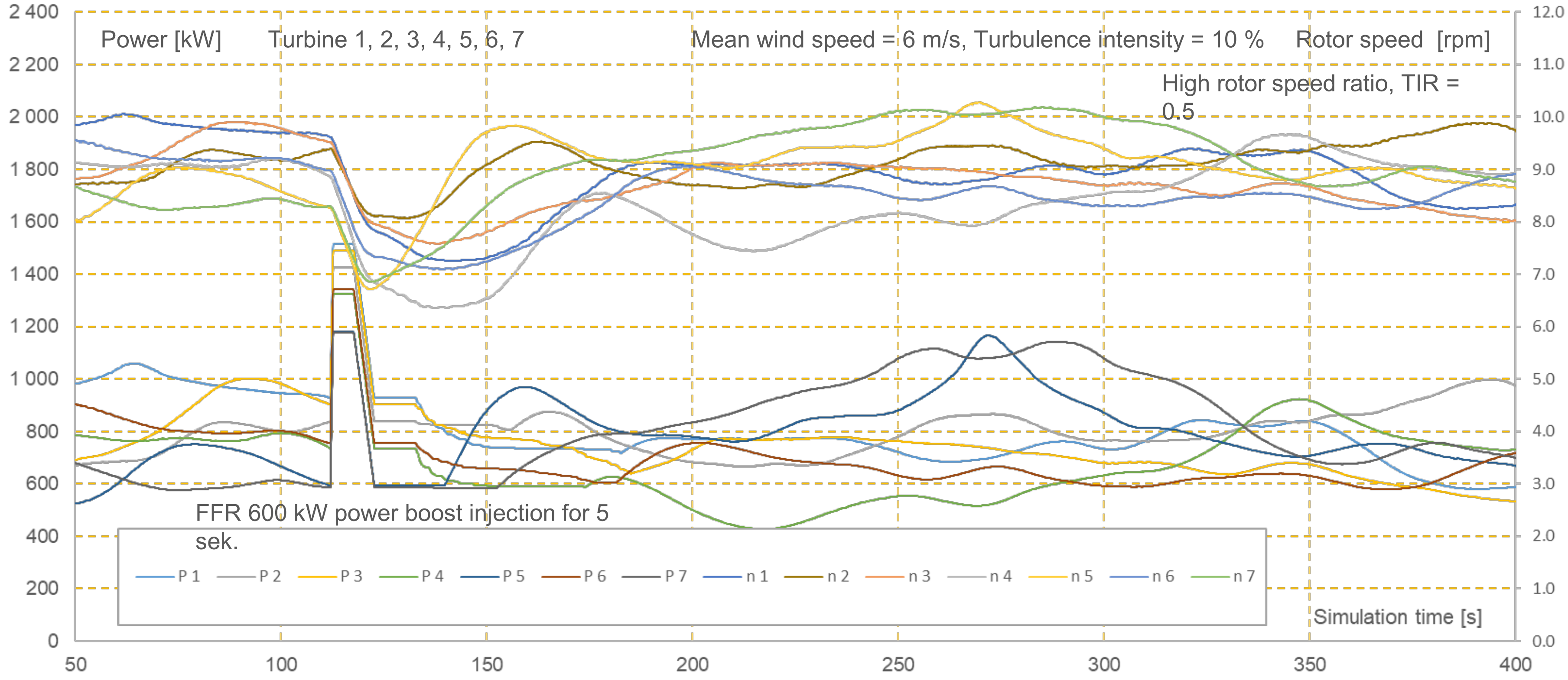
Power and rotor speed during FFR 600 kW power boost

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



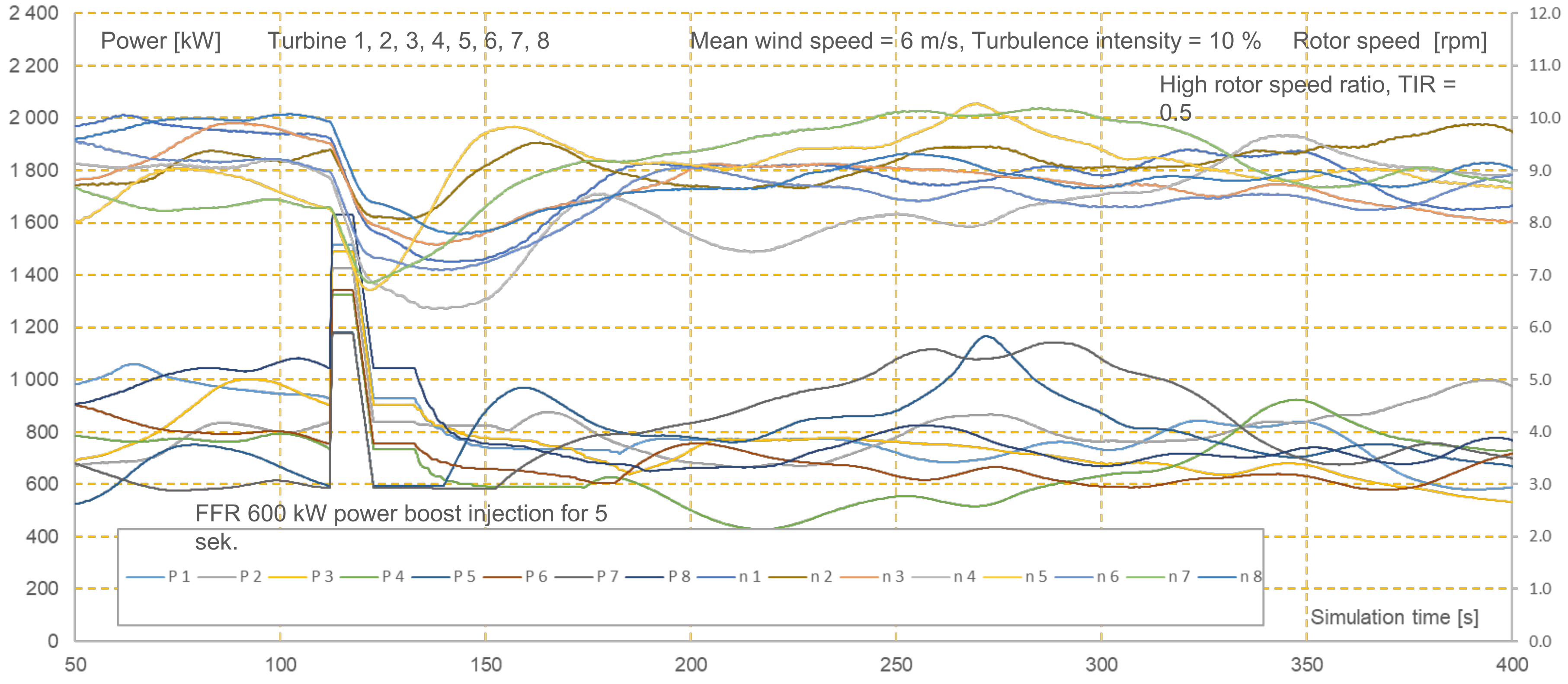
Power and rotor speed during FFR 600 kW power boost

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



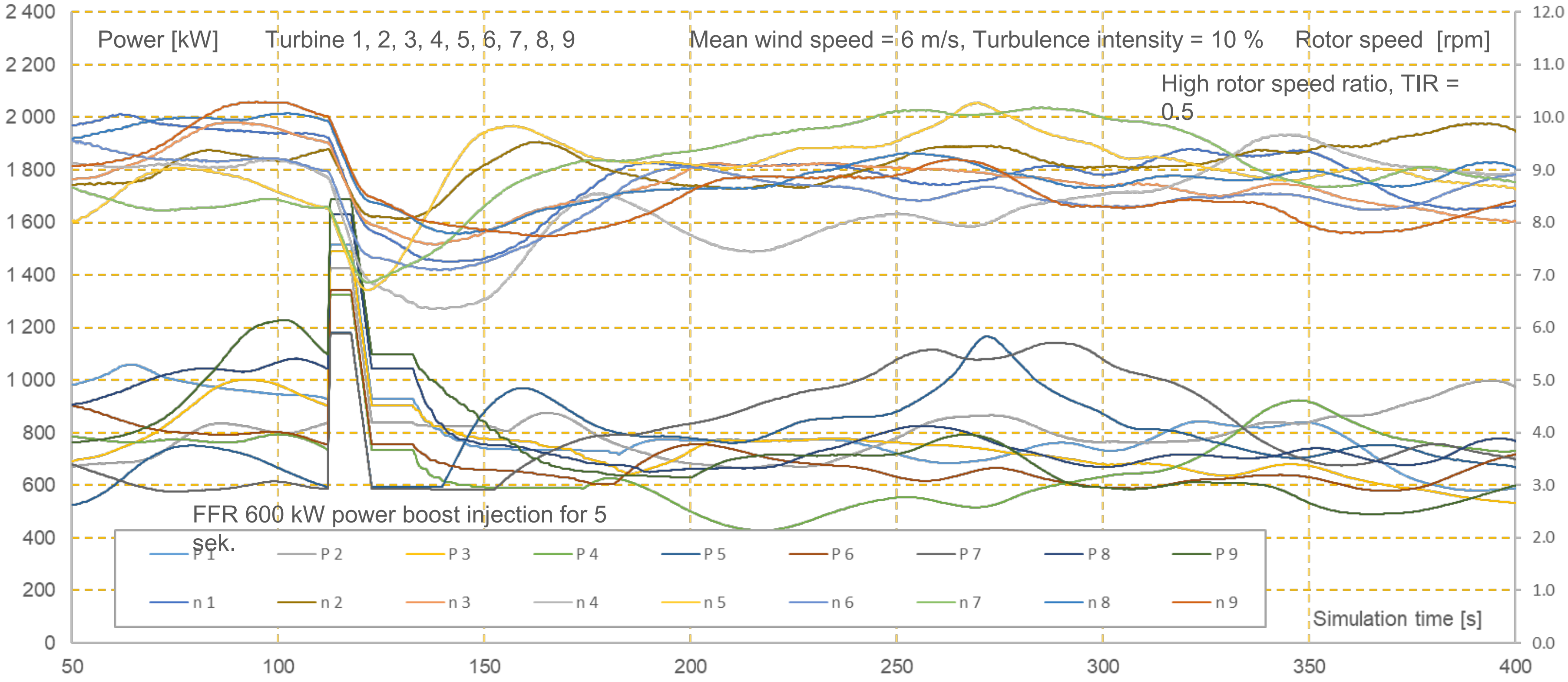
Power and rotor speed during FFR 600 kW power boost

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



Power and rotor speed during FFR 600 kW power boost

Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



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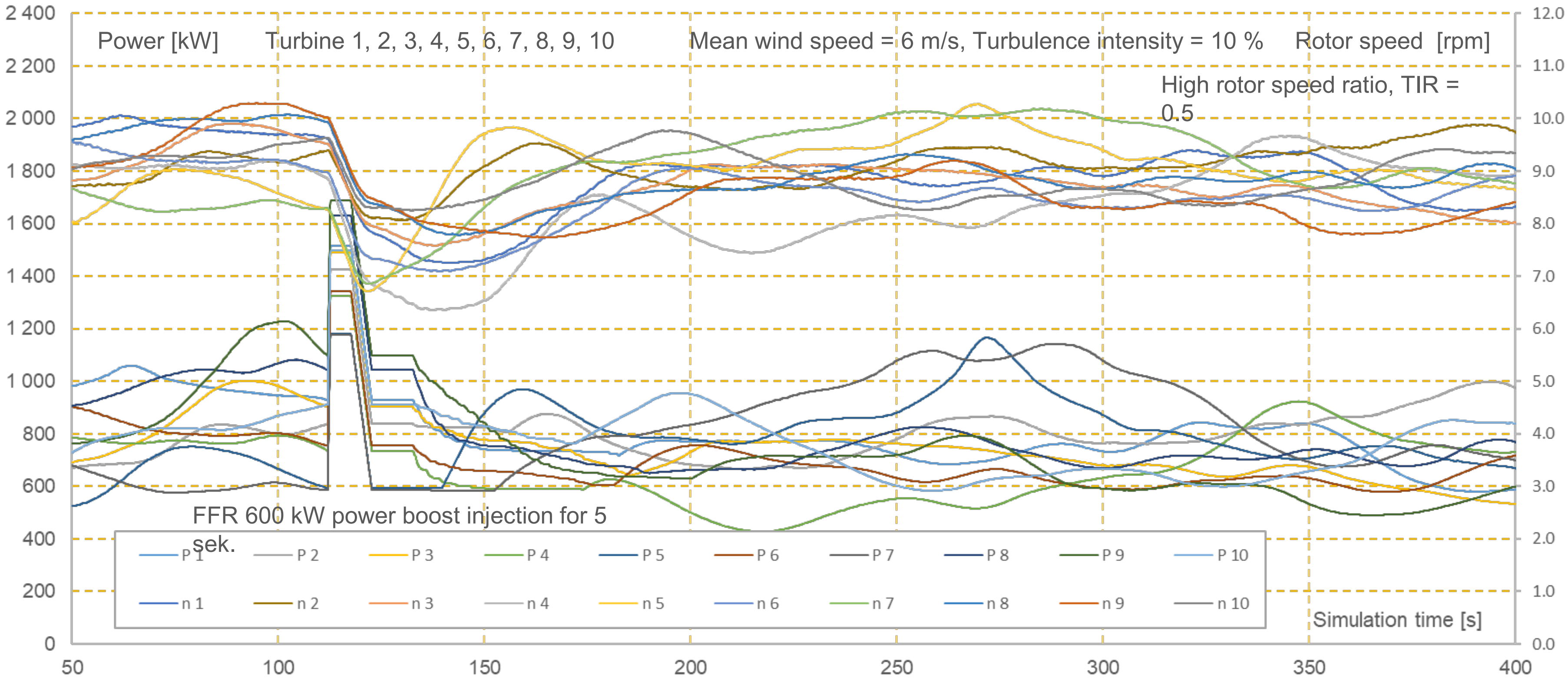

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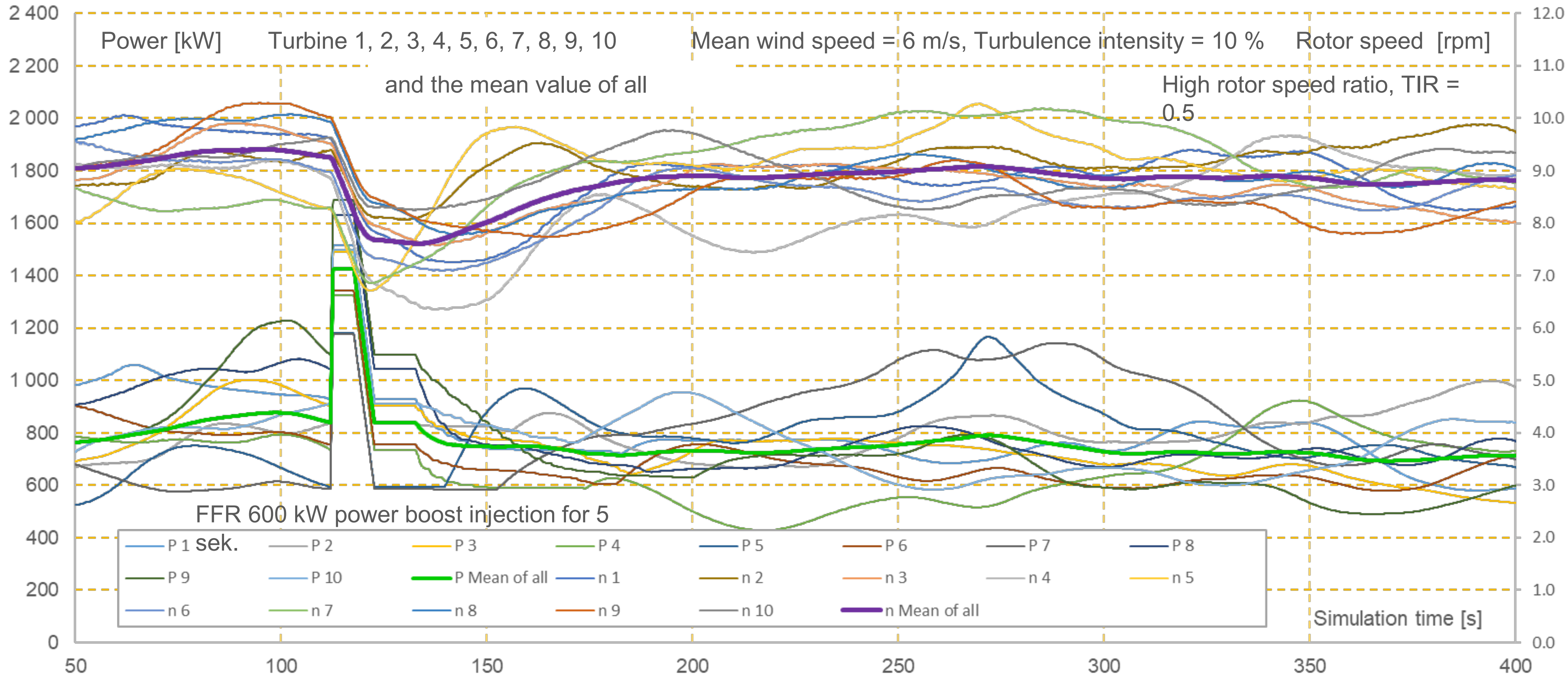
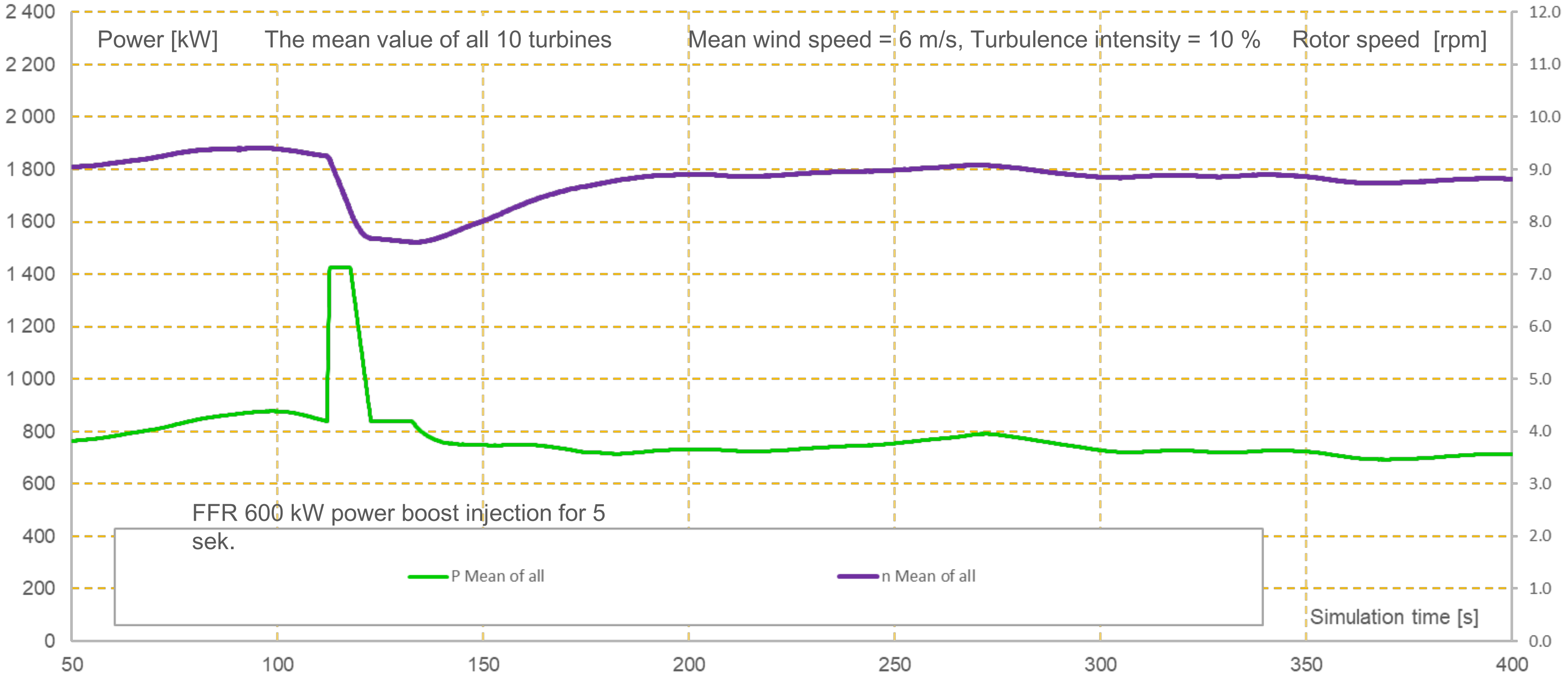


Power and rotor speed during FFR 600 kW power boost

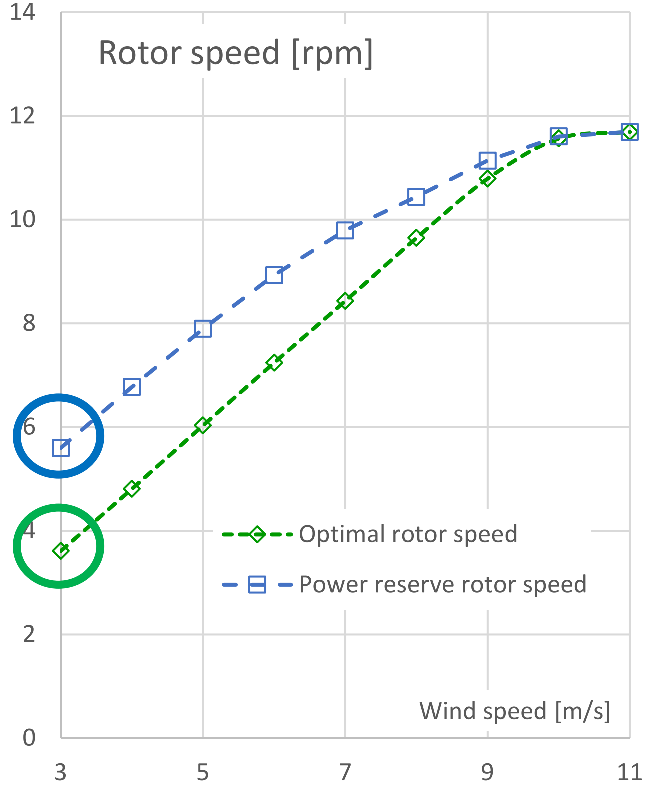
Results from aeroelastic simulations of the IEA 3.4 – 130 turbine for 6 minutes in turbulent wind



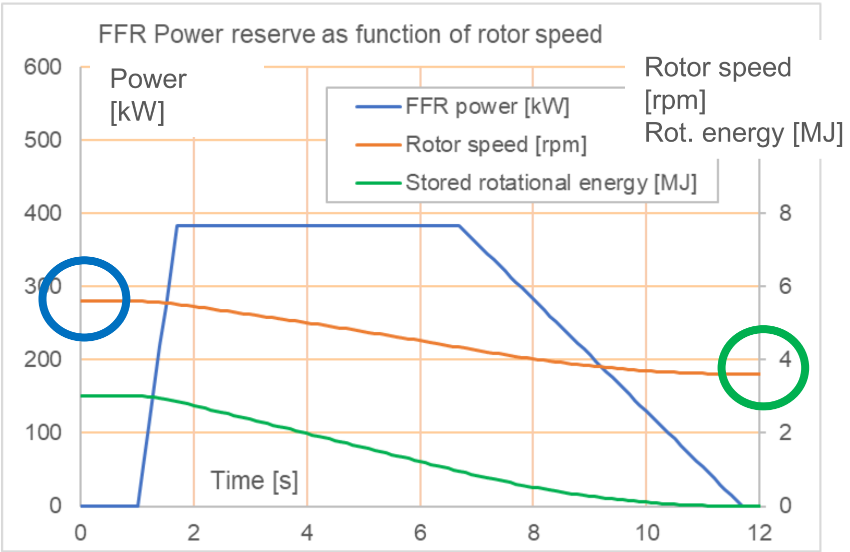
Using several scattered turbines, it is easy to keep turbine power within the requirements

Theoretical power reserve at mean wind speed 3 m/s

At 3 m/s the FFR capacity is 382 kW, based on TIR = 0.8



Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	0.586	rad/s
Rotating energy at start	5.14E+06	J
Angular velocity at end	0.378	rad/s
Rotating energy at end	2.14E+06	J
Extracted energy	3.00E+06	J
FFR capacity	**382**	**kW**



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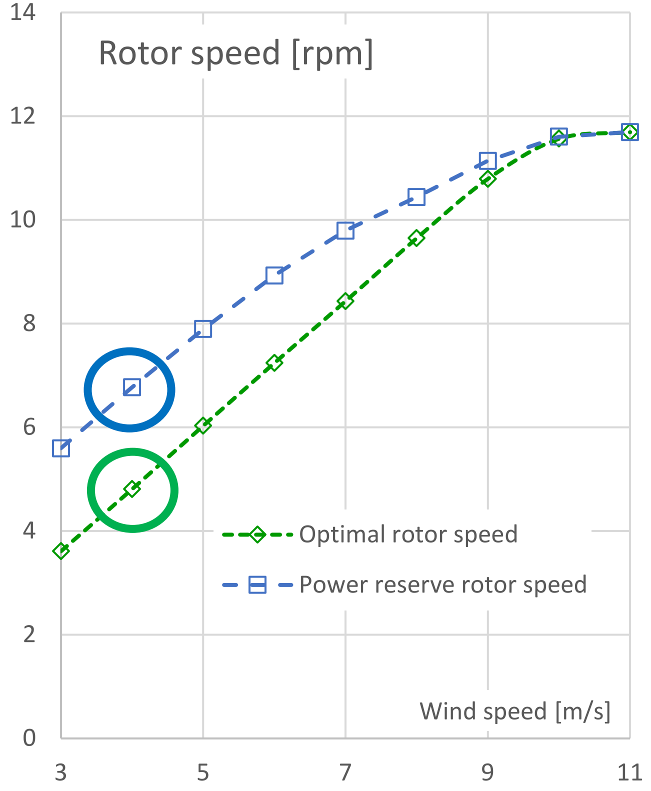
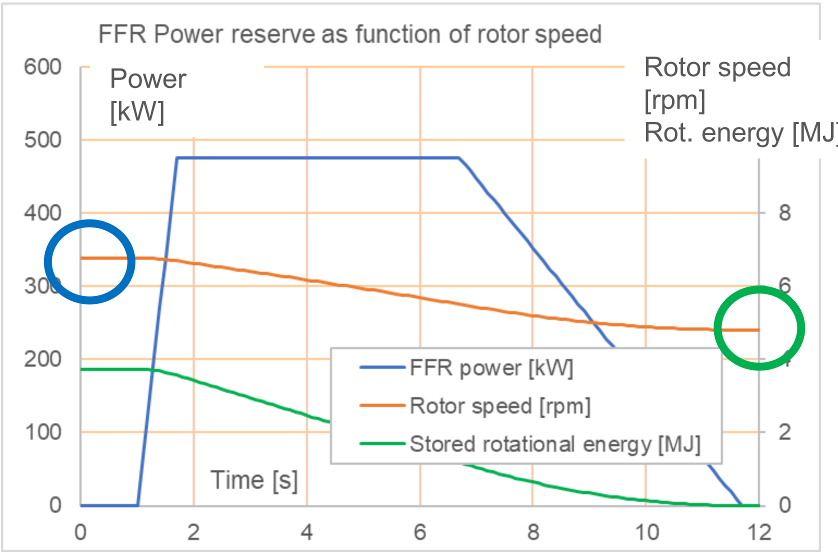
Theoretical power reserve at mean wind speed 4 m/s

At 4 m/s the FFR capacity is 476 kW, based on TIR = 0.7



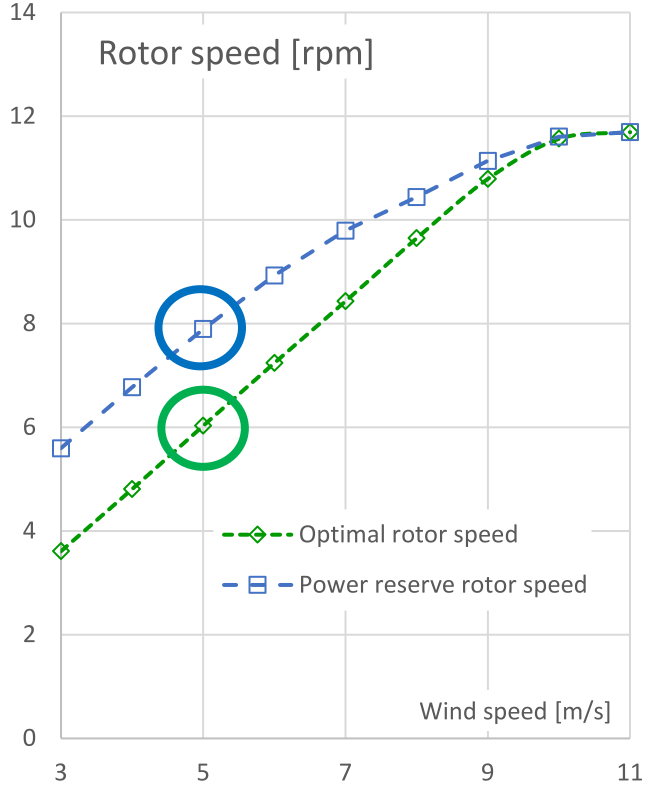
Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	0.709	rad/s
Rotating energy at start	7.54E+06	J
Angular velocity at end	0.503	rad/s
Rotating energy at end	3.80E+06	J
Extracted energy	3.74E+06	J
FFR capacity	**476**	**kW**

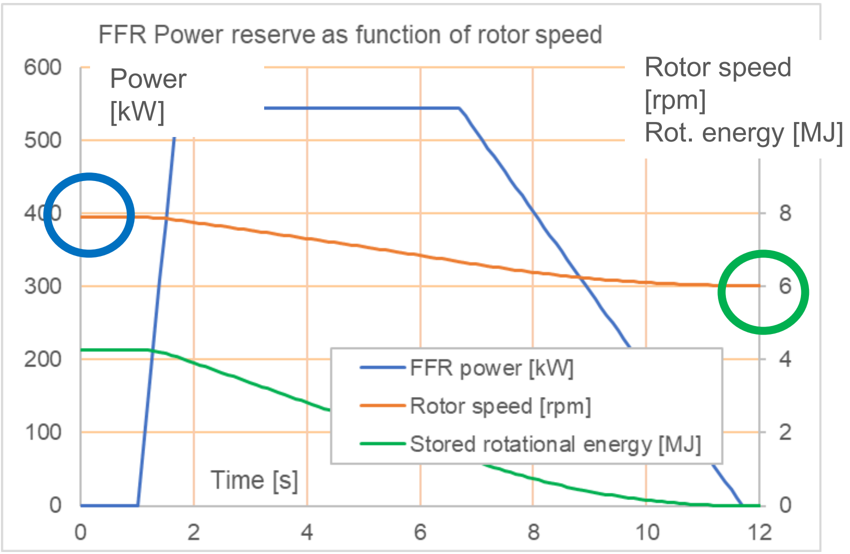


Theoretical power reserve at mean wind speed 5 m/s

At 5 m/s the FFR capacity is 544 kW, based on TIR = 0.6

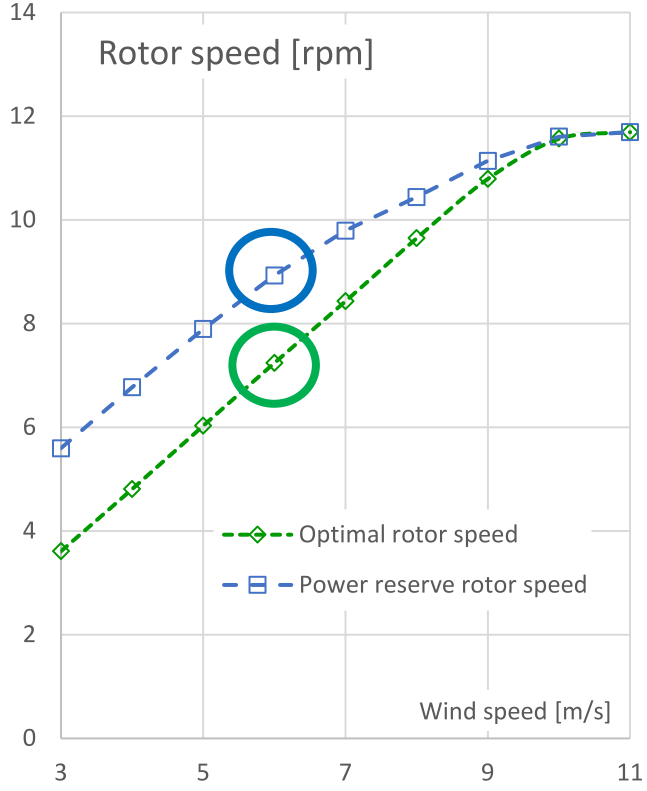
Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	0.827	rad/s
Rotating energy at start	1.02E+07	J
Angular velocity at end	0.631	rad/s
Rotating energy at end	5.98E+06	J
Extracted energy	4.27E+06	J
FFR capacity	**544**	**kW**



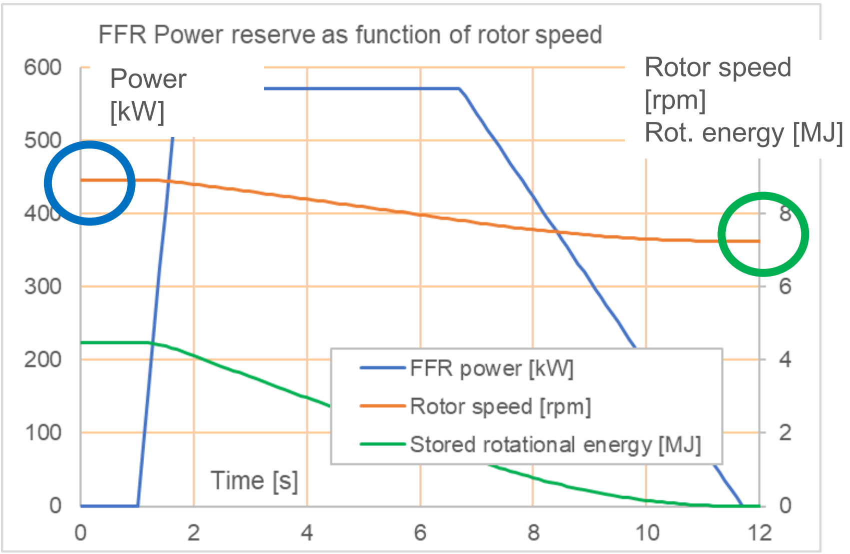


Theoretical power reserve at mean wind speed 6 m/s

At 6 m/s the FFR capacity is 571 kW, based on TIR = 0.5

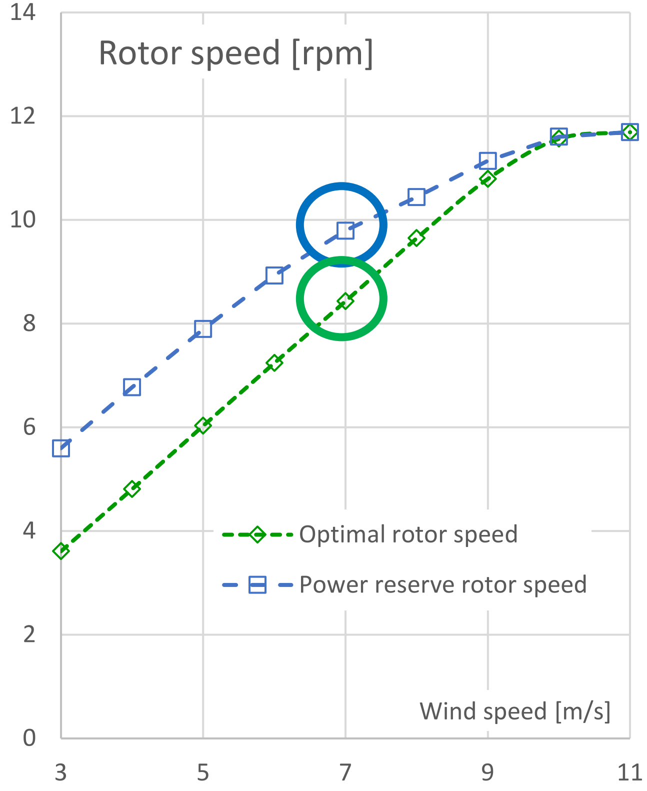


Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	0.935	rad/s
Rotating energy at start	1.31E+07	J
Angular velocity at end	0.758	rad/s
Rotating energy at end	8.62E+06	J
Extracted energy	4.48E+06	J
FFR capacity	**571**	**kW**

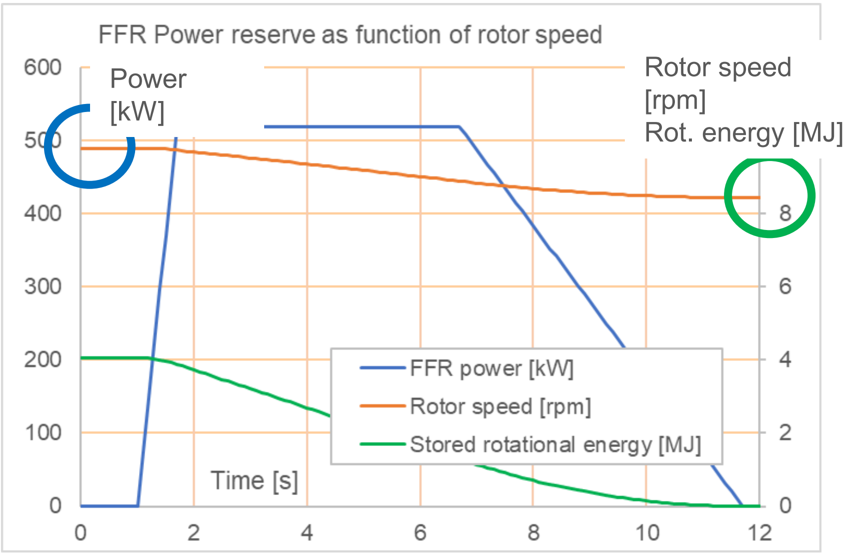


Theoretical power reserve at mean wind speed 7 m/s

At 7 m/s the FFR capacity is 518 kW, based on TIR = 0.4

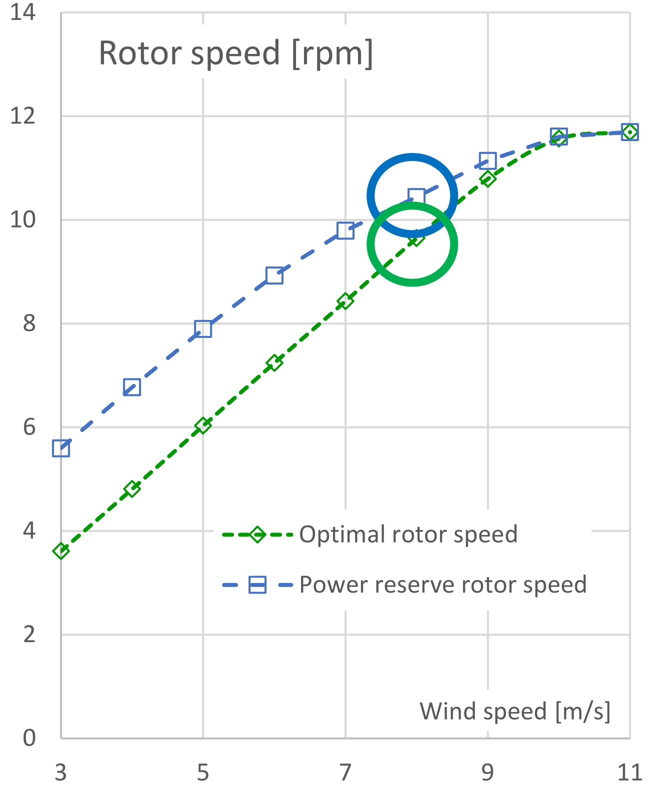


Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	1.025	rad/s
Rotating energy at start	1.58E+07	J
Angular velocity at end	0.883	rad/s
Rotating energy at end	1.17E+07	J
Extracted energy	4.07E+06	J
FFR capacity	**518**	**kW**

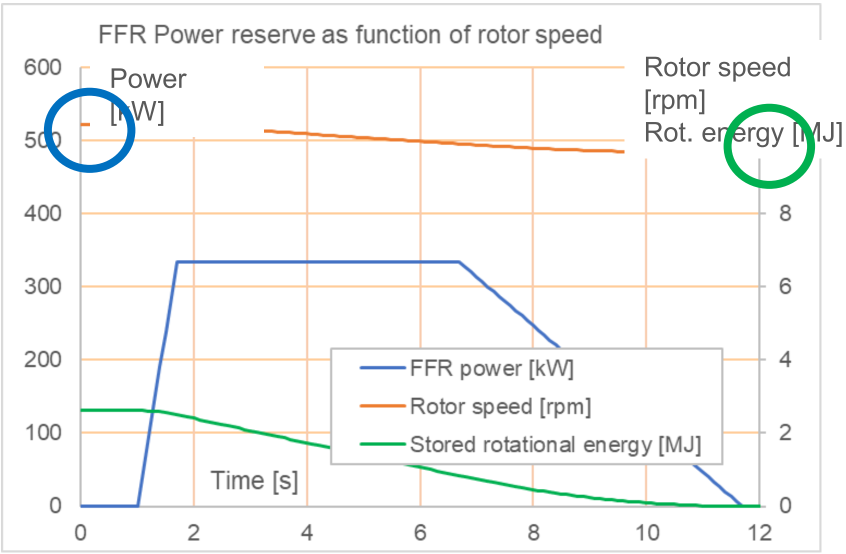


Theoretical power reserve at mean wind speed 8 m/s

At 8 m/s the FFR capacity is 334 kW, based on TIR = 0.3

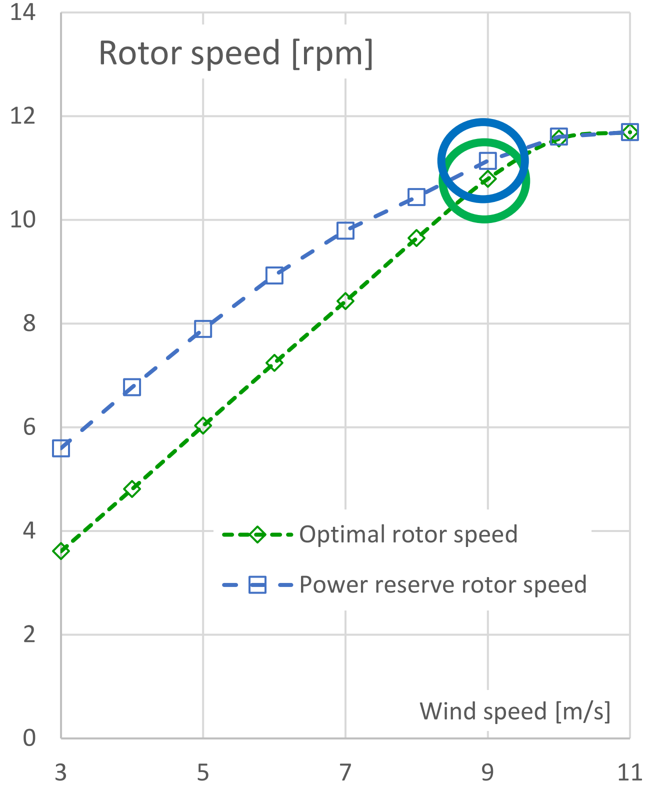


Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	1.093	rad/s
Rotating energy at start	1.79E+07	J
Angular velocity at end	1.010	rad/s
Rotating energy at end	1.53E+07	J
Extracted energy	2.62E+06	J
FFR capacity	**334**	**kW**

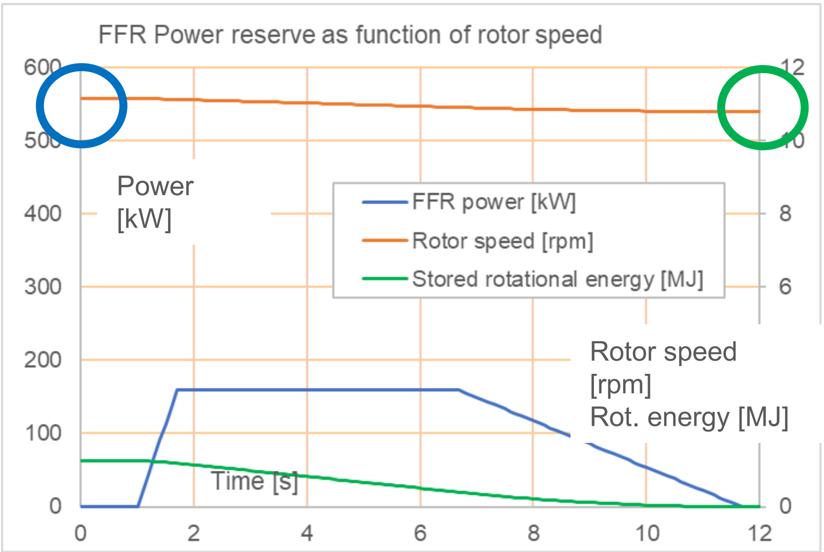


Theoretical power reserve at mean wind speed 9 m/s

At 9 m/s the FFR capacity is 159 kW, based on TIR = 0.3



Summary theoretical power reserve		
Turbine inertia	3.0E+07	kgm2
Angular velocity at start	1.166	rad/s
Rotating energy at start	2.04E+07	J
Angular velocity at end	1.130	rad/s
Rotating energy at end	1.92E+07	J
Extracted energy	1.25E+06	J
FFR capacity	**159**	**kW**



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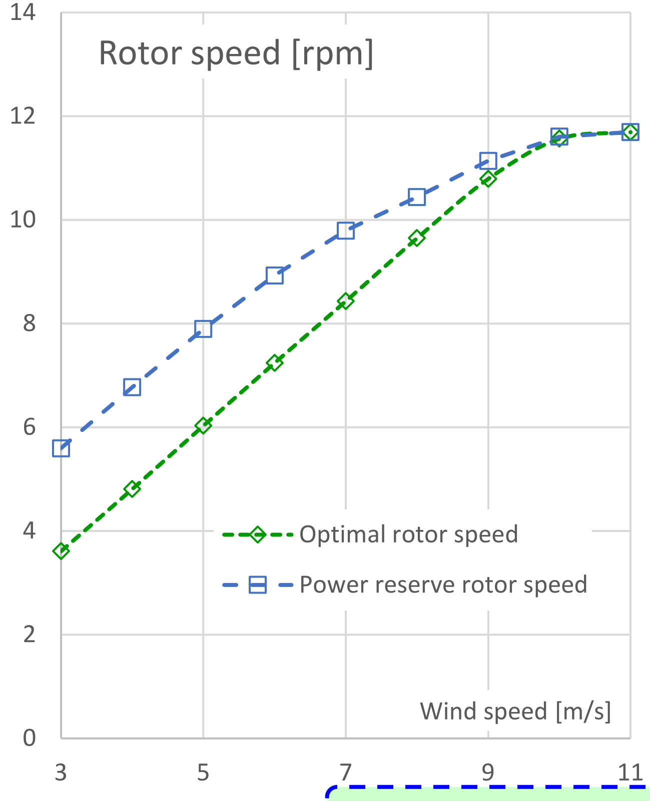
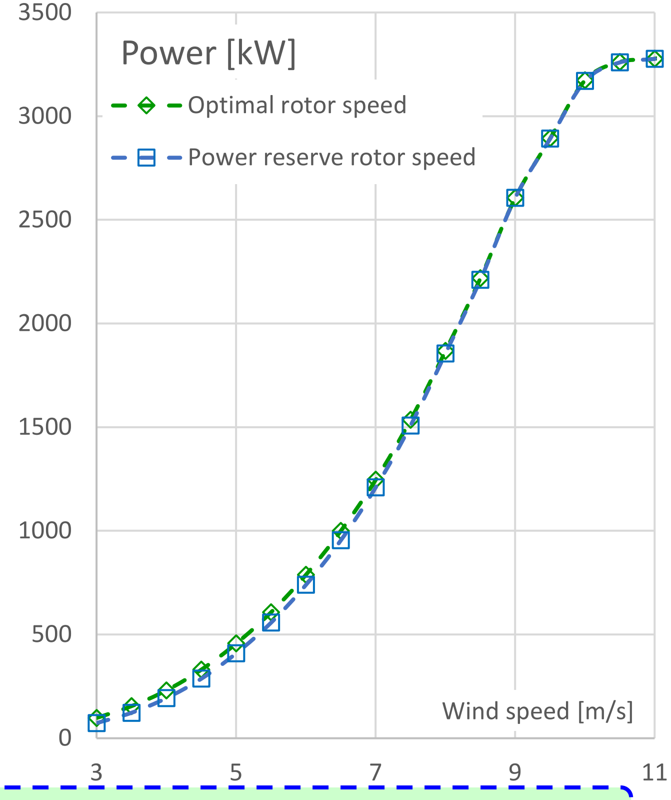
Theoretical power reserve at mean wind speed 3 - 10 m/s

Comparison of AEP between operation at optimal rotor speed vs. power reserve speed





Input wind conditions		
Average wind speed	7.5	m/s

Optimal rotor speed

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.716**	**GWh/år**
Capacity factor	42.7%	

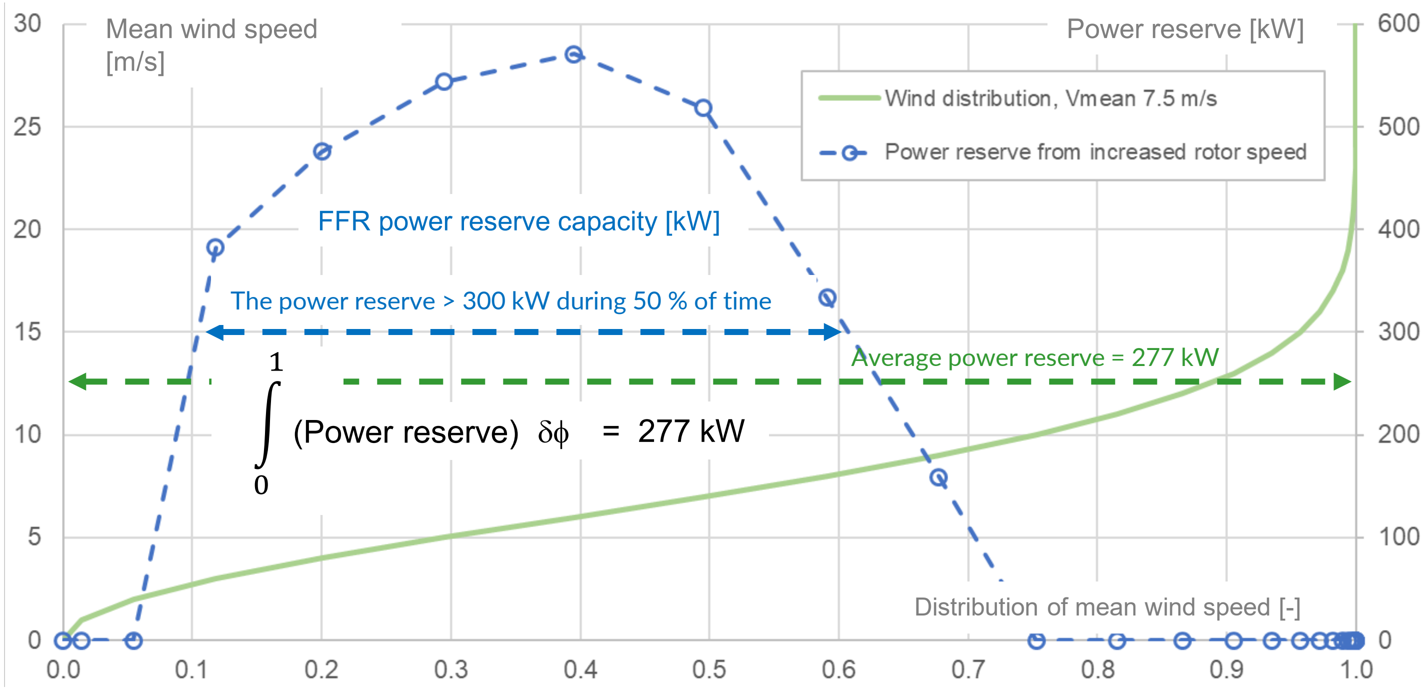
Power reserve rotor speed

Summarized production	IEA 3.4 - 130	
Turbine diameter	130	m
Air density	1.225	kg/m3
Rated power	3.40	MW
Availability	97%	
Park loss factor	95%	
Total production	**12.556**	**GWh/år**
Capacity factor	42.2%	

Power reserve rotor speed ➡ 98.7 % of optimal rotor speed

Correlation between wind speed distribution and FFR power reserve

The calculated FFR capacity plotted in a wind speed distribution graph



Summarized power reserve		
Total wind power production	20	TWh
Curtailment per turbine	0	kW
Production per turbine	12.56	MWh
Number of turbines	1573	
Production reduction	0.16	MWh
Production reduction	1.26	%
Average reserve per turbine	277	kW
Total power reserve	**436**	**MW**

An FFR capacity of 277 kW per turbine is enough for the worst case scenario.
The cost for this rapid reserve is a power production decreased of 1.3 %.

Calculation of total FFR power reserve in Sweden

The annual wind power production in Sweden in 2020 was about 20 TWh.
Based on the production of one IEA 3.4 – 130, 12.65 GWh,
the total production would be covered by 1573 turbines.

Installations in 2020

Total by the end of 2019

Turbines: 4 120 st
Capacity: 9 061 MW
Actual production: 19,5 TWh*
Annual normal production (estimate): 25 TWh**

As the wind situation is varying throughout the country, it is relevant to assume an equal distribution of the integrated power reserve, i.e.

$$\text{The average power reserve} = \int_0^1 (\text{Power reserve})\ \delta\phi \ = \ 277\ \text{kW}$$

is available each and every hour of the year.

This summarizes the total power reserve to 436 MW
which can be released within less than second.

Summarized power reserve		
Total wind power production	20	TWh
Curtailment per turbine	0	kW
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Number of turbines	1573	
Production reduction	0.16	MWh
Production reduction	1.26	%
Average reserve per turbine	277	kW
Total power reserve	**436**	**MW**

The cost for this 436 MW rapid reserve is a decreased power production of 1.3 %

Calculation of total FFR power reserve in Sweden

The annual wind power production in Sweden in 2020 was about 20 TWh.
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Total by the beginning of 2022

Capacity	12,2	GW
Turbines	4835	pcs
Annual normal production*	33,1	TWh

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The average power reserve ... (Power reserve) ... 277 kW

is available each and every hour of the year.

This summarizes the total power reserve to 436 MW which can be released within less than second.

=

2617 IEA turbines
725 MW

Summarized power reserve		
Total wind power production	20	TWh
Curtailment per turbine	0	kW
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Number of turbines	1573	
Production reduction	0.16	MWh
Production reduction	1.26	%
Average reserve per turbine	277	kW
Total power reserve	**436**	**MW**

The cost for this 436 MW rapid reserve is a decreased power production of 1.3 %

Next steps

1. Optimizations of rotor speed concepts to minimize production losses
2. Investigate further and suggest requirement updates to support wind power contribution.
3. How much does the FFR capacity increase if instead going from high to low rotor speed, versus from high to optimal speed (as in this study)?
4. Load consequences, quantification in service life and economic terms?
5. How to control a wind farm for optimizing the FFR power reserve in a park?
6. Forecasts - how to plan operations based on forecasts of need for reserves and expected wind resource?
7. What is a realistic compensation for FFR power reserve, to be attractive for wind turbine owners?
8. Algorithms for turbine control based on Spot market energy price and compensation for FFR reserve, taking loss of energy production and load consequences into account

Thanks! Questions?