# Turbulence Normalisation of Wind Turbine Power Curve Measurements

**For**

**IEC TC88, MT12-1**

**Deutsche WindGuard Consulting GmbH**

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## Contents

1 INTRODUCTION 3

2 HISTORY OF THE PROPOSED TURBULENCE NORMALISATION PROCEDURE 4

2.1 Observation 4

2.2 First Attempt for an Explanation of the Effect 4

2.3 First Attempt for Normalisation of Power Curves According to the Turbulence Intensity 5

2.4 Normal Distribution Model 7

2.5 Improved Procedure for Determination of the Zero Turbulence Power Curve in Combination with the Normal Distribution Model 9

2.6 Simplified Procedure for Determination of the Zero Turbulence Power Curve in Combination with the Normal Distribution Model 10

3 PROPOSED PROCEDURE FOR NORMALISATION OF MEASURED POWER CURVES ACCORDING TO THE TURBULENCE INTENSITY 14

3.1 Turbulence Normalisation Procedure 14

3.2 Determination of the Zero Turbulence Power Curve 15

4 TEST OF TURBULENCE NORMALISATION PROCEDURE 19

4.1 Test Case A: Pitch Controlled Turbine, High Turbulence Site, 1-3 MW Class 20

4.1.1 Case A: Normalisation to I=0 % 20

4.1.2 Case A: Normalisation to I=5 % 21

4.1.3 Case A: Normalisation to I=10 % 23

4.1.4 Case A: Normalisation to I=15 % 24

4.1.5 Case A: Normalisation to I=20 % 26

4.1.6 Case A: Normalisation to I=25 % 27

4.1.7 Case A: Normalisation to I=30 % 29

4.2 Test Case B: Pitch Controlled Turbine, Low Turbulence Site, 5+ MW Class 30

4.2.1 Case B: Normalisation to I=0 % 30

4.2.2 Case B: Normalisation to I=5 % 32

4.2.3 Case B: Normalisation to I=10 % 33

4.2.4 Case B: Normalisation to I=15 % 35

4.2.5 Case B: Normalisation to I=20 % 36

4.3 Test Case C: Stall Controlled Turbine, Medium Turbulence Site, 1-1.5 MW Class 38

4.3.1 Case C: Normalisation to I=0 % 38

4.3.2 Case C: Normalisation to I=5 % 39

4.3.3 Case C: Normalisation to I=10 % 41

4.3.4 Case C: Normalisation to I=15 % 42

4.3.5 Case C: Normalisation to I=20 % 44

4.3.6 Case C: Normalisation to I=25 % 45

5 SUMMARY 47

6 LITERATURE 48

# 1 Introduction

A procedure for the normalisation of power curve measurement data according to the turbulence intensity is suggested to the maintenance team of the IEC-standard 61400-12-1 [1] for integration in the next revision of the standard.

Chapter 2 describes the history of the normalisation procedure. It is advisable to read this chapter in order to understand the reason for different details of the method.

Chapter 3 is an instruction how to implement the procedure. This instruction could potentially become part of a measurement standard. The instruction contains a lot of details, like how to deal with the combination of air density and turbulence normalisation.

Chapter 4 describes a test of the procedure.

The results in this report are based upon generally acknowledged methods and have been neutrally conducted to the best of our knowledge and belief. No guarantee, however, is given and no responsibility is accepted by Deutsche WindGuard Consulting GmbH for the correctness or interpretation of the derived results.

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This report covers 49 pages (including front cover).

# 2 History of the Proposed Turbulence Normalisation Procedure

## 2.1 Observation

A clear observation is that the measured power output of wind turbines tends to increase at lower wind speeds and wind speeds around the maximum power coefficient with increasing turbulence intensity. The opposite effect has often been observed in the transition region to rated power [2], [3], [4].

## 2.2 First Attempt for an Explanation of the Effect

A first explanation of the effect was published in 1996 [5]. At least part of the observed effect of the turbulence intensity on measured power curves originates from the averaging of the power and wind speed measurement over periods of 10 minutes. This can be understood by developing the power output of the wind turbine in a Taylor series. If the power output is only a function of the wind speed, the Taylor series of the instantaneous power output around the 10-minute average of the wind speed up to the second order term is:

$$P(v) = P(\bar{v}) + \frac{dP(\bar{v})}{dv} \cdot (v - \bar{v}) + \frac{1}{2} \cdot \frac{d^2P(\bar{v})}{dv^2} \cdot (v - \bar{v})^2 \qquad (1)$$

where

| | |
|---|---|
| v: | instantaneous wind speed |
| $\bar{v}$: | 10-minute average of wind speed |
| P(v): | instantaneous power output |
| $P(\bar{v})$: | instantaneous power output at wind speed $\bar{v}$ |
| $\frac{dP(\bar{v})}{dv}$: | first derivative of P(v) at wind speed $\bar{v}$ |
| $\frac{d^2P(\bar{v})}{dv^2}$: | second derivative of P(v) at wind speed $\bar{v}$ |

The averaging of P(v) over 10 minutes under consideration of formula (1) leads to:

$$\overline{P(v)} = \frac{1}{T} \cdot \int_0^T P(v)dt$$

$$\Leftrightarrow \overline{P(v)} = P(\bar{v}) + \frac{dP(\bar{v})}{dv} \cdot \frac{1}{T} \cdot \int_0^T (v - \bar{v}) \cdot dt + \frac{1}{2} \cdot \frac{d^2P(\bar{v})}{dv^2} \cdot \frac{1}{T} \cdot \int_0^T (v - \bar{v})^2 dt$$

where T=600s.

The first order term vanishes as $\bar{v} = \frac{1}{T} \cdot \int_0^T v dt$.

Furthermore, the term $\frac{1}{T}\cdot\int_0^T (v-\bar{v})^2\cdot dt$ is the square of the standard deviation of the wind speed $\sigma_v$ within the 10-minute averaging period T:

$$\overline{P(v)} = P(\bar{v}) + \frac{1}{2}\cdot\frac{d^2P(\bar{v})}{dv^2}\cdot\sigma_v^2$$

$P(\bar{v})$ is the power output which would be measured as 10-minute average at zero turbulence intensity, i.e. if the standard deviation of the wind speed within the 10-minute period would be zero.

With the turbulence intensity being defined as $I = \frac{\sigma_v}{\bar{v}}$ then follows:

$$\overline{P(v)} = P_{I=0}(\bar{v}) + \frac{1}{2}\cdot\frac{d^2P_{I=0}(\bar{v})}{dv^2}\cdot\bar{v}^2\cdot I^2 \qquad (2)$$

This formula explains, why the measured power output $\overline{P(v)}$ increases with increasing turbulence intensity in the wind speed range where the power curve is left curved (second derivative positive, low wind speeds and wind speeds around maximum power coefficient) and vice versa in the wind speed range where the power curve is right curved (second derivative negative, transition region to rated power).

### 2.3 First Attempt for Normalisation of Power Curves According to the Turbulence Intensity

As the effect of the turbulence intensity on measured power curves has been found to be significant, it has been already suggested in 1996 to normalise measured power curves to a reference turbulence intensity, similar to the power curve normalisation to a reference air density [5]. Applying formula (2) once to a reference turbulence intensity and once to the measured turbulence intensity and subtracting both equations from each other leads to:

$$\overline{P_{I_{ref}}(v)} = \overline{P(v)} + \frac{1}{2}\cdot\frac{d^2P_{I=0}(\bar{v})}{dv^2}\cdot\bar{v}^2\cdot(I_{ref}{}^2 - I^2) \qquad (3)$$

where

- $\bar{v}$: 10-minute average of wind speed
- $\overline{P(v)}$: 10-minute average of measured power output
- I: measured turbulence intensity
- $I_{ref}$: reference turbulence intensity
- $\overline{P_{I_{ref}}(v)}$: power output normalised to $I_{ref}$
- $\frac{d^2P_{I=0}(\bar{v})}{dv^2}$: second derivative of zero turbulence power curve

If the second derivate of the zero turbulence power curve is known, formula (3) can be applied for normalising the power curve measurement data.

As a first approach, the second derivate of the zero turbulence power curve can be calculated as the second derivative of the measured power curve. Then the power curve data can be normalised to $I_{ref}$=0. The second derivative of the so gained zero turbulence power curve can then be applied again for a normalisation of the measured data to $I_{ref}$=0 until the second derivative of the zero turbulence power curve converges. It has been found that already the second derivative of the not normalised power curve represents a sufficient fit of the second derivative of the zero turbulence power curve, i.e. that the iterative process is not needed [6].

Power curve normalisation by the application of the Taylor series approach has been found to coincide well with power curve normalisation by the application of a more sophisticated model if the reference turbulence intensity is close to the measured turbulence intensity (see Figure 1 and reference [6]). However, if the reference turbulence intensity deviates much from the measured turbulence intensity, turbulence normalisation by the application of the Taylor series approach leads to implausible power curve data in the transition region to rated power (see Figure 2 and reference [6]). The reason is that the second derivative of the zero turbulence power curve does not exist if the zero turbulence power curve has a sharp corner in the transition form below rated power to rated power (local second order polynomial approach of the zero turbulence power curve not valid).

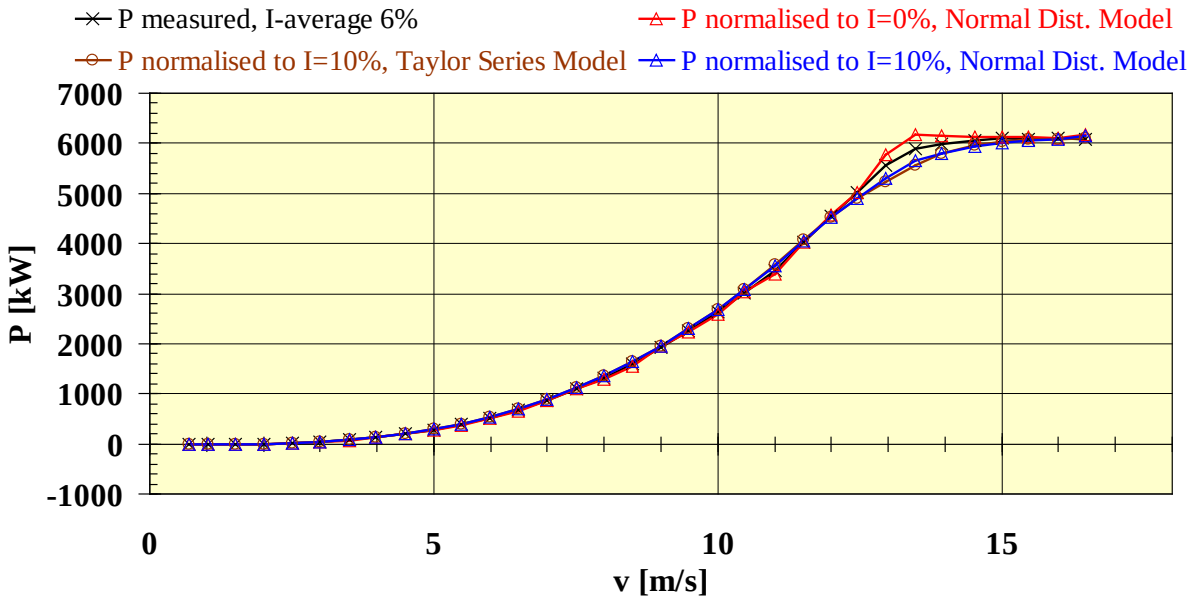


Figure 1: Turbulence normalisation of the power curve measured at a wind turbine of type Enercon E-112 6.0 MW according to reference [6]. Shown are the power curve measured at an average (wind speed dependent) turbulence intensity of about 6 %, the power curve normalised to 0 % turbulence intensity and 10 % turbulence intensity by means of the Normal Distribution Model and the power curve normalised to 10 % turbulence intensity by means of the Taylor series approach.

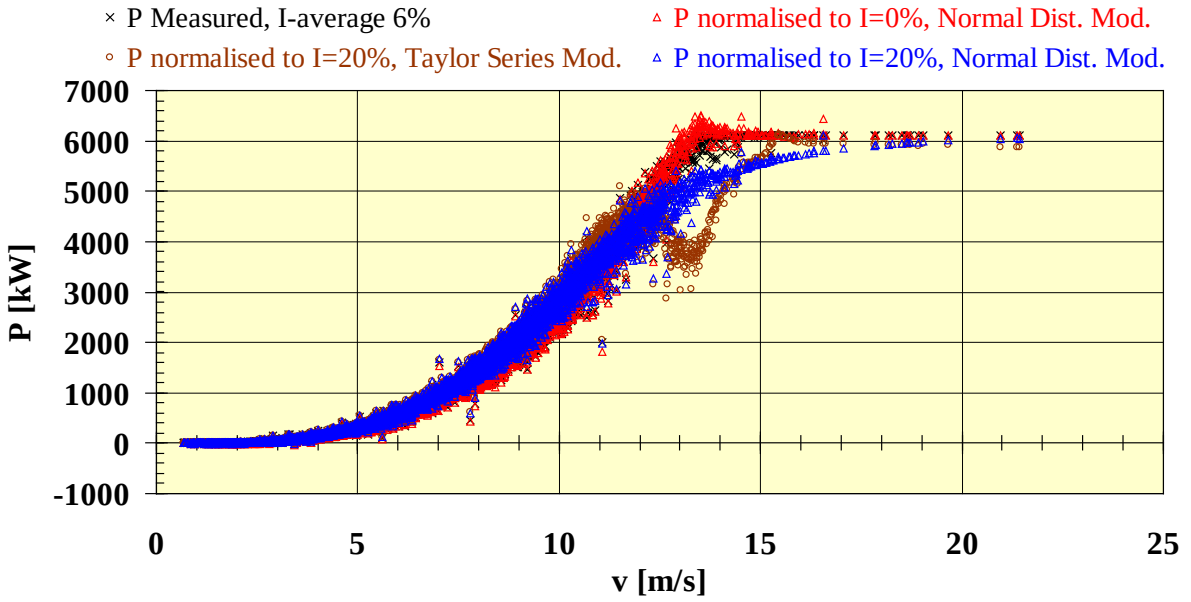


Figure 2: Turbulence normalisation of the power curve raw data measured at a wind turbine of type Enercon E-112 6.0 MW at an average turbulence intensity of 6 % to a high target turbulence intensity of 20 % by means of the Normal Distribution Model and the Taylor series approach according to reference [6].

### 2.4 Normal Distribution Model

The Normal Distribution Model for turbulence normalisation as presented at EWEC 2007 according to reference [6] avoids the assumption of a local second order polynomial approach of the zero turbulence power curve. This procedure is in principle capable for turbulence normalisation of power curve measurement data even if the measured turbulence intensity deviates much from the reference turbulence intensity (see Figure 2 and reference [6]).

The model applies only one assumption:

**The wind turbine follows during each instant the same power curve.**

This power curve would be identical to a power curve based on 10-minute averages of measurements of the power output and the wind speed if the turbulence intensity would be zero. Thus, this power curve is here called zero turbulence power curve.

If the zero turbulence power curve and the wind speed distribution within a 10-minute period would be known, it would be possible to simulate the measured power output as follows:

$$\overline{P_{sim}(v)} = \int_{v=0}^{\infty} P_{I=0}(v) \cdot f(v) dv \qquad (4)$$

where

f(v): wind speed distribution within 10-minute period

$P_{I=0}(v)$: zero turbulence power curve

$\overline{P_{sim}(v)}$: simulated 10-minute average of measured power output

If the wind speed distribution within a 10-minute period is a Gaussian distribution, it is fully determined by the average wind speed and by the turbulence intensity (or standard deviation

of wind speeds within the 10-minute period). Thus, in case of a Gaussian wind speed distribution it is possible to calculate the 10-minute average of the wind turbine power output by formula (4) based on the measured 10-minute average wind speed and the turbulence intensity, provided that at each instant the zero turbulence power curve is followed and that this power curve is known[1]. This means, the power would not have to be measured anymore for the determination of the power curve for a certain reference turbulence intensity once the zero turbulence power curve is known. The determination of the zero turbulence power curve, however, turned out to be complicated. For a practicable application of the method, it must be assumed that within each 10-minute period the same zero turbulence power curve is followed. This assumption may be violated, as the power curve may be dependent on further secondary variables, e.g. on the wind shear. In order to take the measured power output within a 10-minute period into account for the derivation of the turbulence normalised power output (even after determining the zero turbulence power curve) the following procedure is applied:

1. Application of formula (4) with the wind speed distribution as measured in the 10-minute period. If only the average wind speed and standard deviation is recorded per 10-minute period during the power curve test, a Gaussian distribution may be assumed.
2. Application of formula (4) with the average wind speed as measured in the 10-minute period, but with the reference turbulence intensity. A Gaussian wind speed distribution is assumed for the determination of the reference wind speed distribution within the 10-minute period. The same zero turbulence power curve than in step 1 is assumed.
3. The normalised 10-mimnute average of the power output is calculated as:

$$\overline{P_{I_{ref}}(v)} = \overline{P(v)} - \overline{P_{sim,I}(v)} + \overline{P_{sim,I_{ref}}(v)} \qquad (5)$$

where

$\overline{P(v)}$: 10-minute average of measured power output

$\overline{P_{sim,I}(v)}$: simulated 10-minute average of measured power output according to formula (4) for the measured wind speed distribution (measured average wind speed $\bar{v}$ and measured turbulence intensity)

$\overline{P_{sim,I_{ref}}(v)}$: simulated 10-minute average of measured power output according to formula (4) for the measured average wind speed $\bar{v}$ and for the reference turbulence intensity $I_{ref}$ by assuming a Gaussian wind speed distribution

Alternatively to formula (5), the following expression can be applied for the power curve normalisation:

$$\overline{P_{I_{ref}}(v)} = \frac{\overline{P(v)}}{\overline{P_{sim,I}(v)}} \cdot \overline{P_{sim,I_{ref}}(v)}$$

This alternative version, however, is problematic if the measured average wind speed is close to the cut-in wind speed of the tested turbine, as then the denominator can become close to zero, and the normalised power curve data tends to have large scatter. Comparisons of

[1] This is the reason, why the here explained model has been called Normal Distribution Model.

normalisation results by applying the alternative formula and formula (5) have led to very similar results in all other wind speed ranges.

A problem of the Normal Distribution Model is the determination of the zero turbulence power curve $P_{I=0}(v)$. In the work reported in reference [6] an initial zero turbulence power curve has been evaluated form the bin averaged measured power curve by the following condition: The bin-averaged measured power curve should result from the zero turbulence power curve by the application of formula (4) for each wind speed bin, while the wind speed distribution applied in formula (4) is a Gaussian wind speed distribution, which is defined by the average measured wind speed and the average measured turbulence intensity per bin. A Newton-solver has been applied for solving this condition. This step is complicated. The so gained initial zero turbulence power curve has then been applied with formula (5) in order to normalise the power curve raw data to a turbulence intensity of zero. The respective bin averaged normalised power curve has been considered as new zero turbulence power curve, and the normalisation process to zero turbulence has been repeated until convergence of the zero turbulence power curve was reached. Sufficient turbulence normalisation has been reached already after the first normalisation of power curve data in all test cases.

## 2.5 Improved Procedure for Determination of the Zero Turbulence Power Curve in Combination with the Normal Distribution Model

An improvement in the determination of the zero turbulence power curve for the Normal Distribution Model has been introduced in the year 2007. Instead of determining the initial zero turbulence power curve on the basis of the bin averaged measured power curve, it has been determined from the power curve raw data. The following condition has been applied for this: The initial zero turbulence power curve has been determined such that the sum of the absolute deviations of the measured power output and simulated power output according to formula (4) over all 10-minute averages was minimised. Again a Newton solver has been applied in order to fulfil the condition.

In a test case, the so initialised Normal Distribution Model has led to a good agreement of power curves measured in different turbulence classes (filtered power curves) and power curves normalised to the same turbulence classes, without applying data filters (Figure 3). The deviation between the measured and normalised power curves is below +/-2 % of the measured power output in the entire wind speed range above 4 m/s which is covered by sufficient data of the measured power curves.

It is pointed out that the determination of the initial zero turbulence power curve by the use of the power curve raw data seems to be more appropriate than by determining it from the bin averaged measured power curve. This procedure has also the advantage that no certain shape of the wind speed distribution within the 10-minute periods has to be assumed for the determination of the initial zero turbulence power curve, so far all measured wind speed samples are stored during the power curve test. However, the determination of the zero turbulence power curve from the power curve raw data by the application of a Newton solver is even more complicated than evaluating it form the bin averaged measured power curve.

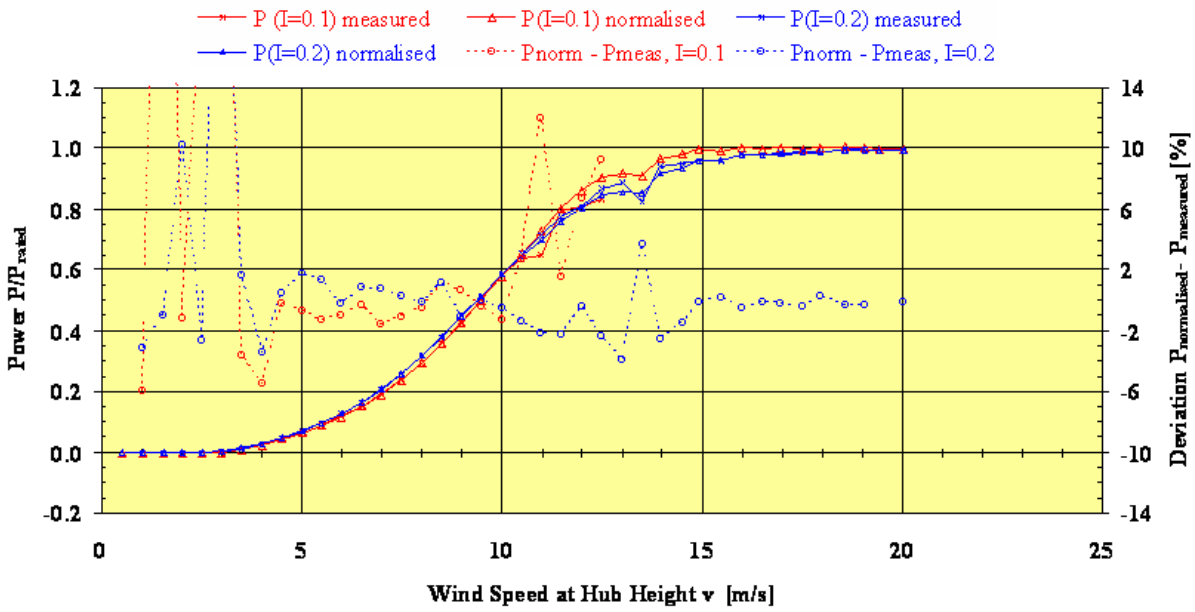


Figure 3: Measured power curves of a wind turbine filtered to the two turbulence intensity classes 7.5-12.5 % and 17.5-22.5% compared with unfiltered power curves normalised to the same turbulence classes by the application of the Normal Distribution Model (initial zero turbulence power curve derived from measured power curve raw data).

## 2.6 Simplified Procedure for Determination of the Zero Turbulence Power Curve in Combination with the Normal Distribution Model

A breakthrough for the determination of the initial zero turbulence power curve has been reached in the year 2008. The author of this report had to estimate power curves of future design wind turbines. In this frame, it has been figured out that the power curve of modern wind turbines is to a high degree determined by the following parameters:

- Rated power (for a certain turbulence intensity)
- Rotor swept area
- Maximum power coefficient $c_P$ (for a certain turbulence intensity)
- Turbulence intensity (wind speed dependent)
- Air density
- Cut-in wind speed (for a certain turbulence intensity)

The key assumption of the theory for determining the power curves on the basis of these parameters is the same then used for the Normal Distribution Model:

**The wind turbine follows during each instant the same power curve.**

This power curve is here called initial zero turbulence power curve.

The initial zero turbulence power curve is determined as follows:

- Assumption of zero power output below cut-in wind speed
- Assumption of constant power coefficient $c_P$ equal to the maximum power coefficient $c_{P,max}$ between cut-in wind speed and rated wind speed.

- Calculation of rated wind speed $v_{rated}$ from rated power $P_{rated}$, rotor swept area A, maximum power coefficient $c_{P,max}$ and air density $\rho$ by: $v_{rated} = \left( \frac{2 \cdot P_{rated}}{\rho \cdot c_{P,max} \cdot A} \right)^{\frac{1}{3}}$.
- Power output equal to rated power for wind speeds above rated wind speed $v_{rated}$.

In order to estimate the power output of a wind turbine with the above given characteristics for a 10-minute average wind speed $\overline{v}$ and a turbulence intensity I, formula (4) is applied with the above described initial zero turbulence power curve by assuming a Gaussian wind speed distribution with average wind speed $\overline{v}$ and the wind speed standard deviation $\sigma = I \cdot \overline{v}$. This is performed for the entire operational wind speed range of the wind turbine. The result is an almost realistic power curve of the wind turbine. The initial zero turbulence power curve should first be applied with the rated wind speed, cut-in wind speed and maximum power coefficient assumed for non-zero turbulence conditions (target turbulence intensity). However, it must be considered that these three parameters are dependent on the turbulence intensity. Thus, the calculated power curve for the target turbulence intensity will in the first step have a rated power, cut-in wind speed and maximum power coefficient which is deviating from the target values. Consequently, the rated power, cut-in wind speed and maximum power coefficient of the initial zero turbulence power curve should be adjusted such that the resulting calculated power curve for the target turbulence intensity has the target values for the rated power, cut-in wind speed and maximum power coefficient. Best experience has been gained by first adjusting the rated power, then the cut-in wind speed and then the maximum power coefficient of the initial zero turbulence power curve. This adjustment should be repeated until all three parameters converge. Convergence is normally reached after one or two iterations.

The above model can be applied in order to simulate measured bin averaged power curves by setting the rated power equal to the maximum measured power (at the referring bin averaged turbulence intensity), the cut-in wind speed equal to the measured cut-in wind speed (at the referring bin averaged turbulence intensity) and the maximum power coefficient equal to the maximum measured power coefficient (at the referring bin averaged turbulence intensity). Figure 4 shows a case where the measured and the respective simulated power curve agree well. The deviation of the simulated and the measured power curves in terms of the annual energy production is below 1 % for the entire range of annual average wind speeds above 4.5 m/s (Figure 5). Such good agreement has been observed in many test cases. In the shown example, the measured turbulence intensity was quite high. Consequently, the simulated initial zero turbulence power curve has a much lower maximum power coefficient and higher cut-in wind speed than the measured power curve, and the rated power of the initial zero turbulence power curve is about 0.3 % higher than the maximum power output according to the measured bin-averaged power curve.

As the above model is simple to apply for the simulation of measured power curves and as it provides reasonably accurate results, it is proposed to be applied for the determination of the initial zero turbulence power curve in the frame of power curve turbulence normalisation with the Normal Distribution Model. Even in case of larger deviations between the measured and the simulated power curve, the model is believed to be sufficiently accurate for determining the initial zero turbulence power curve, because the final zero turbulence power curve is gained from a normalisation of the power curve raw data to zero turbulence intensity anyhow (based on the initial zero turbulence power curve, see chapter 2.4).

There are a variety of other applications for the above described simulation model, for instance:

- Adjustment of wind turbine power curves to different rated power values (e.g. noise reduction, power limitation, calculation of effect of increased rated power)
- Study of improvements in annual energy production by increasing the maximum power coefficient
- Plausibility check of power curves
- Simulation of turbulence effects on power curves

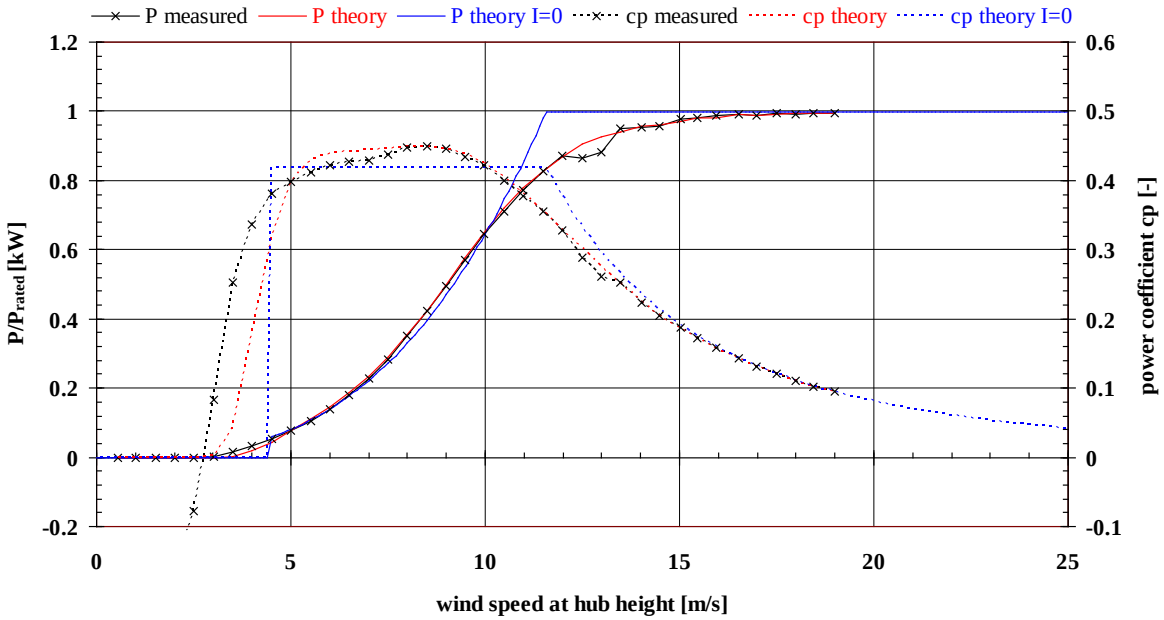


Figure 4: Comparison of a measured bin averaged power curve (black), the referring initial zero turbulence power curve (blue) and the simulated measured power curve (red).

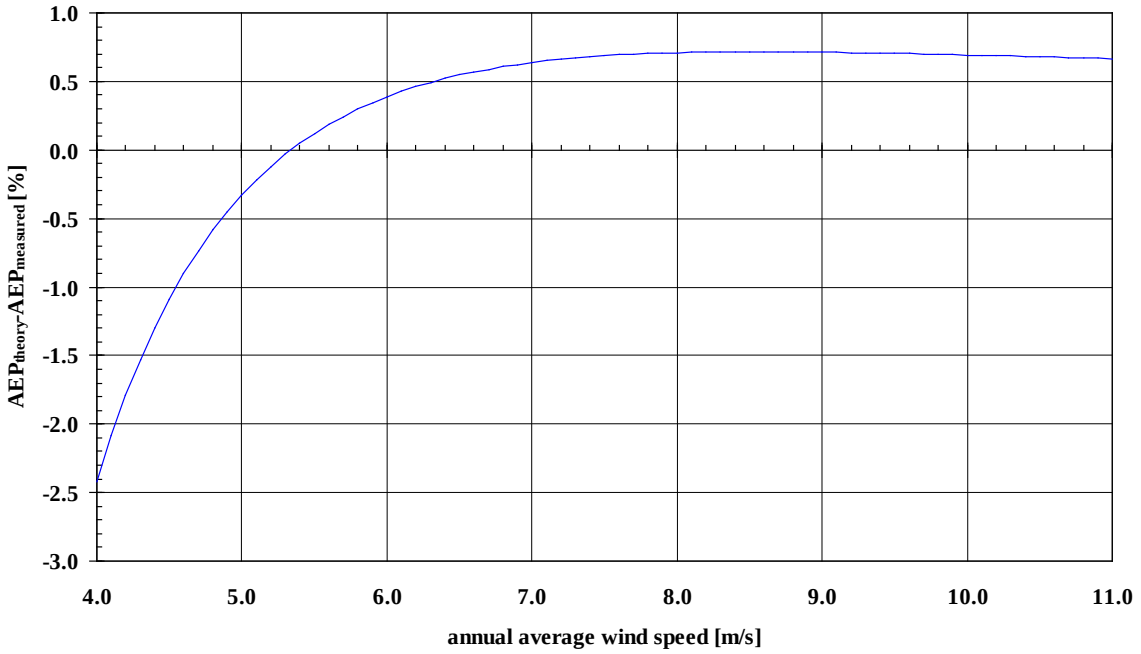


Figure 5: Comparison of a measured bin averaged power curve and the referring simulated measured power curve in terms of AEP for different annual average wind speeds (assumption: Rayleigh wind speed distribution).

# 3 Proposed Procedure for Normalisation of Measured Power Curves According to the Turbulence Intensity

Measured wind turbine power curve are influenced by the turbulence intensity. A significant part of the turbulence intensity effect is due to the averaging of the measured power output and the measured wind speed over 10-minute periods. This effect shall be removed from the measurements by normalising the power curve raw data to a reference turbulence intensity. The reference turbulence intensity shall be defined prior to the power curve test. It may be defined in dependence of the wind speed at hub height. If not defined otherwise, a reference turbulence intensity of 10 % shall be applied.

## 3.1 Turbulence Normalisation Procedure

It is assumed for the turbulence normalisation that the wind turbine follows at each instant a certain power curve, here defined as zero turbulence power curve. The determination of the zero turbulence power curve is described in chapter 3.2.

Based on the zero turbulence power curve and the wind speed distribution within a 10-minute period, the 10-minute average of the wind turbine power output can be simulated by the following formula:

$$\overline{P_{sim}(v)} = \int_{v=0}^{\infty} P_{I=0}(v) \cdot f(v) dv \qquad (6)$$

where

f(v): wind speed distribution within 10-minute period

$P_{I=0}(v)$: zero turbulence power curve

$\overline{P_{sim}(v)}$: simulated 10-minute average of measured power output

Formula (4) shall be applied for all power curve raw data with:

1. The wind speed distribution as measured in the 10-minute period. A Gaussian distribution f(v) may be assumed, which is fully determined by the average wind speed and the standard deviation of the wind speed as recorded within the 10-minute period. In case of a wind turbine with active power control, formula (6) shall be evaluated for the air density corrected wind speed. Then, the standard deviation of wind speeds to be applied for the definition of the Gaussian wind speed distribution must be calculated as product of the measured turbulence intensity (measured standard deviation of wind speed divided by the average wind speed) and the air density corrected average wind speed.
2. A Gaussian wind speed distribution with the average wind speed equal to the measured 10-minute average of the wind speed and a standard deviation equal to the product of the 10-minute average of the measured wind speed and the reference turbulence intensity for the referring average wind speed. In case of a wind turbine with active power control, formula (6) shall be evaluated for the air density corrected wind speed.

The measured power output is then normalised to the reference turbulence intensity by the following formula:

$$\overline{P_{I_{ref}}(v)} = \overline{P(v)} - \overline{P_{sim,I}(v)} + \overline{P_{sim,I_{ref}}(v)} \quad (7)$$

where

$\overline{P(v)}$: 10-minute average of measured power output

$\overline{P_{sim,I}(v)}$: simulated 10-minute average of measured power output according to step 1: formula (6) applied for the measured wind speed distribution (measured average wind speed $\bar{v}$ and measured turbulence intensity)

$\overline{P_{sim,I_{ref}}(v)}$: simulated 10-minute average of measured power output according to step 2: formula (6) applied for the measured average wind speed $\bar{v}$ and for the reference turbulence intensity $I_{ref}$ by assuming a Gaussian wind speed distribution

In case of a wind turbine with passive power control, formula (7) must be applied with the air density corrected measured power output.

The power coefficient raw data (as applied only for graphical demonstration of the measurements) shall be calculated on the basis of the power output normalised to the reference turbulence intensity. In case of a wind turbine with passive power control the power coefficient raw data shall be calculated on the basis of the power output normalised to the reference turbulence intensity and on the basis of the reference air density (not on basis of the measured air density).

### 3.2 Determination of the Zero Turbulence Power Curve

An initial zero turbulence power curve is calculated on the basis of the measured bin-averaged power curve normalised according to the air density, but not normalised according to the turbulence intensity. The initial zero turbulence power curve is determined as a first approach as follows (see also illustration in Figure 6):

- Assumption of zero power output below cut-in wind speed. As a first approach, the cut-in wind speed is set to the average wind speed of the wind speed bin, where the measured power output reaches at least 0.1 % of the rated power.
- Assumption of constant power coefficient $c_P$ equal to the maximum power coefficient $c_{P,max}$ between cut-in wind speed and rated wind speed. This assumption is equal to an increase of the power output with the third power of the wind speed. The initial zero turbulence power curve shall be calculated with this assumption between the cut-in wind speed and the rated wind speed in increments of at least 0.1 m/s. As a first approach, the maximum power coefficient $c_{P,max}$ shall be set to the maximum power coefficient of the measured bin-averaged power curve.
- Calculation of rated wind speed $v_{rated}$ from rated power $P_{rated}$, rotor swept area A, maximum power coefficient $c_{P,max}$ and air density $\rho$ by: $v_{rated} = \left( \frac{2 \cdot P_{rated}}{\rho \cdot c_{P,max} \cdot A} \right)^{\frac{1}{3}}$. As a first approach, the rated power is set to the highest bin-averaged power output of all wind speed bins.

- Power output equal to rated power for wind speeds above rated wind speed $v_{rated}$. As a first approach, the rated power is set to the highest bin-averaged power output of all wind speed bins of the measured power curve. This power output shall be assumed for wind speeds far above cut-off wind speeds (e.g. 100 m/s) for the definition of the initial zero turbulence power curve.

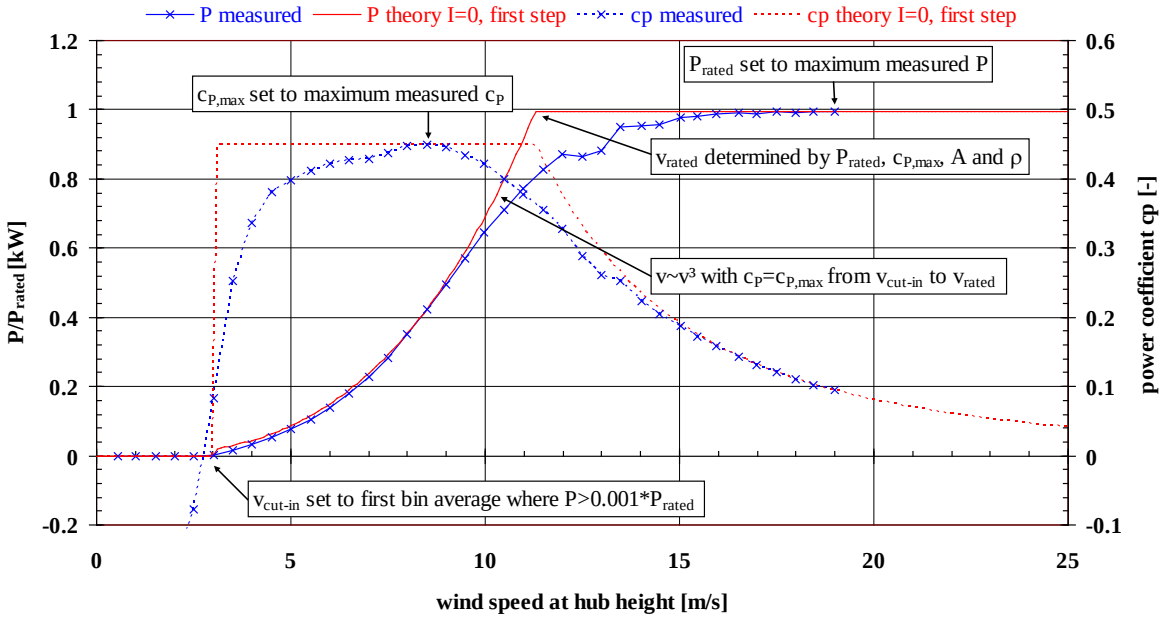


Figure 6: First approch for initial zero turbulence power curve

In the next step, the rated power, the cut-in wind speed and the maximum power coefficient of the initial zero turbulence power curve shall be adjusted because these three parameters are dependent on the turbulence intensity and because values for these parameters as observed for the measured turbulence intensity have been applied in the previous step instead the values corresponding to the turbulence intensity of zero. A bin average of the measured turbulence intensity as function of the measured wind speed shall be performed. In case of a wind turbine with active power control, the turbulence intensity shall be bin averaged according to the air density corrected wind speed.

The initial zero turbulence power curve shall be integrated over a Gaussian wind speed distribution according to formula (6) with the average wind speed equal to the bin average of the measured power curve and with the standard deviation calculated as product of the bin-averaged wind speed and the bin averaged turbulence intensity. The air density corrected wind speed shall be applied in case of a wind turbine with active power control. By this, the measured power curve shall be simulated for each wind speed bin, while the simulated power curve refers to exactly the same wind speed bins than the measured power curve. The rated power, the cut-in wind speed and the maximum power coefficient of the initial zero turbulence power curve shall then be adjusted as follows:

1. The rated power shall be adjusted such that the maximum power of the simulated power curve fits the maximum bin averaged power of the measured power curve.

2. The cut-in wind speed shall be adjusted such that the cut-in wind speed of the simulated power curve fits the cut-in wind speed of the bin averaged measured power curve. Cut-in wind speed is for both power curves defined as lowest wind speed bin where the power output reaches at least 0.1 % of the rated power.
3. The maximum power coefficient shall be adjusted such that the maximum power coefficient of the simulated power curve fits the maximum power curve of the measured power curve

Steps 1. to 3. shall be repeated in the given order until the three parameters converge. Sufficient convergence is normally reached after the first or second iteration. Figure 7 illustrates how the adjustments change the initial zero turbulence power curve from the first step.

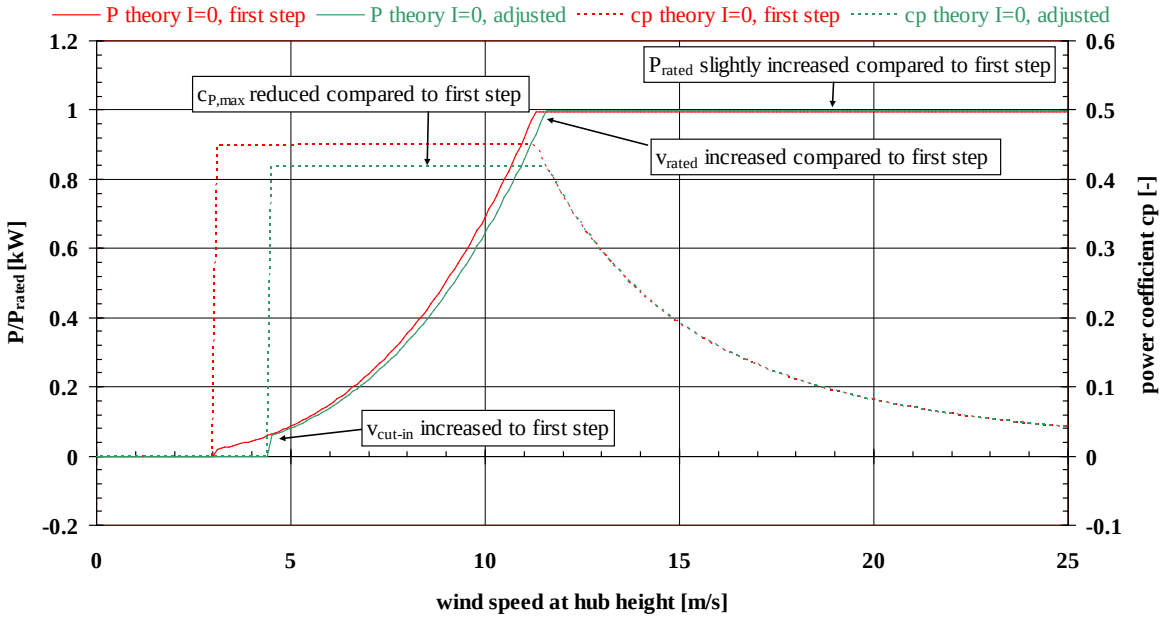


Figure 7: adjusted initial zero turbulence power curve (green) compared to first approach (red)

The zero turbulence power curve shall then be determined by applying the raw data normalisation process described in chapter 3.1 with the zero turbulence power curve set to the initial zero turbulence power curve in equation (6) and by assuming a turbulence intensity of zero (constant wind speed during 10-minute period). The final zero turbulence power curve is gained by bin-averaging the so normalised power curve raw data. This bin averaged power curve shall be extended with the power output of the highest bin to wind speeds far above cut-off wind speeds (e.g. 100 m/s) when applying formulas (6) and (7) for turbulence normalisations. Figure 8 illustrates how the final zero turbulence power curve typically compares to the initial zero turbulence power curve.

Figure 8: adjusted initial zero turbulence power curve (green) compared to final zero turbulence power curve (black)

# 4 Test of Turbulence Normalisation Procedure

The turbulence normalisation procedure has been tested with power curve data of the following 3 wind turbines:

- Case A: pitch controlled turbine, high turbulence site, 1-3 MW class
- Case B: pitch controlled turbine, low turbulence site, 5+ MW class
- Case C: stall controlled turbine, medium turbulence intensity, 1-1.5 MW class

Due to reason of confidentiality, the exact types and locations of the test turbines are not named here. All 3 sites are located in flat terrain. Site calibrations did not take place.

The turbulence intensity bin averaged as function of the wind speed at hub height for all three test sites is shown in Figure 9.

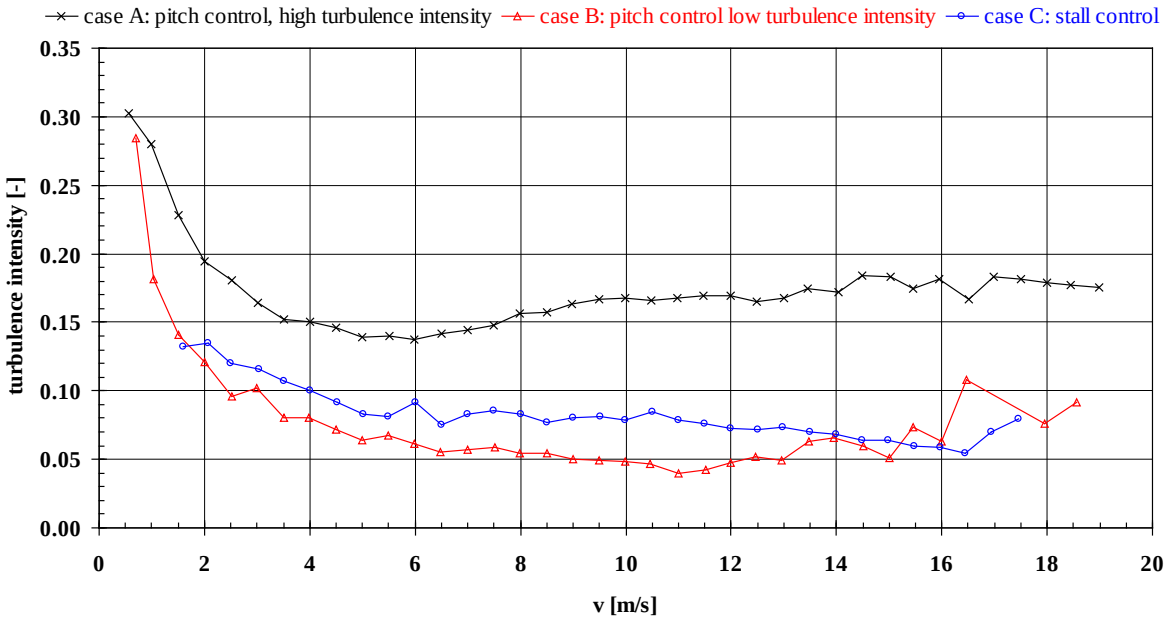


Figure 9: Turbulence intensity as function of wind speed at the 3 test sites.

The turbulence normalisation procedure has been tested as follows:

- Power curves for different turbulence classes have been evaluated by filtering the power curve data. The intention of this filtering is to evaluate the true power curves within the different turbulence classes. Turbulence classes with a width of 5 % turbulence intensity centred around multiple integers of 5 % have been applied (i.e. 0 %-2.5 %, 2.5 %-7.5 %, 7.5 %-12.5 %, 12.5 %-17.5 %, 17.5 %-22.5 % etc.). The power curves and the turbulence intensities have been bin averaged according to the wind speed for each turbulence class.
- The turbulence normalisation procedure has been applied in order to normalise all (unfiltered) power curve measurement data to the different turbulence classes. The measured bin averages of the turbulence intensity in each turbulence class have been defined as the wind speed dependent reference turbulence intensities in order to make the normalised power curves comparable to the filtered power curves.

- The normalised power curves have been compared with the filtered power curves and with the not normalised power curves in order to evaluate the effectiveness of the normalisation procedure.

Notice: The wind speed distributions within each 10-minute period have been described from the power curve tests by the assumption of Gaussian wind speed distributions as evaluated from the average wind speed and standard deviation of wind speed per 10-minute interval. The true wind speed distribution per 10-minute interval has not been considered for the 3 test cases.

## 4.1 Test Case A: Pitch Controlled Turbine, High Turbulence Site, 1-3 MW Class

### 4.1.1 Case A: Normalisation to I=0 %

At low wind speeds, the filtered power curve is about 20 % below the non-filtered power curve (Figure 11). Here, the data normalisation captures only part of the observed turbulence effect. In the transition region to rated power, the data normalisation leads to a corner of the bin averaged power curve at rated wind speed like it is expected for a pitch controlled turbine.

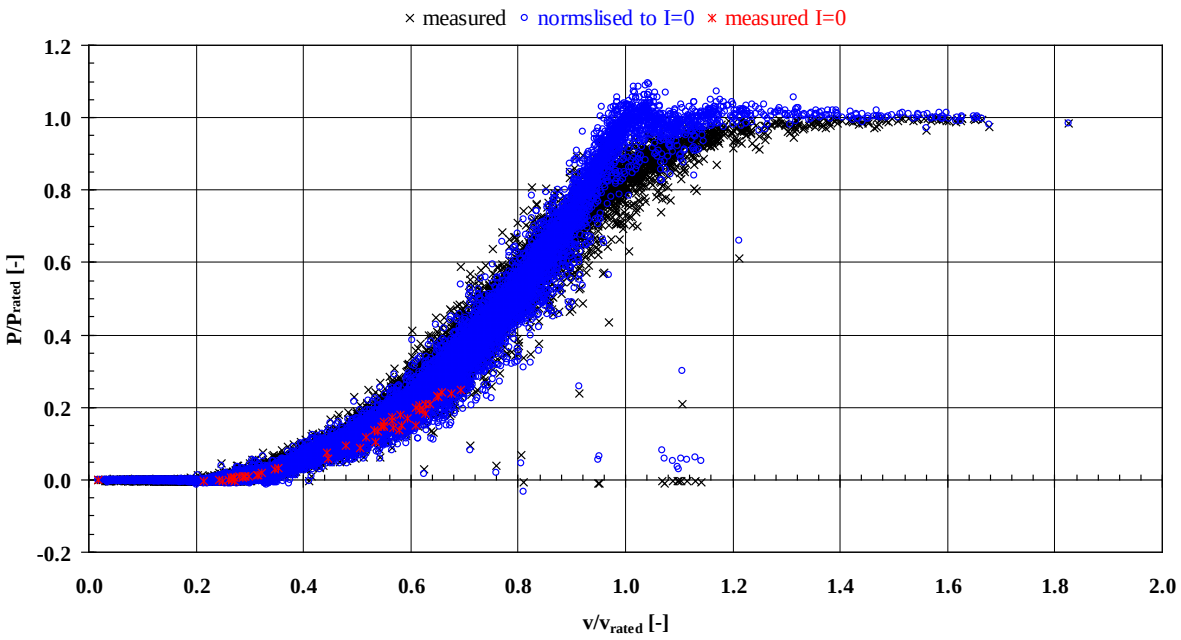


Figure 10: Case A: raw data of measured power curve (black), power curve normalised to turbulence intensity 0 %-2.5 % (blue) and power curve filtered to turbulence intensity range 0 %-2.5 % (red)

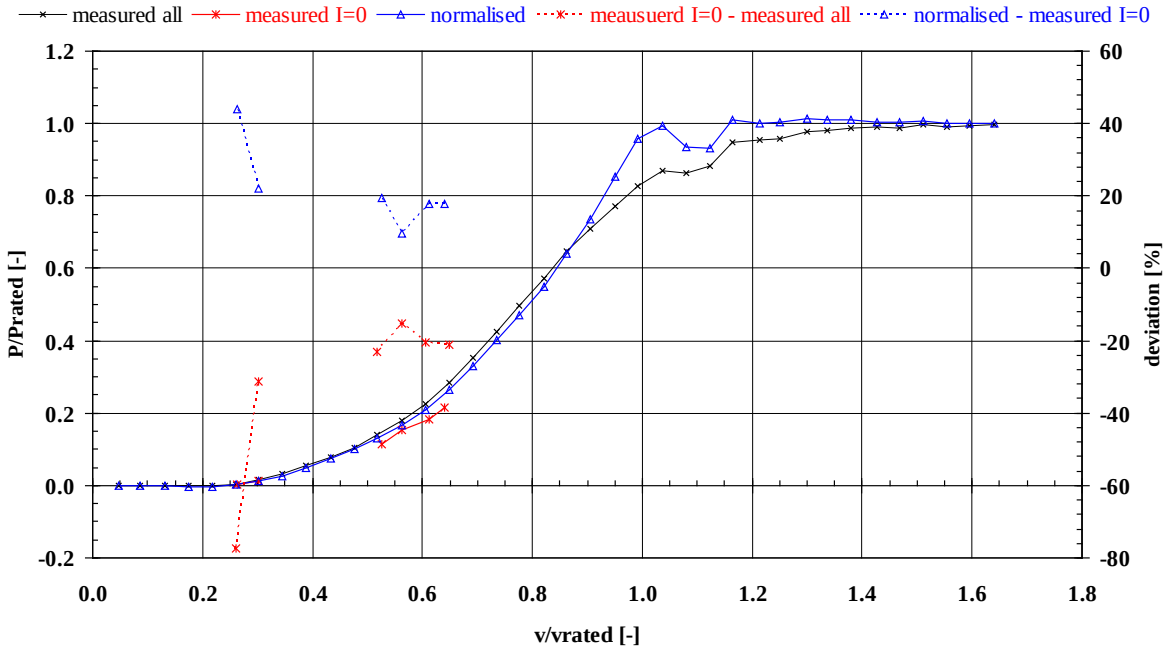


Figure 11: Case A: bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 0 %-2.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 0 %-2.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.1.2 Case A: Normalisation to I=5 %

At low wind speeds, the filtered power curve is about 10 % below the non-filtered power curve (Figure 13). Here, the data normalisation captures about half of the observed turbulence effect.

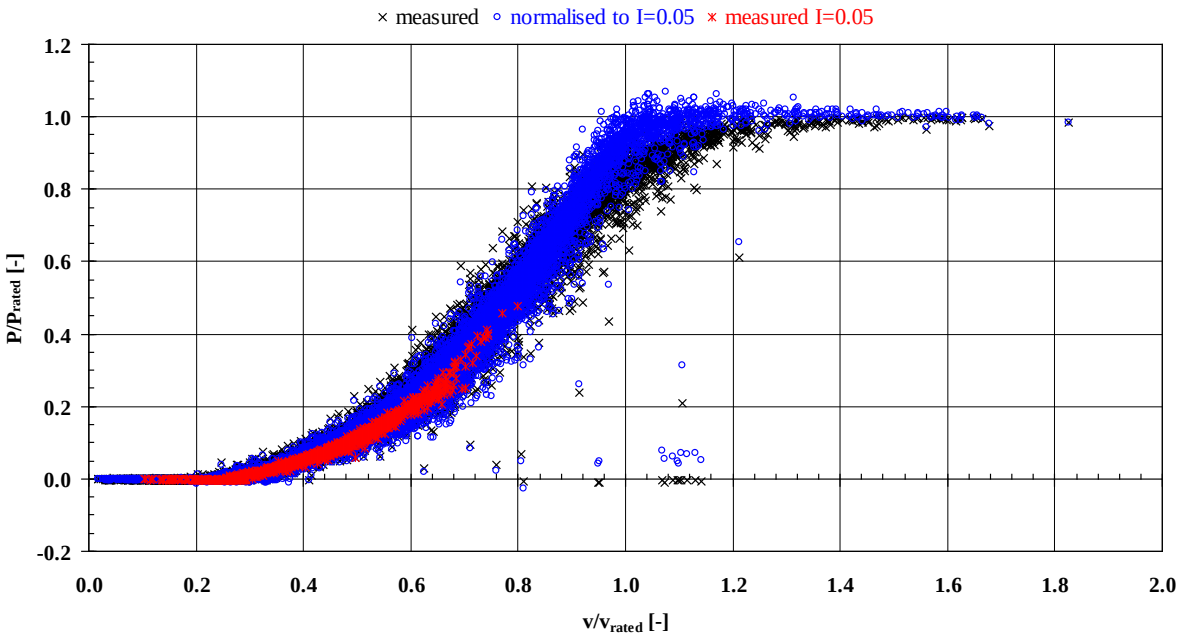


Figure 12: Case A: raw data of measured power curve (black), power curve normalised to turbulence intensity 2.5 %-7.5 % (blue) and power curve filtered to turbulence intensity range 2.5 %-7.5 % (red)

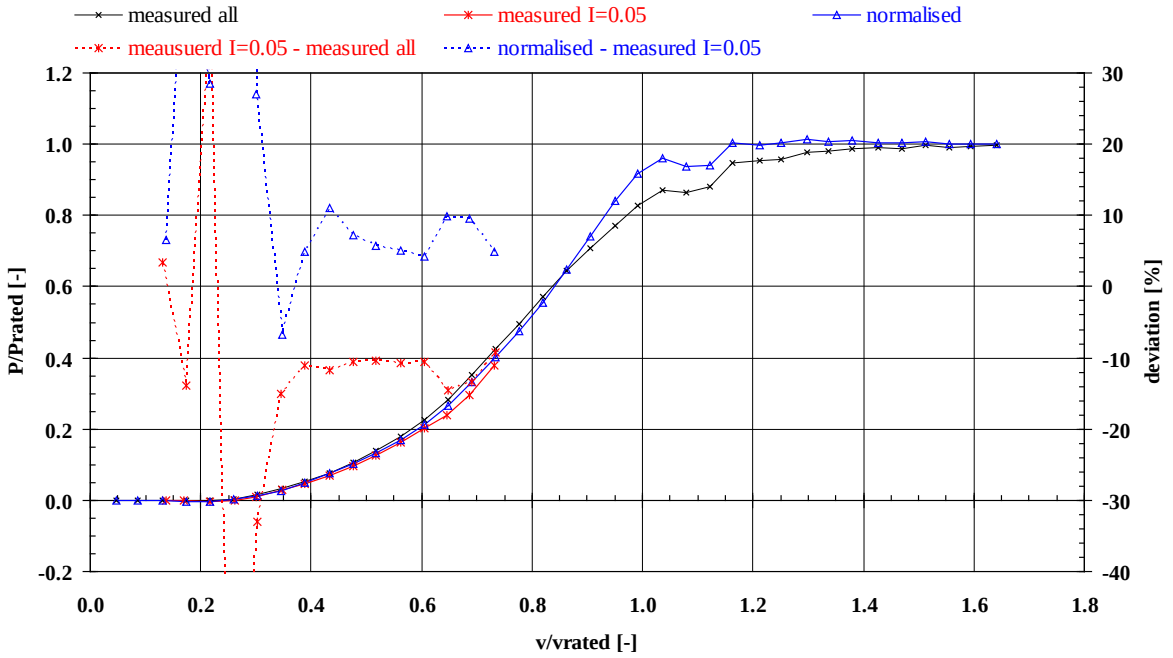


Figure 13: Case A: bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 2.5 %-7.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 2.5 %-7.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.1.3 Case A: Normalisation to I=10 %

At wind speeds above 4 m/s and below 0.8*$v_{rated}$ the normalised and the filtered power curve agree by +/-2 %, although the observed turbulence effect is 2-6 % (Figure 15). Here the normalisation procedure works well. Above 0.8*$v_{rated}$ the normalisation procedure predicts an increase of power compared to the unfiltered power curve, while the filtered power curve is hardly above the unfiltered power curve. However, the filtered power curve does not contain much data in this wind speed range (Figure 14).

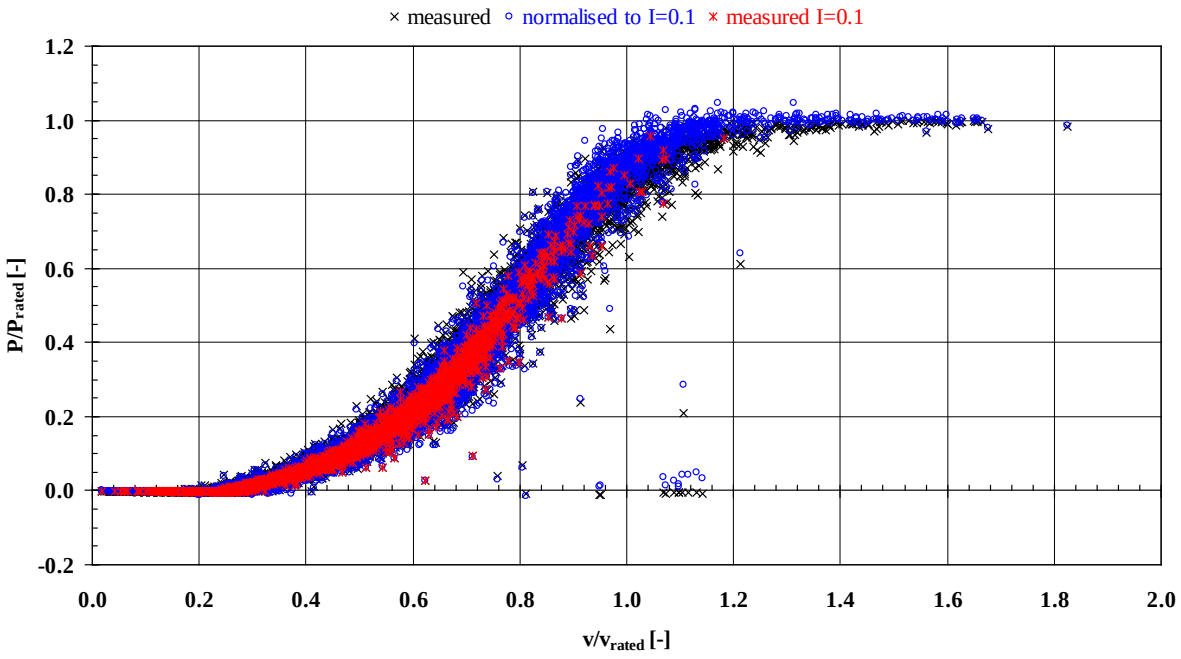


Figure 14: Case A: raw data of measured power curve (black), power curve normalised to turbulence intensity 7.5 %-12.5 % (blue) and power curve filtered to turbulence intensity range 7.5 %-12.5 % (red)

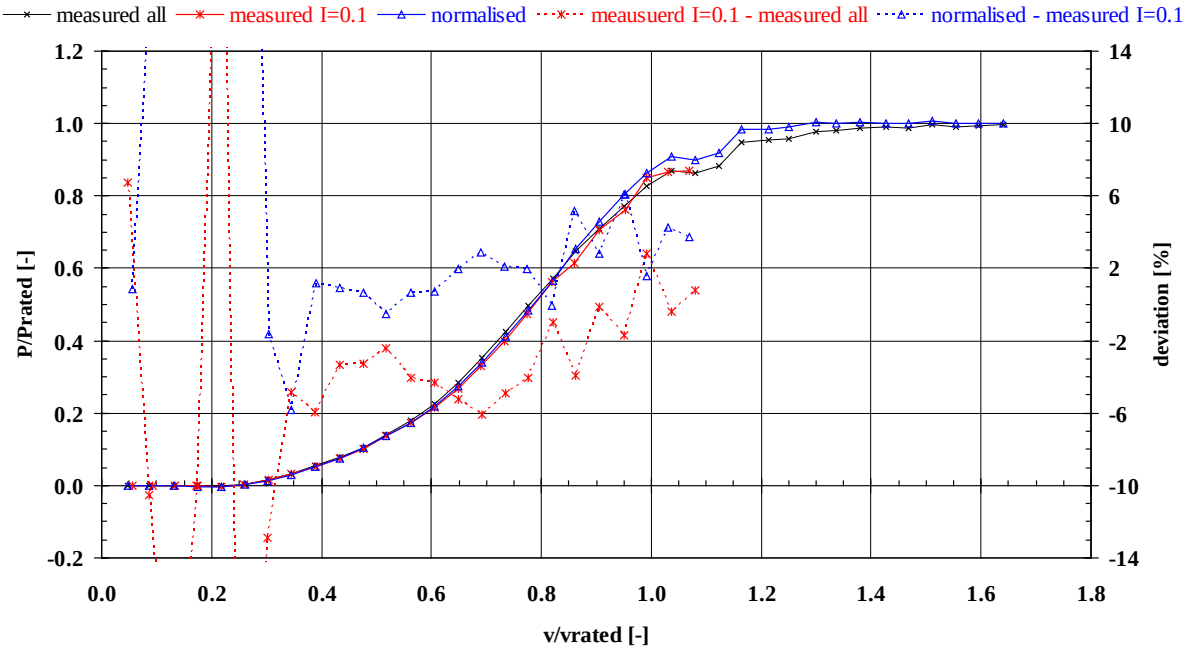


Figure 15: Case A: bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 7.5 %-12.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 7.5 %-12.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.1.4 Case A: Normalisation to I=15 %

The reference turbulence intensity 12.5 %-17.5 % is close to the measured bin averaged turbulence intensity. Consequently, the measured, the normalised and the filtered power curves agree well. The data normalisation has hardly any effect here.

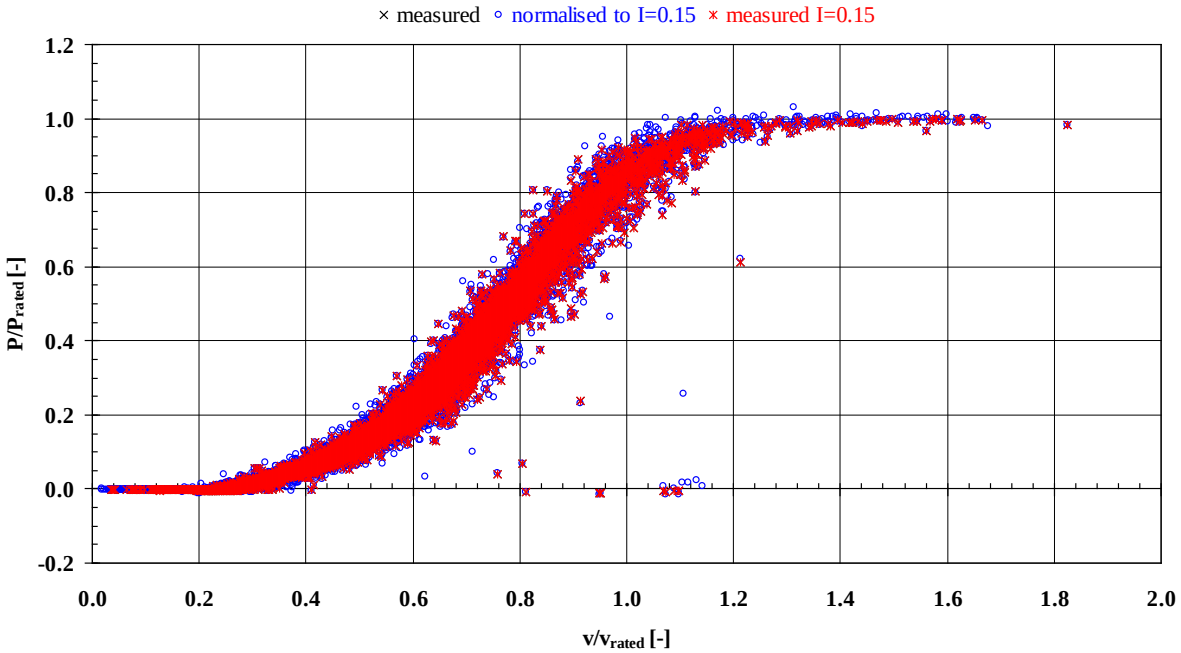


Figure 16: Case A: raw data of measured power curve (black), power curve normalised to turbulence intensity 12.5 %-17.5 % (blue) and power curve filtered to turbulence intensity range 12.5 %-17.5 % (red)

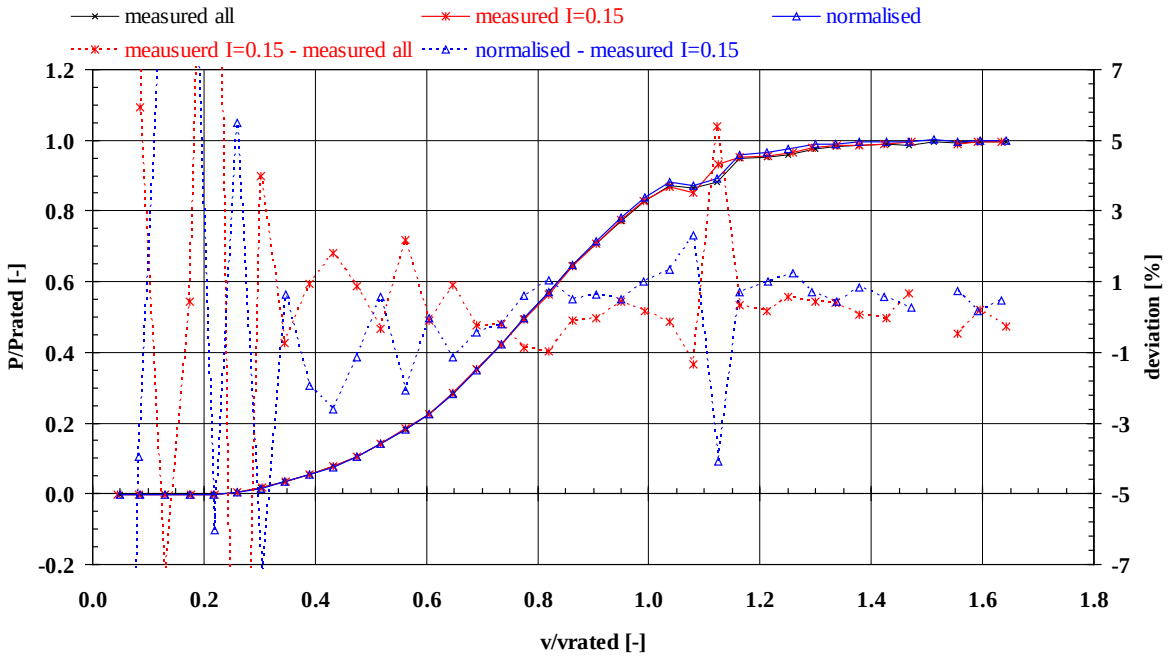


Figure 17: Case A: bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 12.5 %-17.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 12.5 %-17.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.1.5 Case A: Normalisation to I=20 %

The normalised power curve is close to the filtered power curve over almost the entire wind speed range (deviation about +/-2 %), while the filtered power curve is clearly exceeding the unfiltered power curve at low wind speeds (Figure 19). Here, the normalisation works well.

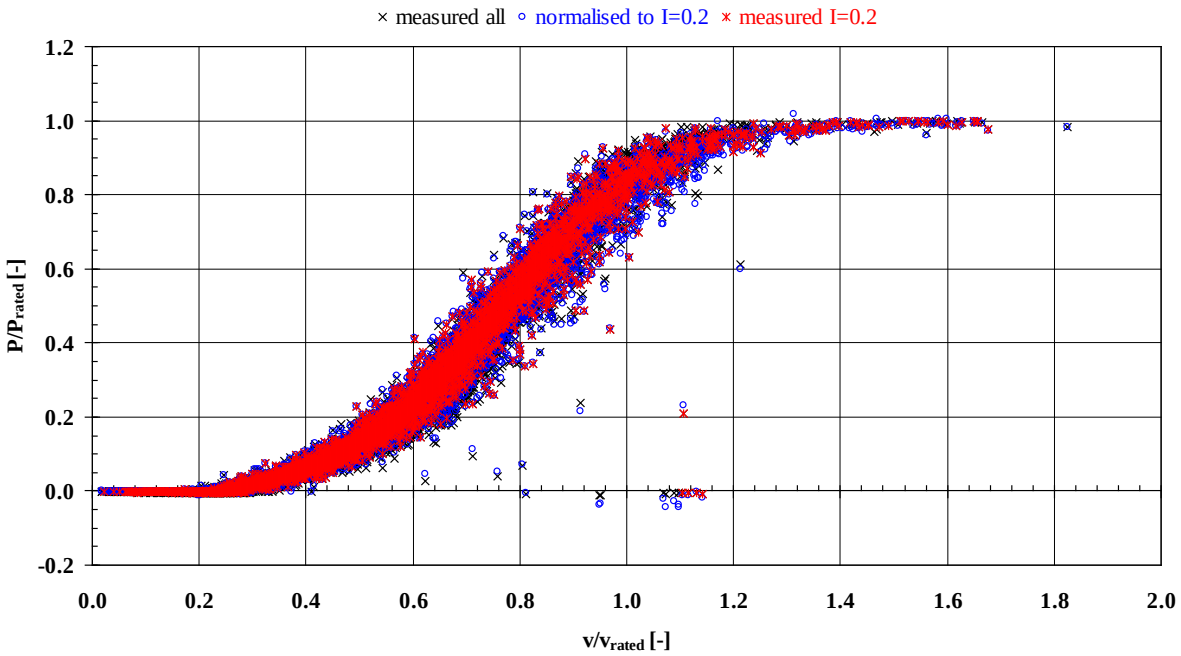


Figure 18: Case A: raw data of measured power curve (black), power curve normalised to turbulence intensity 17.5 %-22.5 % (blue) and power curve filtered to turbulence intensity range 17.5 %-22.5 % (red)

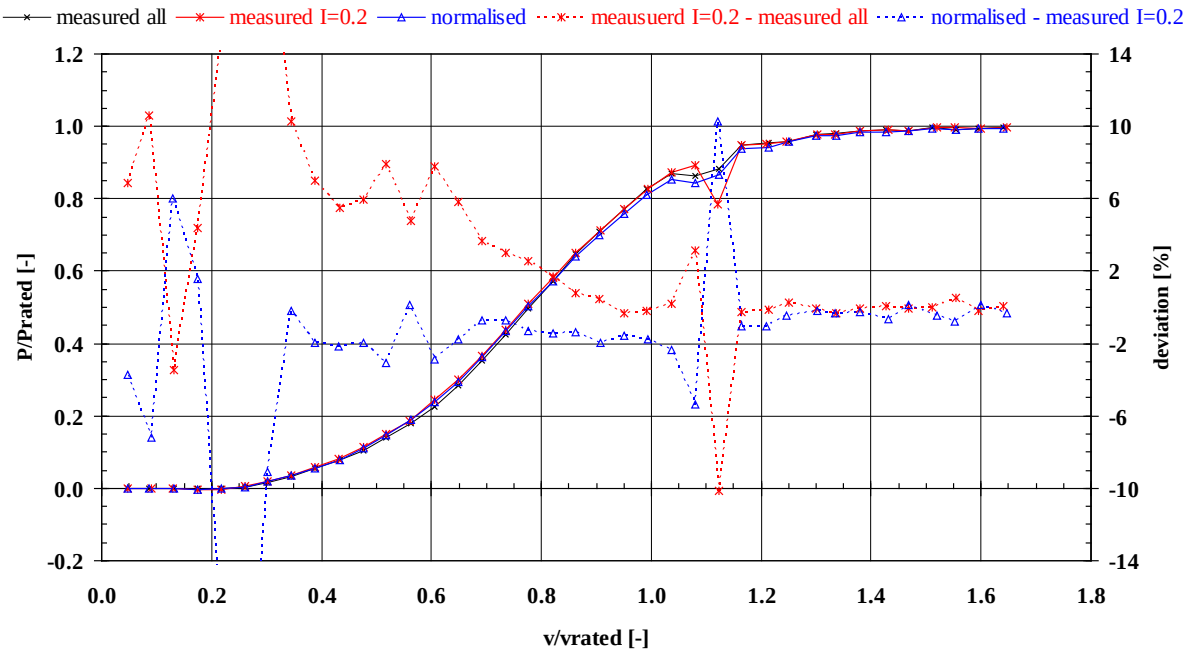


Figure 19: Case A: bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 17.5 %-22.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 17.5 %-22.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.1.6 Case A: Normalisation to I=25 %

The filtered and the normalised power curve agree well over the entire wind speed range (Figure 21) despite large turbulence effects on the power curve (large deviation between unfiltered and filtered power curve). The normalisation procedure works well.

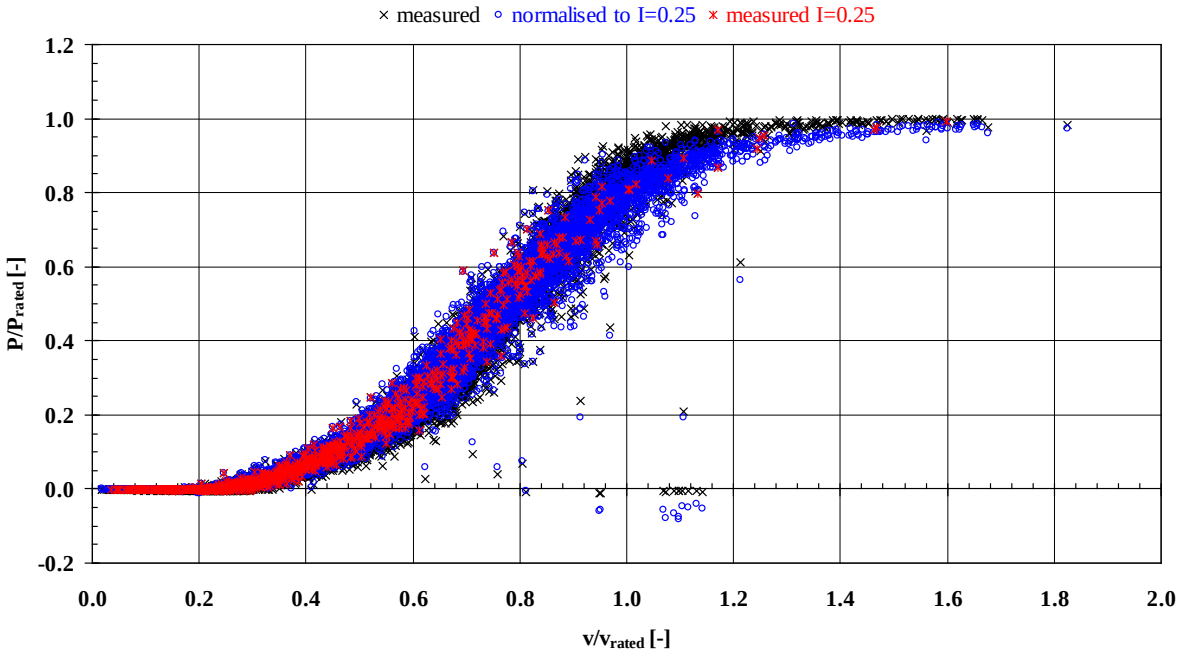


Figure 20: Case A: raw data of measured power curve (black), power curve normalised to turbulence intensity 22.5 %-27.5 % (blue) and power curve filtered to turbulence intensity range 22.5 %-27.5 % (red)

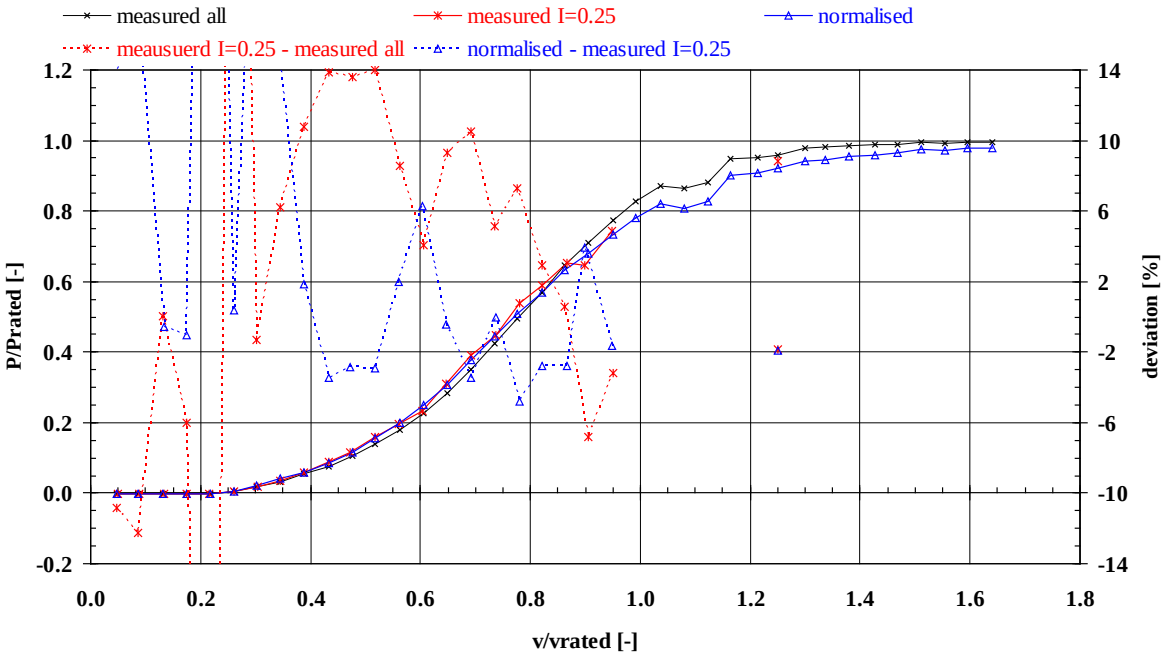


Figure 21: Case A: bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 22.5 %-27.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 22.5 %-27.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.1.7 Case A: Normalisation to I=30 %

Despite very high turbulence effects (filtered power curve at low wind speeds about 20 % above unfiltered power curve), the filtered power curve and the normalised power curve agree well, i.e. the normalisation procedure works well. At high wind speeds, however, no high turbulence measurement data is available to verify the procedure.

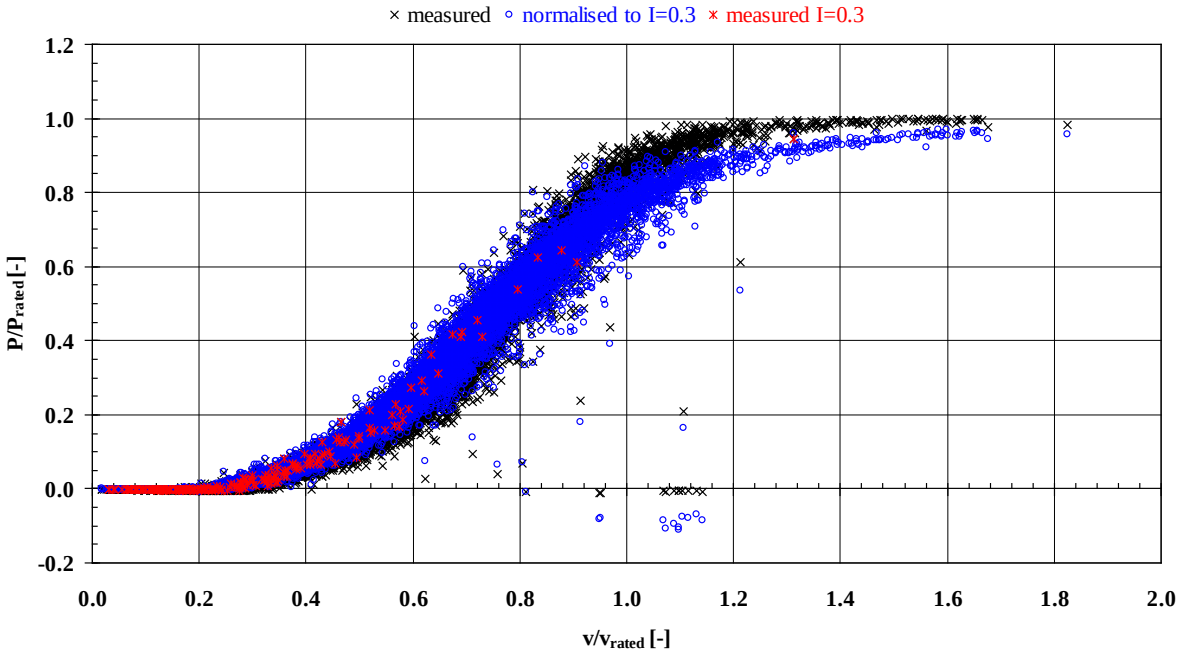


Figure 22: Case A: raw data of measured power curve (black), power curve normalised to turbulence intensity 27.5 %-32.5 % (blue) and power curve filtered to turbulence intensity range 27.5 %-32.5 % (red)

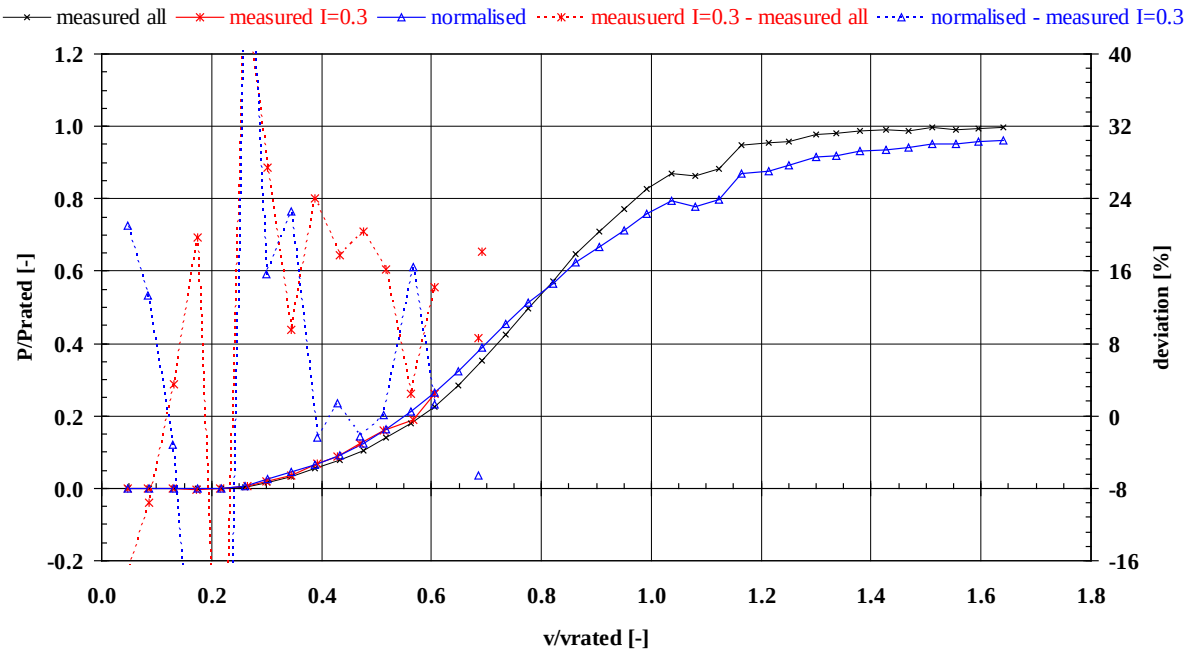


Figure 23: Case A: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 27.5 %-32.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 27.5 %-32.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

## 4.2 Test Case B: Pitch Controlled Turbine, Low Turbulence Site, 5+ MW Class

### 4.2.1 Case B: Normalisation to I=0 %

Below rated power, the normalised power curve is close to the unfiltered power curve, while the filtered power curve is about 5 % below the unfiltered power curve (Figure 25). Here, the normalisation procedure does not capture the observed turbulence effect. At rated power, the normalised power curve has a sharp corner, what is expected for a pitch controlled turbine.

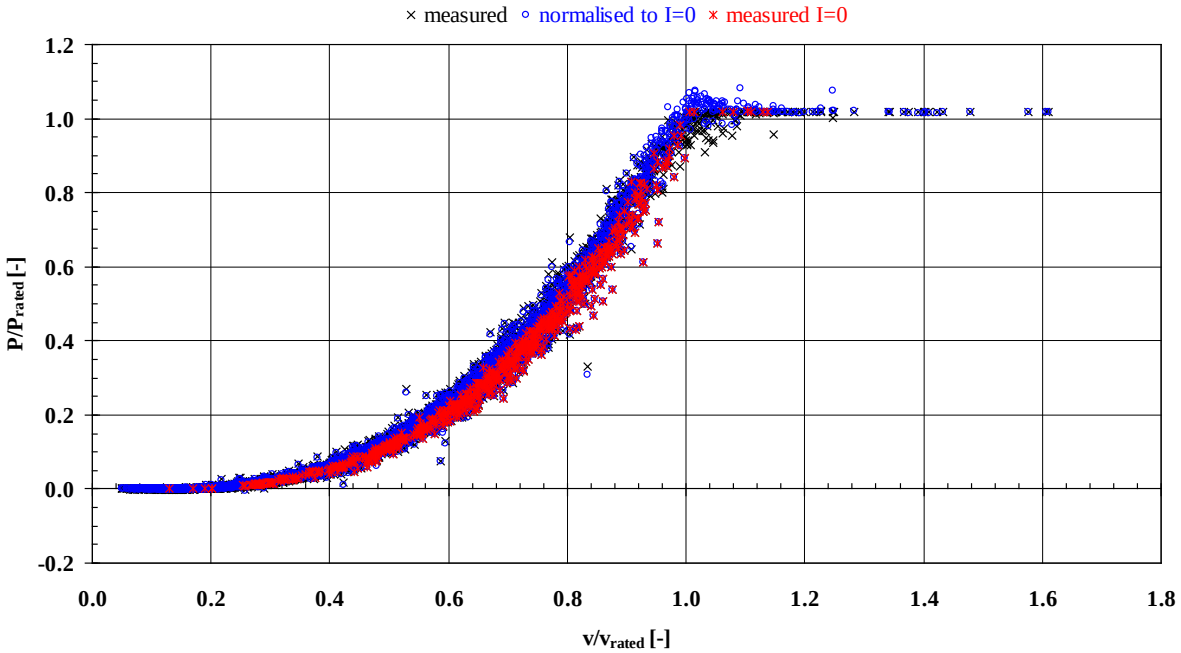


Figure 24: Case B: raw data of measured power curve (black), power curve normalised to turbulence intensity 0 %-2.5 % (blue) and power curve filtered to turbulence intensity range 0 %-2.5 % (red)

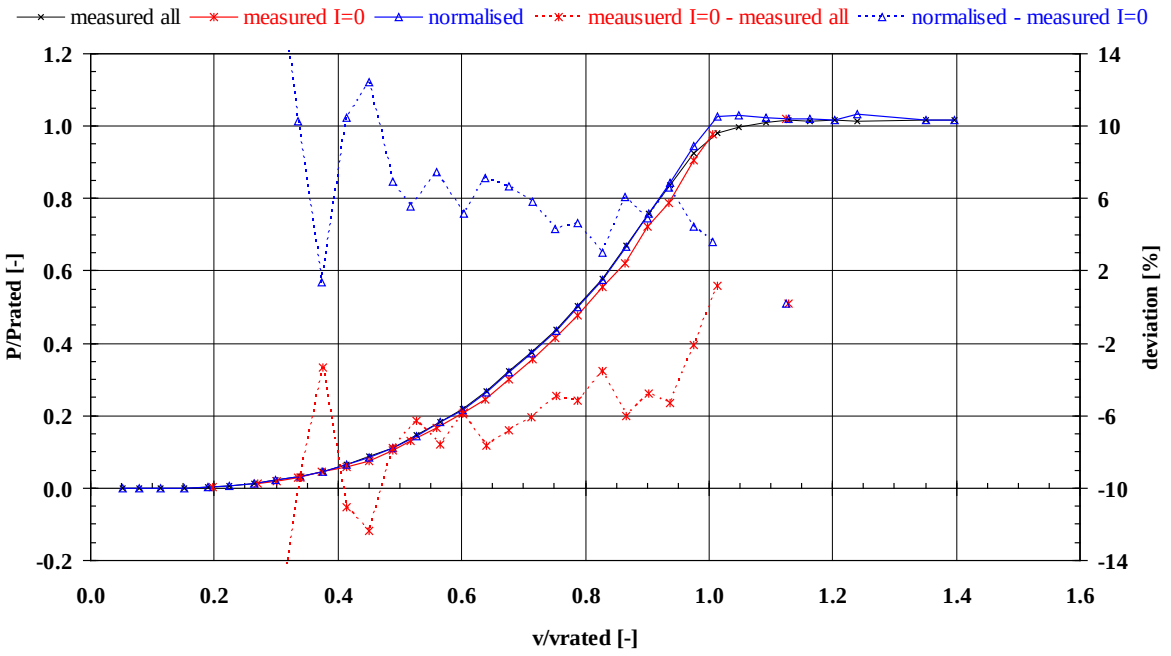


Figure 25: Case B: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 0 %-2.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 0 %-2.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.2.2 Case B: Normalisation to I=5 %

The reference turbulence intensity 2.5 %-7.5 % is close to the measured bin averaged turbulence intensity. Consequently, the measured, the normalised and the filtered power curves agree well. The data normalisation has hardly any effect here.

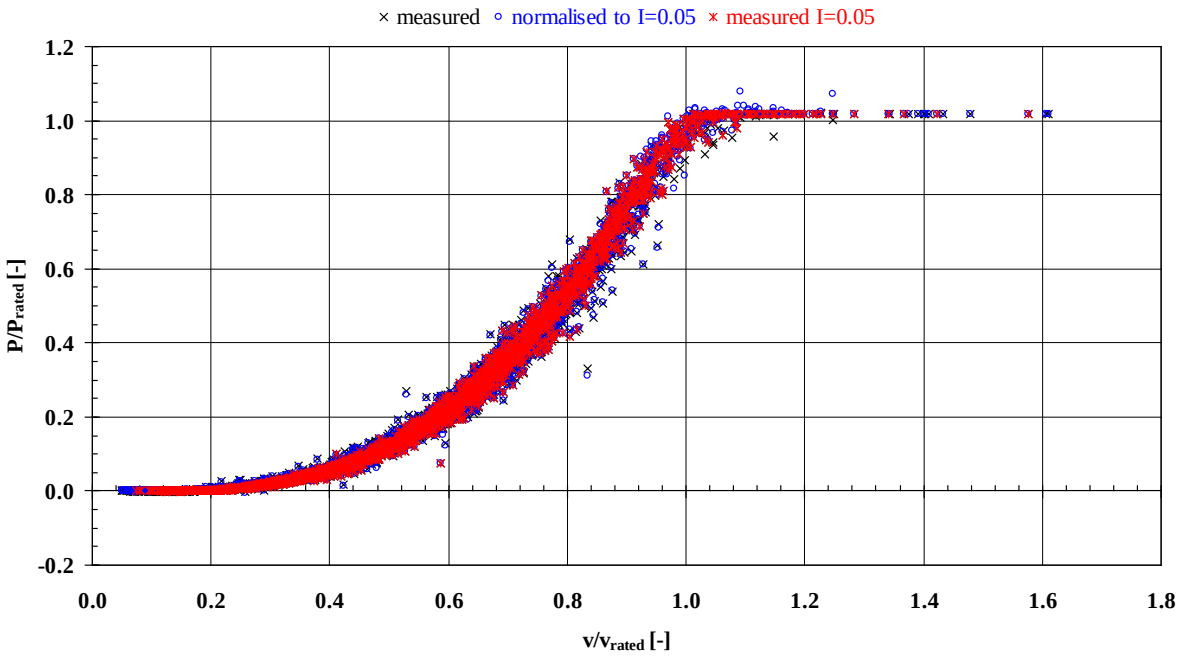


Figure 26: Case B: raw data of measured power curve (black), power curve normalised to turbulence intensity 2.5 %-7.5 % (blue) and power curve filtered to turbulence intensity range 2.5 %-7.5 % (red)

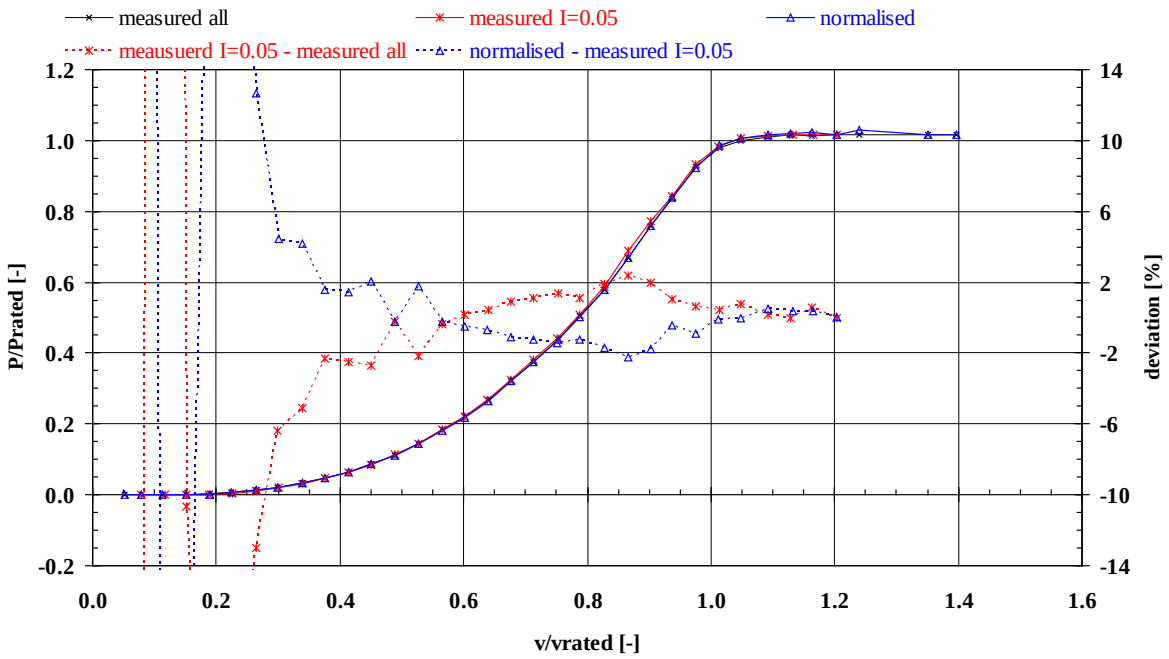


Figure 27: Case B: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 2.5 %-7.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 2.5 %-7.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.2.3 Case B: Normalisation to I=10 %

Below rated power, the normalisation as only a small effect, while the filtered power curve clearly exceeds the unfiltered power curve (Figure 29). The normalisation procedure covers only part of the observed turbulence effect.

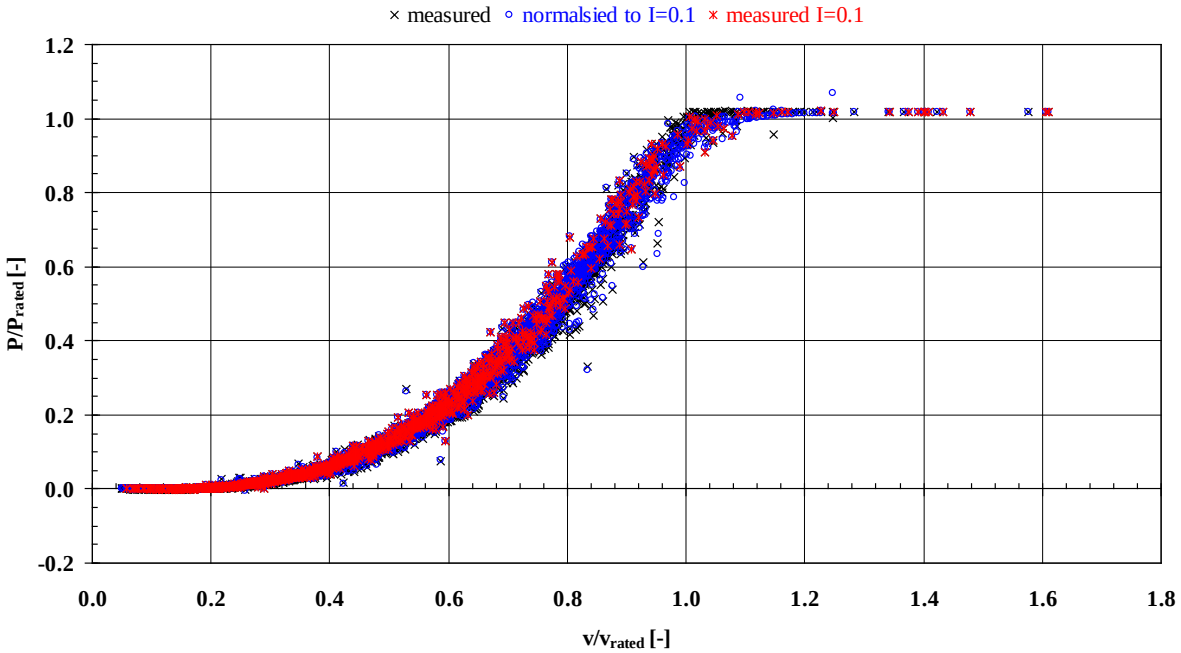


Figure 28: Case B: raw data of measured power curve (black), power curve normalised to turbulence intensity 7.5 %-12.5 % (blue) and power curve filtered to turbulence intensity range 7.5 %-12.5 % (red)

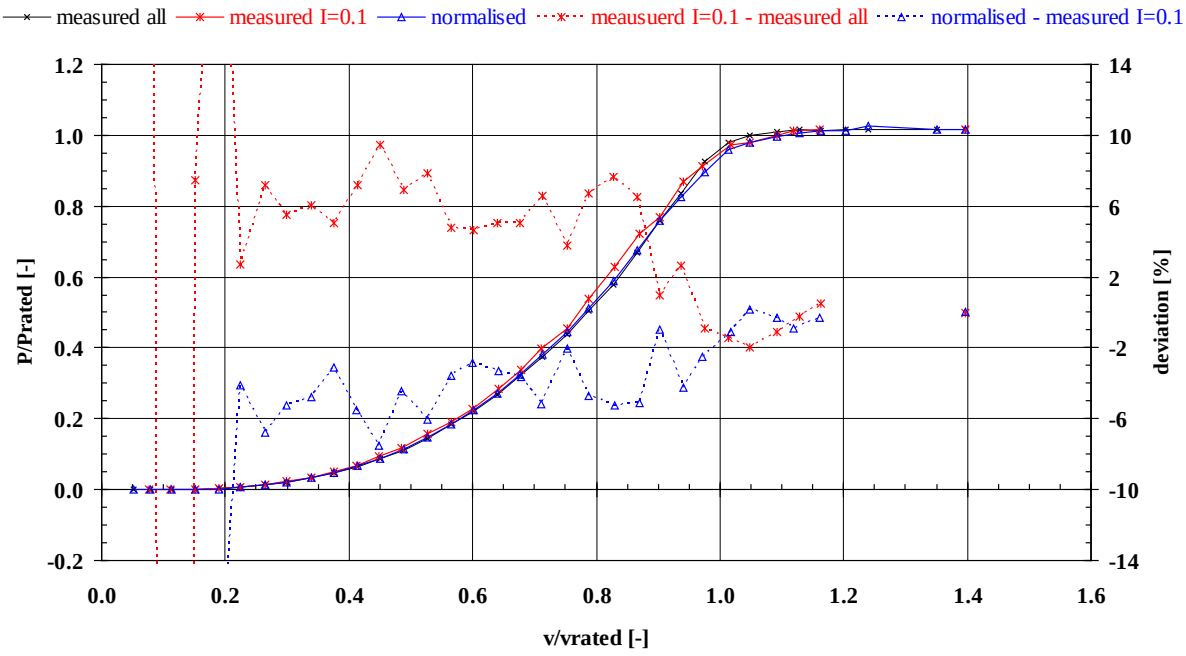


Figure 29: Case B: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 7.5 %-12.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 7.5 %-12.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.2.4 Case B: Normalisation to I=15 %

At low wind speeds, the filtered power curve is almost 20 % above the unfiltered power curve. The normalisation procedure covers about half of this effect (Figure 31). There are only a few measured values of the filtered power curve in the transition region to rated power. These values are well in line with the normalised power curve data (Figure 30).

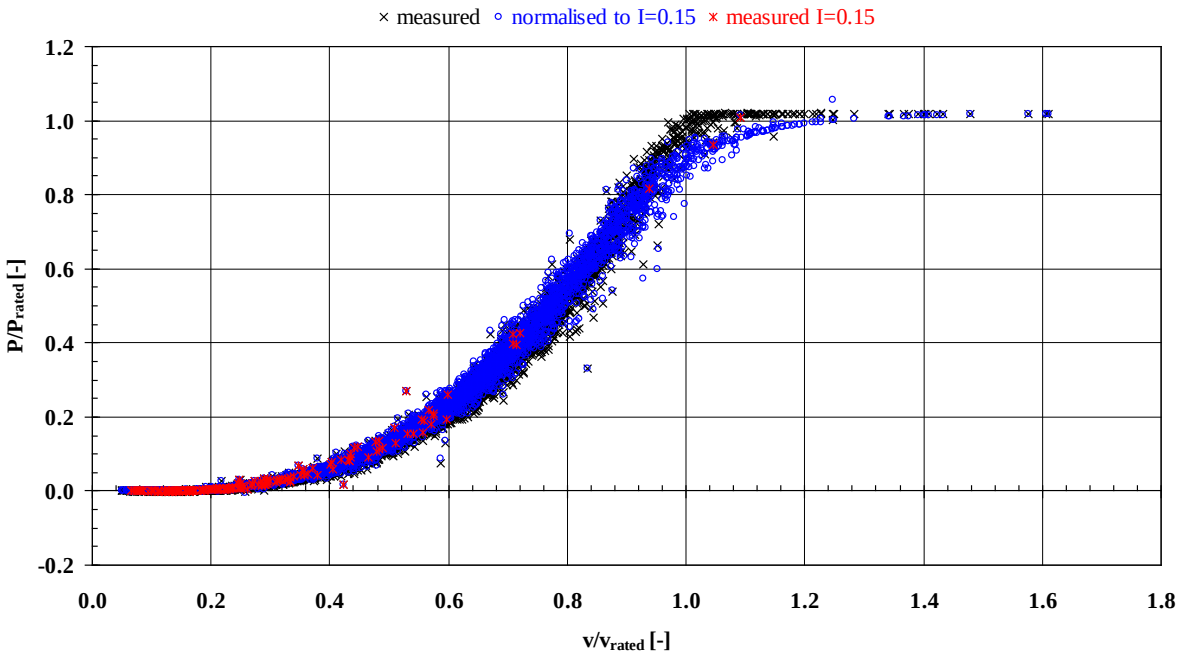


Figure 30: Case B: raw data of measured power curve (black), power curve normalised to turbulence intensity 12.5 %-17.5 % (blue) and power curve filtered to turbulence intensity range 12.5 %-17.5 % (red)

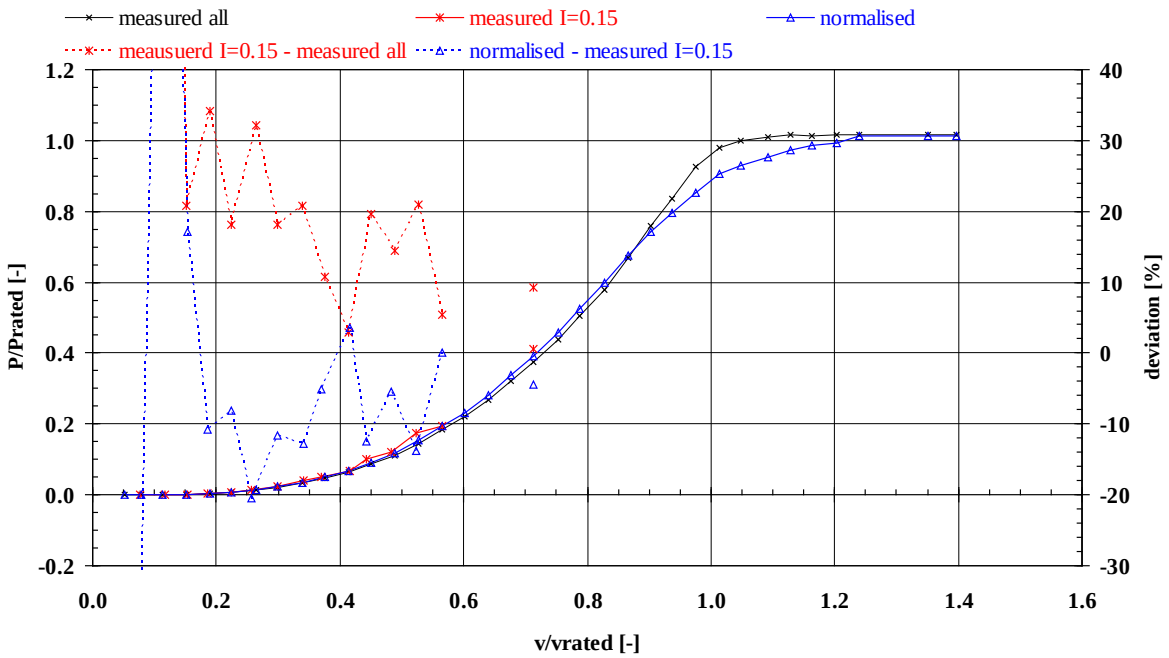


Figure 31: Case B: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 12.5 %-17.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 12.5 %-17.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.2.5 Case B: Normalisation to I=20 %

There are only a few bins covered by the filtered power curve at low wind speeds. Here, the filtered power curve is far above the unfiltered power curve. The normalisation procedure describes at least half of this effect (Figure 33). There are only 2 data points above rated power covered by the filtered data. These data points are quite well in line with the normalised power curve (Figure 32).

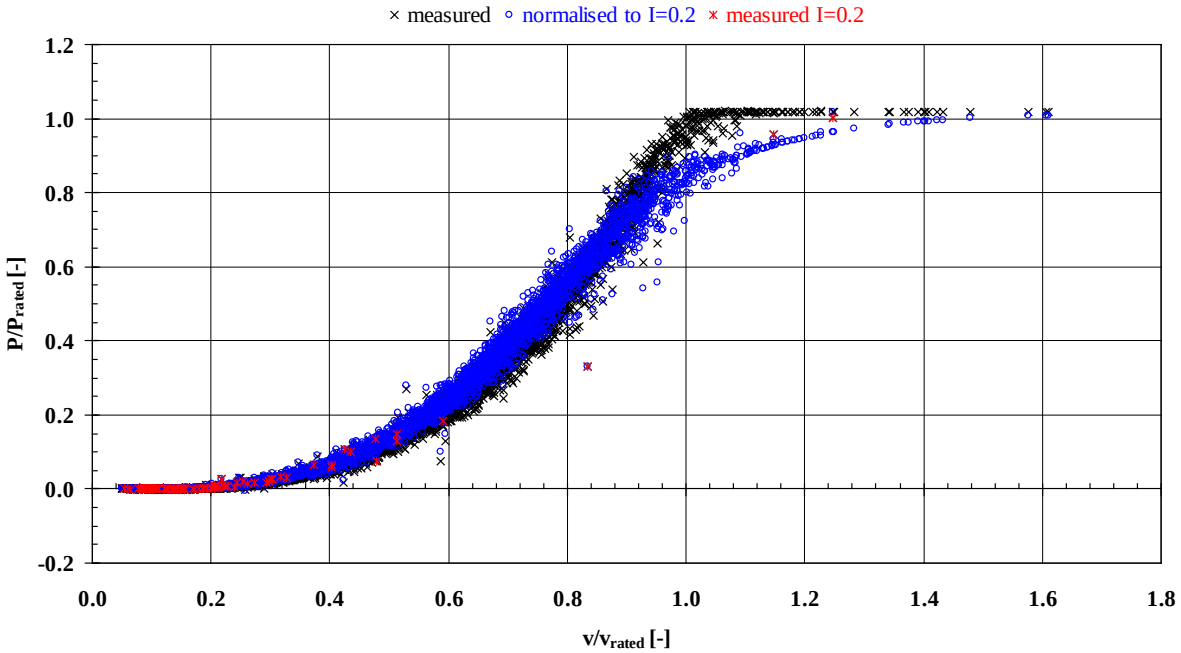


Figure 32: Case B: raw data of measured power curve (black), power curve normalised to turbulence intensity 17.5 %-22.5 % (blue) and power curve filtered to turbulence intensity range 17.5 %-22.5 % (red)

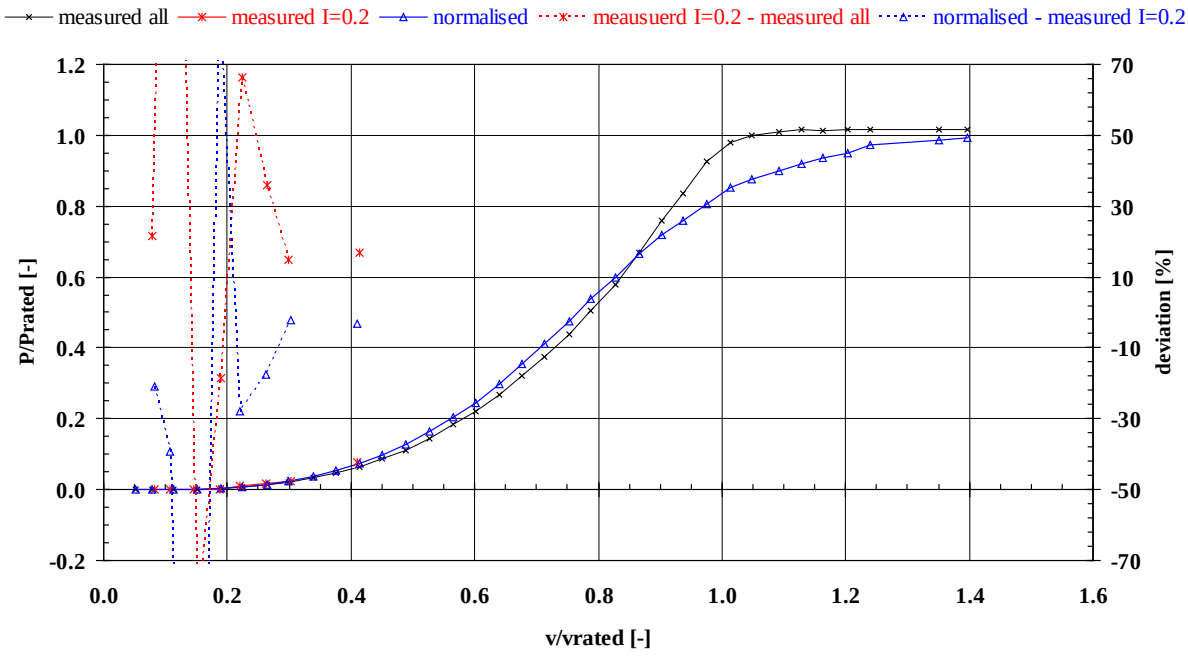


Figure 33: Case B: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 17.5 %-22.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 17.5 %-22.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

## 4.3 Test Case C: Stall Controlled Turbine, Medium Turbulence Site, 1-1.5 MW Class

### 4.3.1 Case C: Normalisation to I=0 %

The normalised power curve exceeds the measured (unfiltered) power curve above rated wind speed. At rated wind speed, the normalised power curve has a small bump (Figure 35). There is hardly any data of the filtered power curve which could be compared to the normalised data.

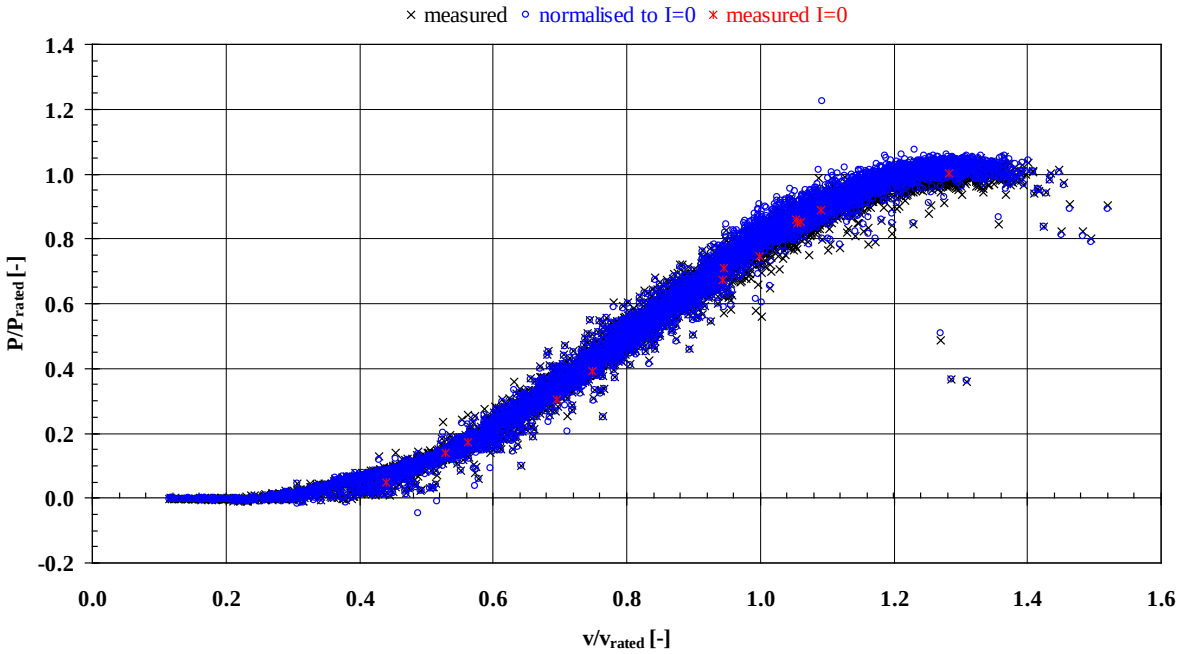


Figure 34: Case C: raw data of measured power curve (black), power curve normalised to turbulence intensity 0 %-2.5 % (blue) and power curve filtered to turbulence intensity range 0 %-2.5 % (red)

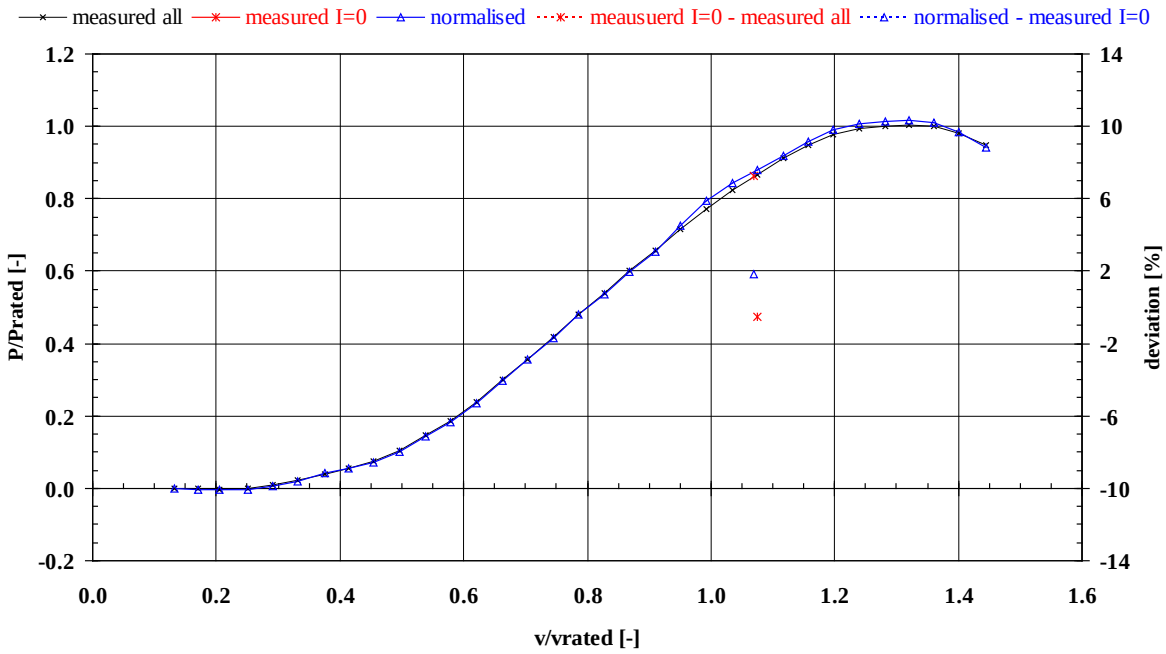


Figure 35: Case C: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 0 %-2.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 0 %-2.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.3.2 Case C: Normalisation to I=5 %

The filtered power curve varies only slightly from the unfiltered power curve. The filtered power curve agrees a bit better with the normalised power curve than with the unfiltered power curve, indicating that the normalisation shifts the data to the right direction (Figure 37).

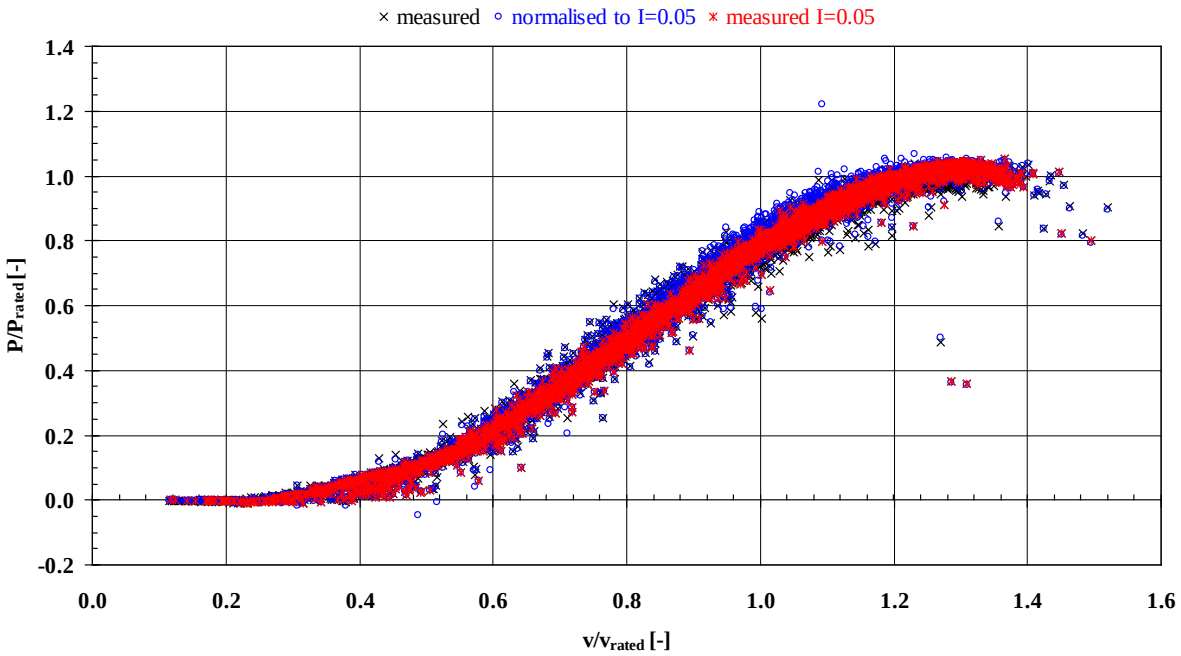


Figure 36: Case C: raw data of measured power curve (black), power curve normalised to turbulence intensity 2.5 %-7.5 % (blue) and power curve filtered to turbulence intensity range 2.5 %-7.5 % (red)

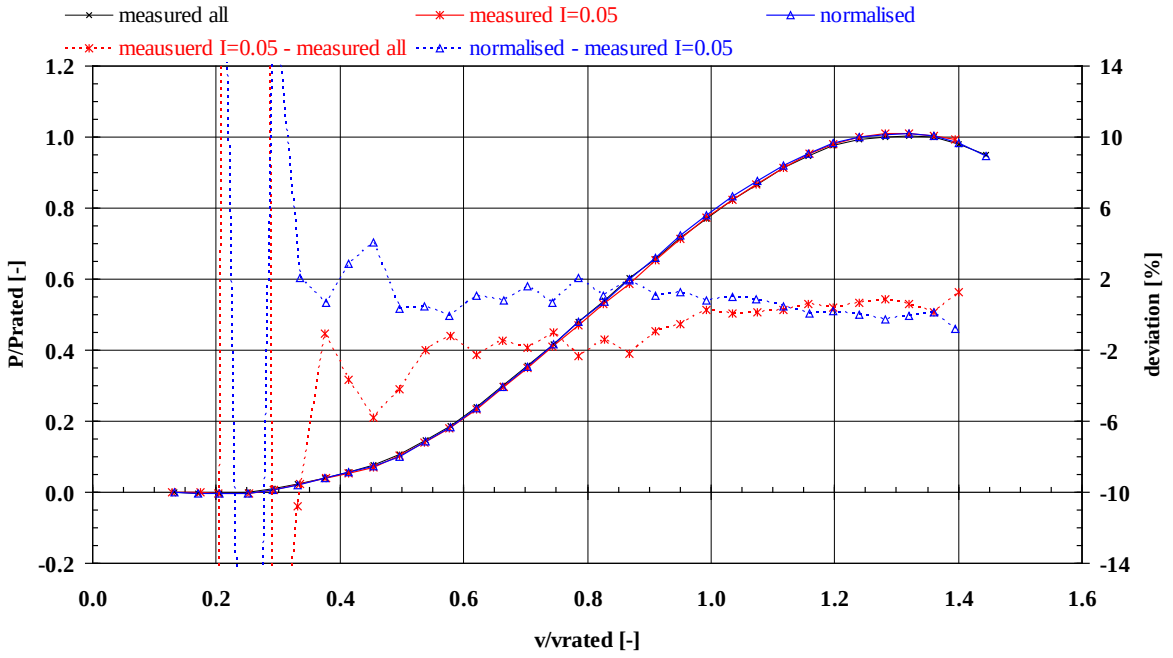


Figure 37: Case C: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 2.5 %-7.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 2.5 %-7.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.3.3 Case C: Normalisation to I=10 %

The reference turbulence intensity 7.5 %-12.5 % is close to the measured bin-averaged turbulence intensity. Consequently, the measured, the normalised and the filtered power curves agree well. At wind speeds around 1.3*$v_{rated}$ the filtered power curve is clearly below the unfiltered power curve. This effect is well described by the normalisation procedure.

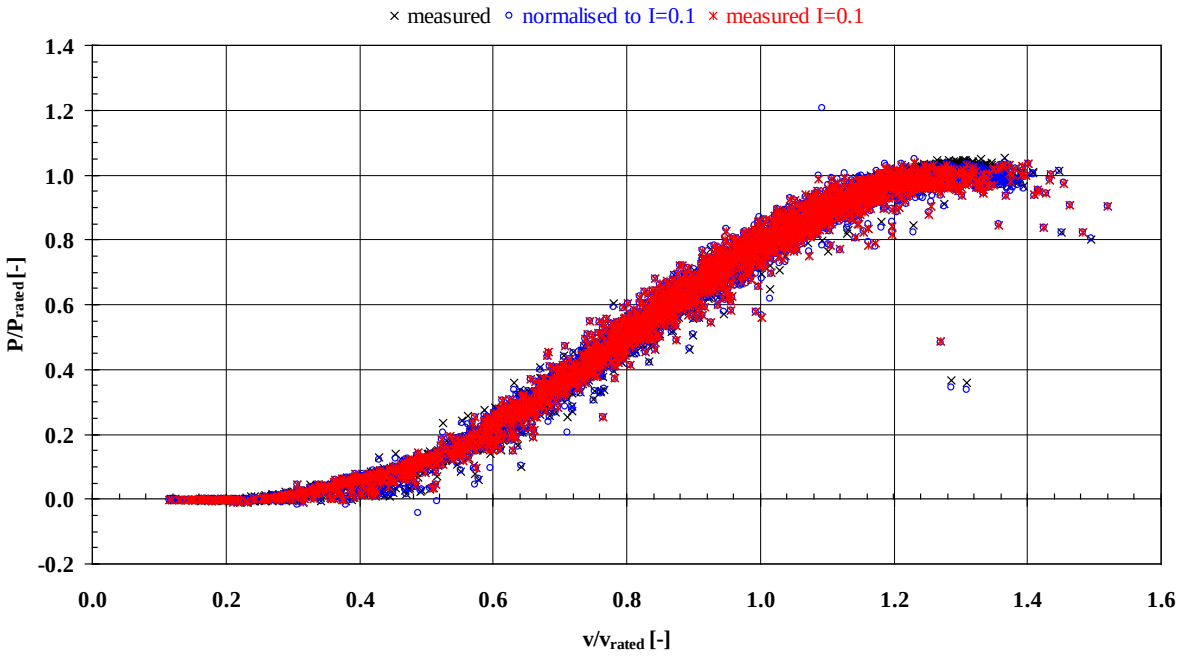


Figure 38: Case C: raw data of measured power curve (black), power curve normalised to turbulence intensity 7.5 %-12.5 % (blue) and power curve filtered to turbulence intensity range 7.5 %-12.5 % (red)

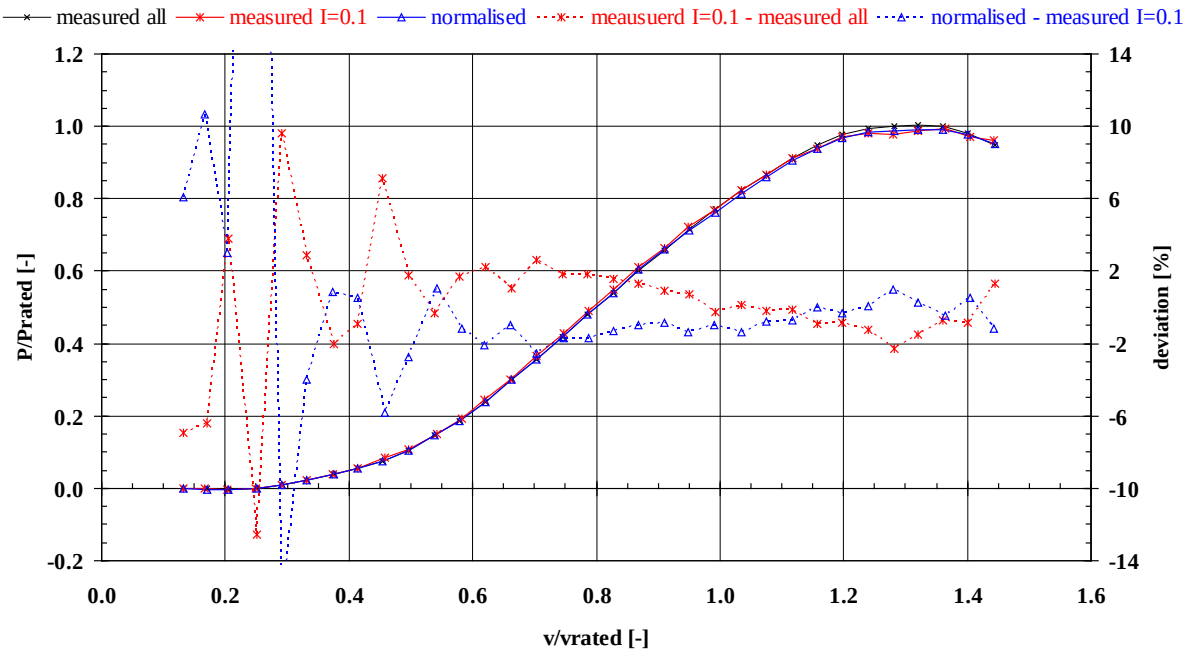


Figure 39: Case C: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 7.5 %-12.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 7.5 %-12.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.3.4 Case C: Normalisation to I=15 %

The filtered power curve agrees well with the normalised power curve (Figure 41). Especially above rated wind speed, the filtered power curve agrees much better with the normalised power curve than with the unfiltered power curve. The normalisation procedure seems to work also in case of stall controlled turbines.

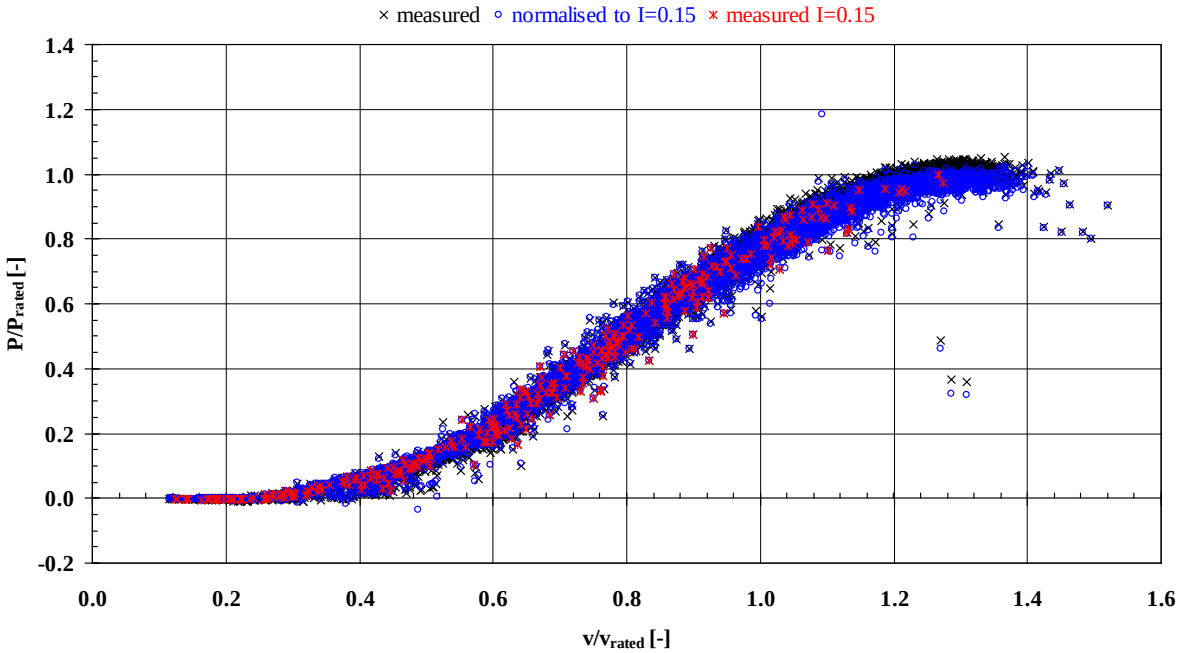


Figure 40: Case C: raw data of measured power curve (black), power curve normalised to turbulence intensity 12.5 %-17.5 % (blue) and power curve filtered to turbulence intensity range 12.5 %-17.5 % (red)

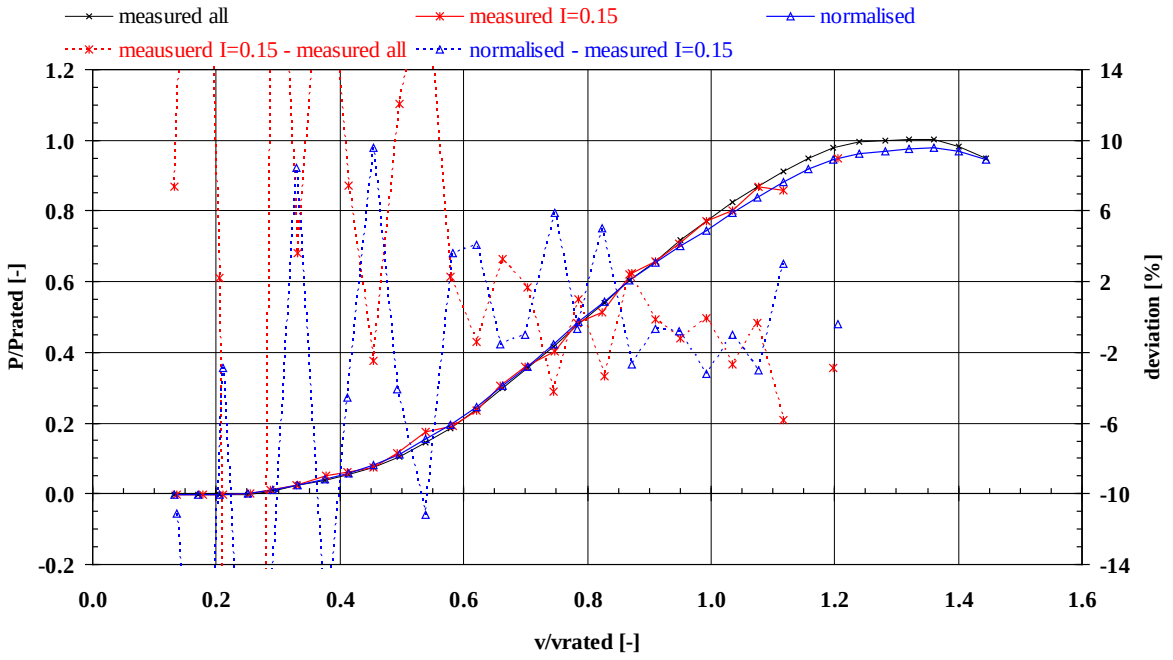


Figure 41: Case C: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 12.5 %-17.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 12.5 %-17.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.3.5 Case C: Normalisation to I=20 %

The filtered power curve is at low wind speeds about 20 % above the unfiltered power curve (Figure 43). The normalised power curve describes a large part of this effect. The filtered power curve deviates by about 10 % from the filtered power curve. At around rated wind speed, the normalised power curve has a small bump.

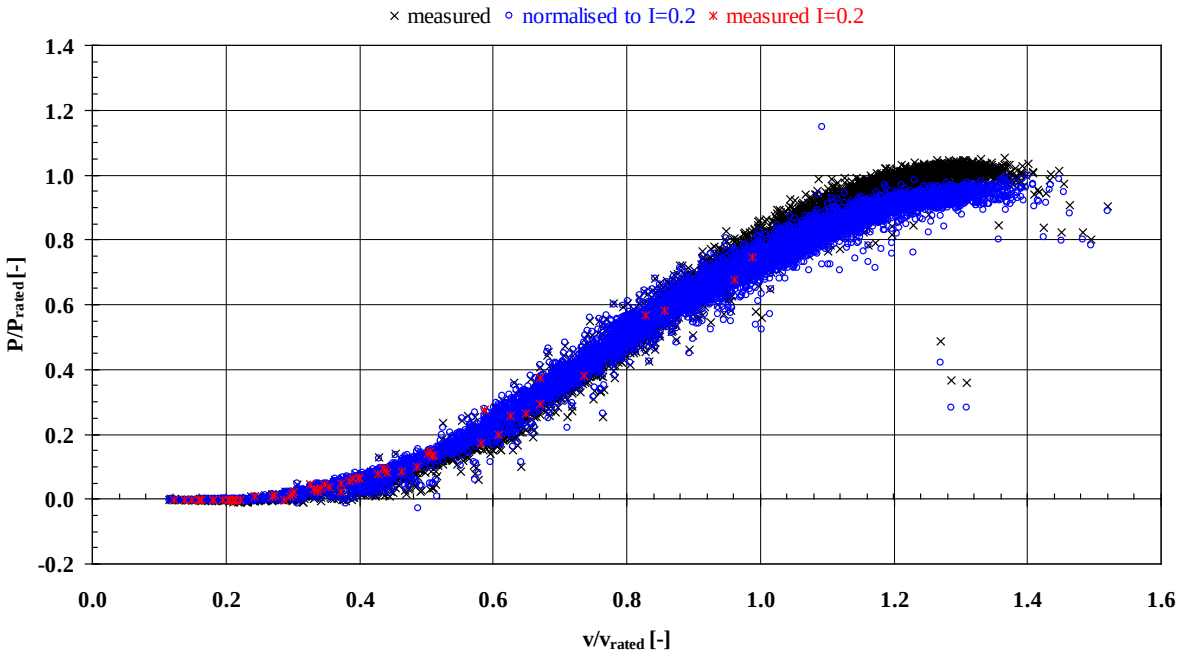


Figure 42: Case C: raw data of measured power curve (black), power curve normalised to turbulence intensity 17.5 %-22.5 % (blue) and power curve filtered to turbulence intensity range 17.5 %-22.5 % (red)

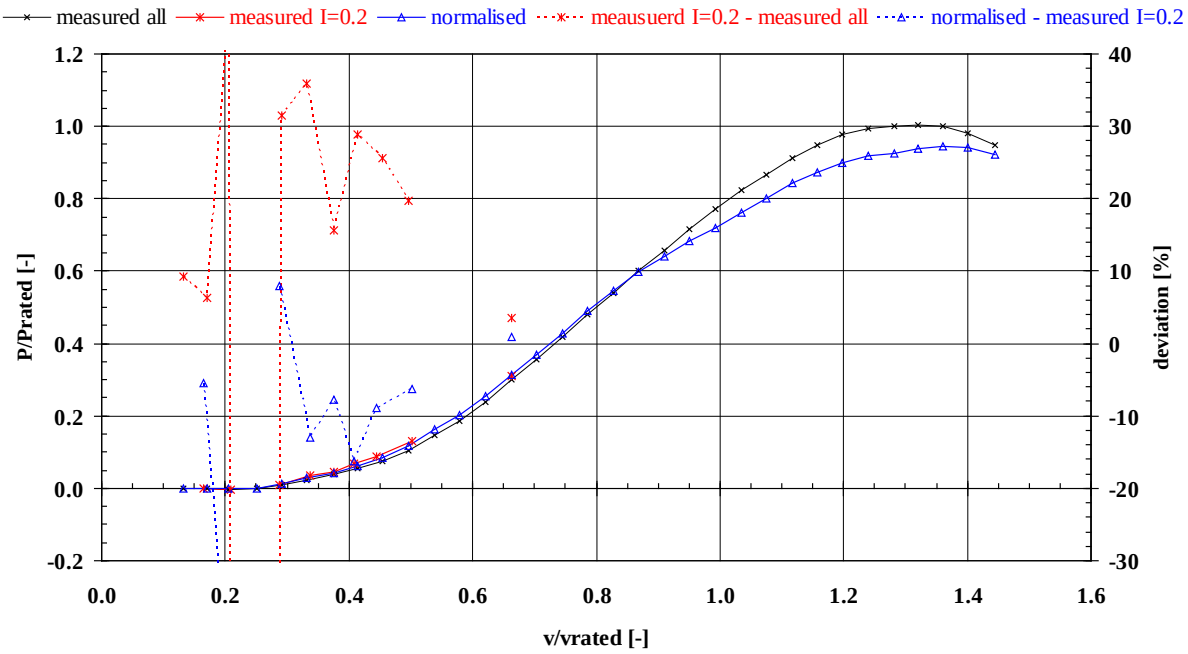


Figure 43: Case C: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 17.5 %-22.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 17.5 %-22.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

### 4.3.6 Case C: Normalisation to I=25 %

There are only two bins covered by the filtered power curve. At the only bin above 4 m/s, the filtered power curve exceeds the unfiltered power curve by almost 20 %, while the one bin fits well to the normalised power curve (Figure 45). The normalisation procedure seems to work reasonably even in such extreme cases where the reference turbulence intensity deviates much from the measured turbulence intensity. However, the normalised power curve has an unrealistic bump at around rated wind speed.

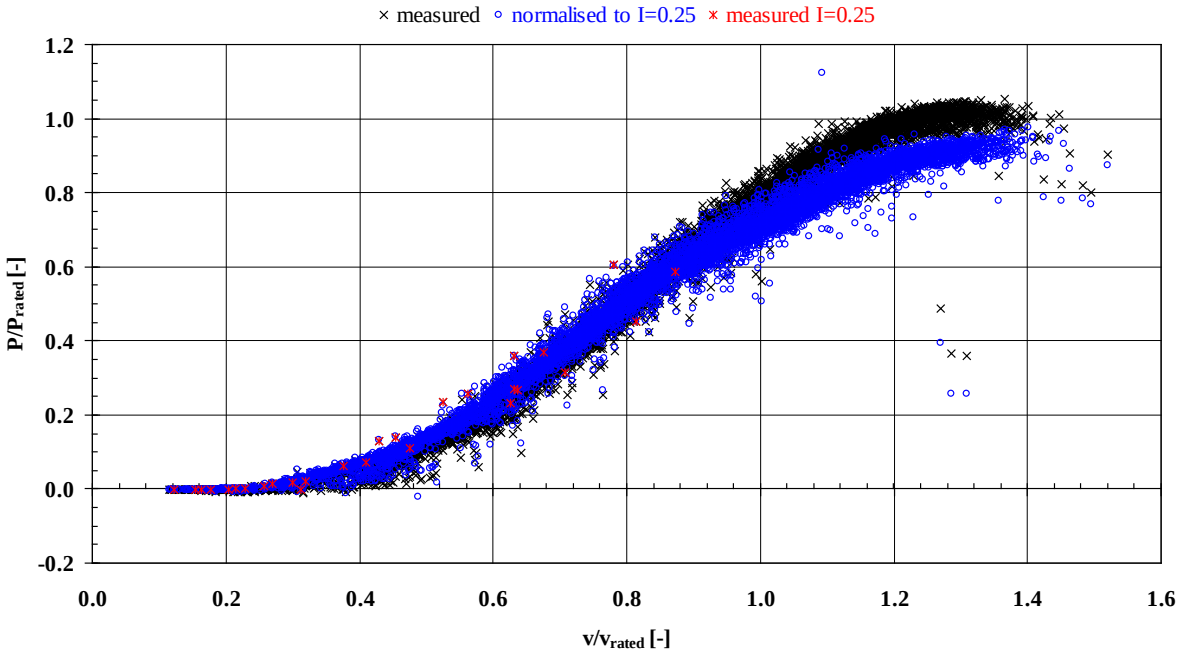


Figure 44: Case C: raw data of measured power curve (black), power curve normalised to turbulence intensity 22.5 %-27.5 % (blue) and power curve filtered to turbulence intensity range 22.5 %-27.5 % (red)

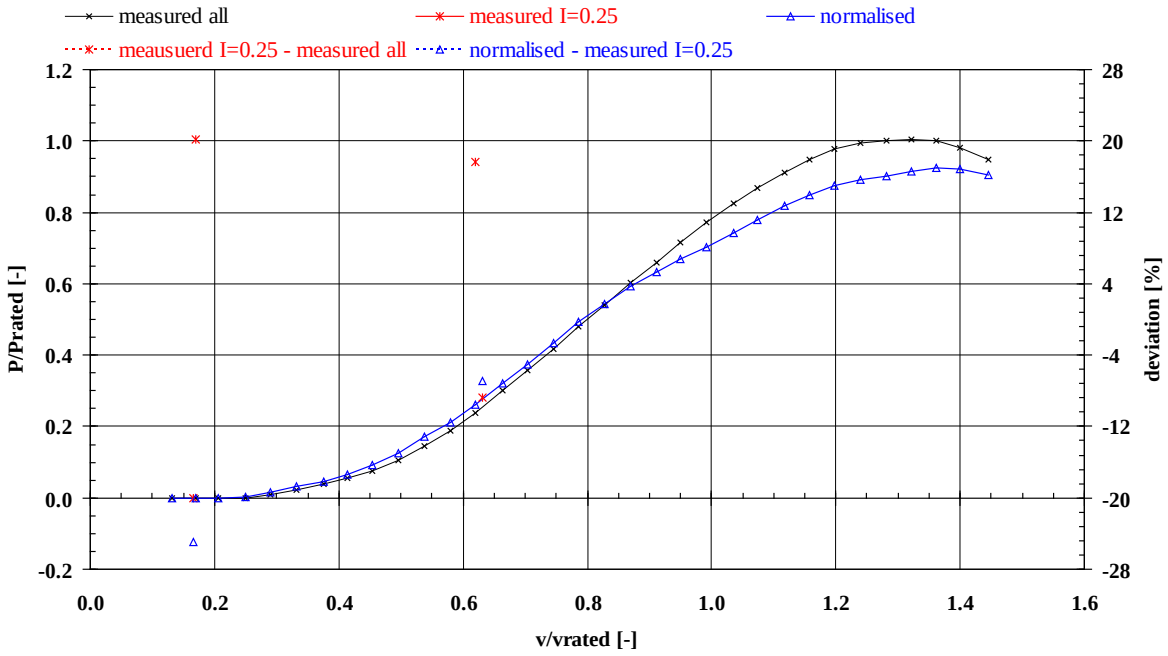


Figure 45: Case C: Bin averaged measured power curve (black), bin averaged power curve normalised to turbulence intensity 22.5 %-27.5 % (blue) and bin averaged power curve filtered to turbulence intensity range 22.5 %-27.5 % (red). The doted lines indicate the percentage deviation of the filtered power curve and the measured power curve (red) and of the normalised and filtered power curve (blue).

# 5 Summary

A simple normalisation procedure for wind turbine power curves has been presented, which is intended to describe and correct the effect of averaging power curve measurement data over 10-minute periods. The method is simple to implement and thus believed to be suitable for integration in a measurement standard.

The procedure has been tested on the bases of measurements at two pitch controlled test turbines at a high turbulent site and at a low turbulent site, as well as at a stall controlled turbine. The measured effects of the turbulence intensity on wind turbine power curves are described qualitatively well by the normalisation procedure. Often, the normalisation procedure describes also the magnitude of the turbulence intensity on measured power curves well. Sometimes, the procedure underestimates the true turbulence effects, especially when the reference turbulence intensity deviates much from the measured turbulence intensity. However, as the turbulence effects on the measured power curves are quite strong, measured power curves can be made much better comparable by application of the normalisation procedure. The normalisation procedure has the advantage over data filters that no measurement data is lost.

# 6 Literature

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[4] H. van Radecke; Turbulence Correction of Power Curves, DEWI-Magazine 24, February 2004, p. 56-62

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