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PEMSWECS

Performance Evaluation Methods for Autonomous, Applications Orientated Wind Turbine Systems

Final Report

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Partners		
NEL	:	Project management and testing of the 6kW Proven wind turbine
ECN	:	Technical coordination and testing of the 4kW Fortis Montana wind turbine
DEWI	:	Testing of the 30kW Südwind wind turbine

CONTENTS

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Part I

Executive summary

The primary objective of the PEMSWECS project is to provide a technical basis for the standardisation of power performance evaluation methods. This can serve as the basis for commercial warranties for autonomous, application orientated wind turbine systems. The project is largely testing based. It is complemented by analytical modelling, to provide a better understanding of system characteristics as well as to assist in performance prediction.

This report gives an overview of the result of the project. Measurements and simulations to develop a method for the power performance evaluation of autonomous wind turbine systems are described. The report is a compilation of the detailed reports on measurements and evaluations on three stand alone wind turbine systems:

- a 6 kW Proven system, equipped with a permanent magnet generator, diode rectifier, voltage controller and resistive load;
- a 4 kW Fortis Montana system, with a permanent magnet generator, diode rectifier, batteries, inverter and AC load;
- a 30 kW Südwind system, with synchronous generator and controlled resistive load.

The analysis concentrates on the effect of the load on the power-windspeed curve of the turbine and the choice of the pre-averaging time.

For systems with controlled DC voltage and resistive load it was concluded that the load does not have a significant effect on the power performance. This enables a straight forward determination of the power curve.

For system with batteries, it is demonstrated that, although the effect of the load on the DC voltage is substantial (a 30% variation is not unusual), the effect on the power curve remains relatively small. The effect on the yearly averaged energy production, although dependent on the wind regime, is also small: in the range of 5%. This justifies a simple method for the measurement of the power curve in these type of systems.

Systems with synchronous generators, resistive loads and speed controls are found to be similar to the grid connected turbines. As a result, the same methods for performance evaluation of grid connected turbines can be applied to autonomous wind turbine systems of this type.

Since autonomous systems often incorporate with relatively small turbines, the optimal pre-averaging time was determined in this study. A value in the range between 30s and 60s is being recommended, depending on the size of the machine.

The results of the study will be used as a technical basis for:

- developing a standard, by feeding results directly into formal standardisation committee;
- developing a national and European certification scheme for autonomous, application orientated wind energy systems;
- developing an in-house performance measurement procedure.

It is anticipated that this will give users more confidence in the performance of autonomous wind turbine systems and hence help the industry to develop.

Part II

Synthesis and Detailed Final Report

1 OBJECTIVES AND STRATEGIC ASPECTS

Autonomous, application orientated wind energy systems vary in design, size (from about 100 W to several times 10 kW) and loading characteristics. This poses particular difficulties in evaluating their power performance, when compared to grid-connected machines, for a number of reasons:

- the wind speed is not the only significant independent parameter; other climatic factors are also relevant, especially the turbulence level. Small wind turbines in particular, are more affected by turbulence than larger ones;
- aerodynamic effects may not completely dominate system efficiency, relatively poor mechanical and electrical efficiencies are also possible;
- the complete system has to be considered, not only the wind turbine; System performance will depend strongly on matching the electrical load with the turbine characteristics.

The primary objectives of the PEMSWECS project are to provide a technical basis for the:

- standardisation of performance evaluation methods for autonomous, application orientated wind turbine systems;
- guarantee of results to enable commercial warranties for autonomous, application orientated wind based systems.

A practical generic approach is recommended for standardising the power performance evaluation of autonomous, application orientated turbines. This project

- treated the system primarily as a *black box* where the performance, turbine characteristics and control system are evaluated against rotational speeds of the turbine and electrical outputs of the system under influences of wind climates and loading conditions (loads are simulated using effective electrical impedance);
- predicted and verified turbine behaviour/performance in a variety of applications;
- provided physical relationships between key parameters (eg shaft speed, torque and electrical performance), which can help both turbine and system developers to optimise overall turbine efficiencies.

PEMSWECS addresses all three levels mentioned above. Wind turbines of various sizes have been obtained and tests have been carried out to determine their characteristics under controlled conditions. Computer models have been developed and compared with measurements. Having established criteria and methods for identifying key characteristics, the objective was to demonstrate the possibility to predict how a turbine would perform in a range of wind climates when incorporated in any combination of systems and loads. The project was undertaken by combining experimental work and computer modelling, backed up by simple statistical analysis.

Although the project was largely testing based, it was complemented by computer modelling with a view to provide better understanding of system characteristics. Computer models have been generated using MATLAB, VisSin, ANSYS and Tina Pro. Results obtained from analytical models are compared and verified with measurements from controlled and end user tests.

To meet the objectives, the project was divided into the following main tasks:

1. Preparation of test systems (acquisition of hardware and instrumentation).
2. Tests to define turbine characteristics (controlled load and fixed speed tests).
3. Development of understanding of real load impedance behaviour.
4. Prediction of performance in real load situations.
5. Tests to verify performance in real load situations.
6. Comparison of end-user test data with predictions based on controlled load tests.
7. Formalisation of recommended testing and interpretation procedures.

This report is a summary of the results documented in the following PEMSWECS project reports:

- PEMSWECS Task 2: Tests to define turbine characteristics [5], Task 3: Development of understanding of real load impedance behaviour - Task 4: Prediction of performance in real load situations [6] and Task 5: Tests to verify performance in real load situations [7];
- Performance evaluation methods for autonomous, applications orientated wind turbine systems: Systems with batteries [8];
- Tests of the Südwind 30 kW wind turbine [2].

2 SCIENTIFIC AND TECHNICAL DESCRIPTION OF RESULTS

2.1 Description of test systems

The methods developed in the PEMSWECS project apply to autonomous wind turbine systems for the generation of electricity, in the range of 100 W to about 30 kW. The main application is the supply of electric power to household and small industrial appliances. These systems are often equipped with batteries, to store a surplus of wind power and to supply power during a wind power shortage. Since there is no backup grid, a surplus of wind power which can not be stored in the batteries, is either dissipated in a dump load or not generated at all. The presence of batteries requires a charge controller to prevent overcharging of the batteries. Other applications of autonomous wind turbines are for instance domestic heating and water pumping, in the latter case by means of a pump driven by an electrical motor.

Autonomous systems incorporate a number of different electrical loads. The ways these loads are being controlled and/or interacted with the operation of the turbine will influence the overall system performance. A power performance evaluation method has to take this interaction into account, unless it is shown that it does not have a significant effect on the overall power production. This project investigates and quantifies these interactions in three different systems to draw conclusions on the methods of evaluation of autonomous wind turbine systems.

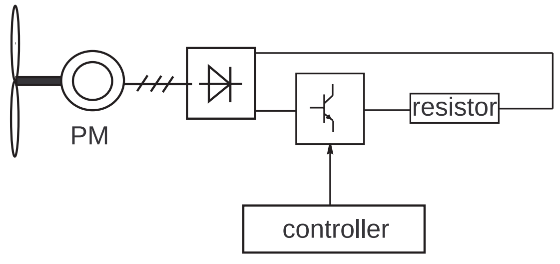

Figure 1: *Proven System with permanent magnet generator, rectifier, resistor and voltage controller*

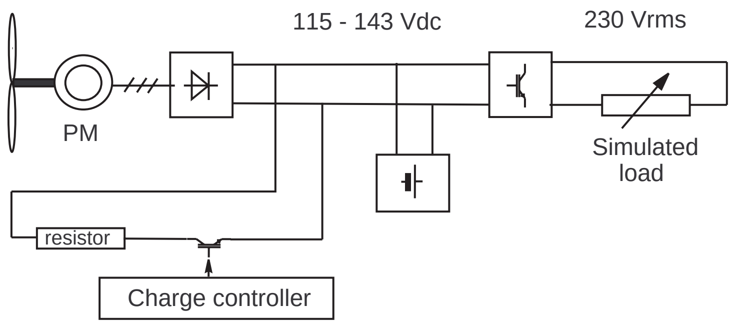

Figure 2: *Fortis system with permanent magnet generator, batteries, charge controller, inverter and AC load*

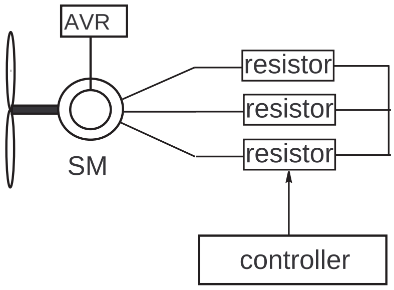

Figure 3: *Sudwind system: synchronous generator, resistive load, voltage and speed control*

The following stand alone wind turbine systems have been investigated:

- a 6 kW Proven system (Fig. 1) equipped with a Permanent Magnet (PM) generator, diode rectifier, voltage controller and resistive load. This system is mainly intended for domestic heating and was tested and analysed by NEL;
- a 4 kW Fortis Montana system (Fig. 2) with a permanent magnet generator in the turbine, a diode rectifier and batteries. Its main purpose is the supply of domestic appliances through a single phase 230V-50Hz inverter. It was tested and analysed by ECN;
- a 30 kW Südwind system (Fig. 3) with synchronous generator and resistive load. This system can be used for the supply of domestic and small industrial appliances and produces heat as a by-product. It was tested and analysed by DEWI.

Two systems, Proven and Fortis, are equipped with a permanent magnet generator, which is preferred in small wind turbines for reasons of robustness and efficiency. The Proven and Fortis system are similar in a second way: both have a diode rectifier and a DC voltage controller (in the Fortis system operating as voltage limiter) operating on an IGBT or MOSFET switch. The Südwind system also includes a controller, but its purpose is to control the speed, the voltage control is already taken care of by the synchronous generator. Finally, the Fortis system includes an inverter which converts the DC voltage of 115-143V to 230 AC. Any standard household appliance can be connected to this inverter as long as the maximum power of the inverter is not exceeded. The reactive power of an AC load can also be a limiting factor when connecting to the inverter, for instance in case of a pump driven by an asynchronous generator.

The power performance and general characteristics of the three turbine systems have been obtained under simulated conditions with well defined load control behaviour. Measurements have also been taken under real load conditions, representing the conditions at an end user. The Proven systems was also tested at an actual end user site. To have a better understanding of how the systems behave under real and simulated load conditions, computer models have been developed for the Proven and the Fortis system. These models were used to predict the system behaviour and were found to be sufficiently accurate. These models were not intended to be used in the recommended methods however since they require accurate electrical parameter data of a particular system.

The actual analysis for the development of a power performance method concentrates on two aspects:

- the effect of the load on the power-windspeed curve of the turbine;
- the choice of the pre-averaging time for the determination of the power curve.

2.2 Systems with Permanent Magnet generator, rectifier and resistive load

Figure 4: *Proven turbine installed at NEL test site*

The Proven turbine (Fig. 4) is a 6 kW down-wind turbine with passive pitching/coning to limit the aerodynamic power. It is a three bladed machine with a rotor diameter of 5 m and a hub height of 10 m. The cut-in wind speed is about 2.5 m/s and the rated power is reached at 10 m/s. The turbine reaches a rotational speed of 200 rpm at a wind speed of 12 m/s. The passive pitching/coning can be tuned by applying either 3, 4 or 5 springs or by varying the pretension on the springs. The permanent magnet generator is direct driven: no gearbox is required. The three phase AC power is fed through a diode rectifier to resistors of 5.2, 6.8, 8.2, 9.6 or 14.4 Ω. The system is equipped with an IGBT switch controlled by the generator voltage. The IGBT switch operates at a frequency of 1 kHz and enables intermittent connection of the load. The way in which the voltage control operates, determines the power performance of the system, as will now be demonstrated.

To characterize the system, two modes of operation have been investigated:

- without voltage control: the IGBT switch is bypassed and the diode rectifier is directly connected to a fixed value resistor;
- with voltage control.

2.2.1 Performance without control of the DC voltage

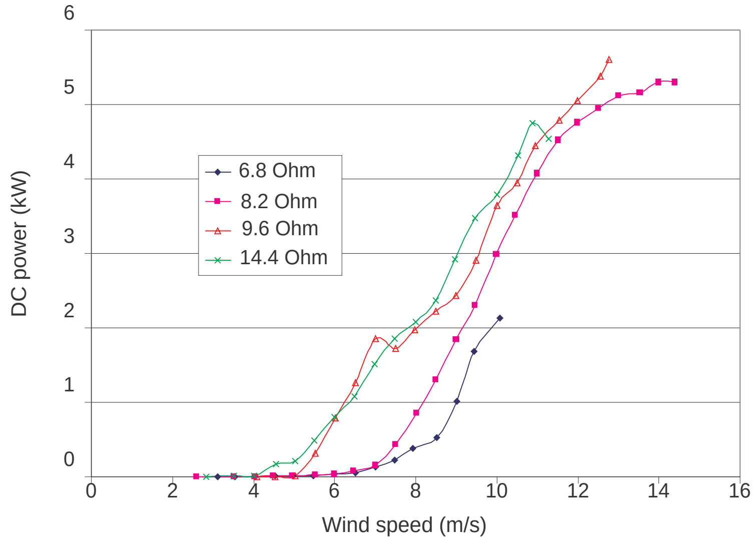

Figure 5: *DC power vs wind speed at different loads for the Proven turbine (no control of the DC voltage)*

Figure 5 demonstrates the strong effect of the load on the power performance of the system without voltage control. Since the load is connected to the turbine regardless of the voltage, a low value resistor will present a high load, which will prevent the turbine from producing power at low wind speeds. If the wind speed increases, the power produced with the low value resistor is also significantly less than at higher resistor values, which is caused by the low operational speed. The highest resistor tested, 14.4 Ω gives the best matching of the rotor and the electrical load and thus the best overall performance. These measurements clearly demonstrate the effect of the electrical load on the energy production of an autonomous system and the need to consider the load and its control (if any) in the evaluation of these systems.

Conclusion: For systems without voltage control, the size of the load will strongly influence the power performance.

2.2.2 Performance with IGBT control of the DC voltage

Next, the Proven generator was fitted with an IGBT, which is programmed to reduce the generator load at low rotor speeds and increase the load if a preset speed is reached. To achieve this, the controller sends electrical pulses to switch the IGBT on and off at a frequency of 1kHz. The width of the pulses is determining by the voltage of the generator. At low generator voltage, the switch-on time of the pulse is shorter, reducing the average load power and consequently the electrical torque between the rotor and stator. Since the open-circuit voltage of the generator is linear with its speed (the generator field is constant), this type of control allows the rotor to gain speed before being connected to the load.

The IGBT controller connected to the Proven turbine is programmed with a minimum pulse width of 50 ms per second upto a generator voltage of 165 V, which effectively disconnects the load. The width of the pulse increases linearly with the increase of the generator voltage, until the voltage equals 210 V when the pulse width reaches a maximum of 950 ms per second. Beyond 210 V, the pulse width remains at its maximum. Figure 6 shows the measured and the simulated voltage-rotor speed curve in case of a 6.8 Ω load. The turbine now operates in a speed range of 110-230 rpm.

Figure 6: *Voltage-rotor speed curve for a 6.8 Ω load*

The effect of different resistive loads for controlled DC voltage is demonstrated in figure 7. It is also compared to one case without voltage control. The result shows that the effect of the different resistive loads now almost has disappeared. The differences above 12 m/s are caused by a different number of rotor springs, which changes the coning behaviour and the maximum aerodynamic power. For comparison one case without voltage control is included: it has a significatly lower performance, as was expected.

Conclusion: For systems with voltage controller, the tuning of the controller will influence the power performance of the autonomous system. In systems with voltage control, the influence of the load on the power performance is small.

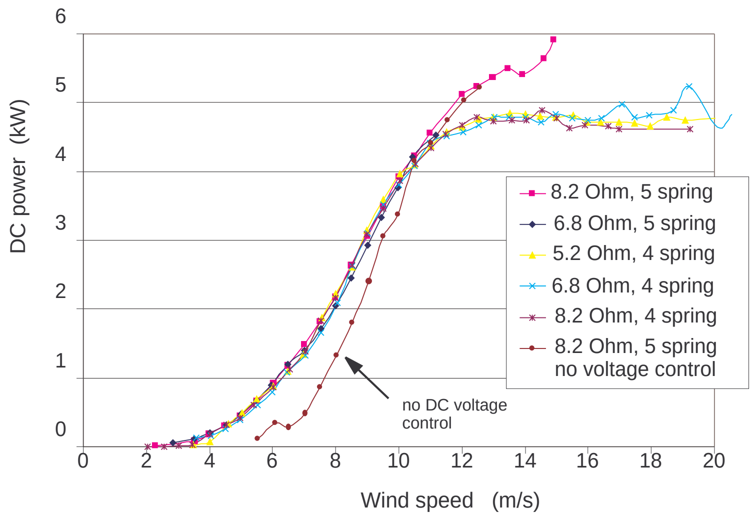

Figure 7: *DC power vs wind speed at different load for the Proven turbine (4 or 5 rotor springs, with control of DC voltage)*

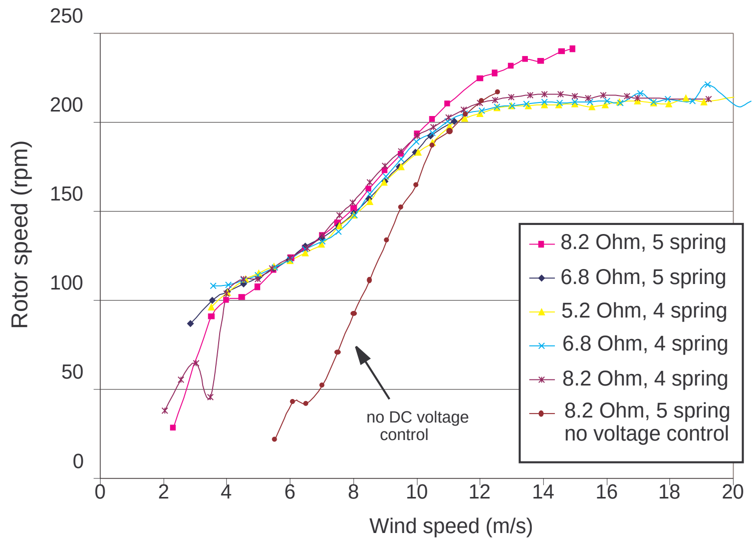

Figure 8: *Rotor speed vs wind speed at different load for the Proven turbine (4 or 5 rotor springs)*

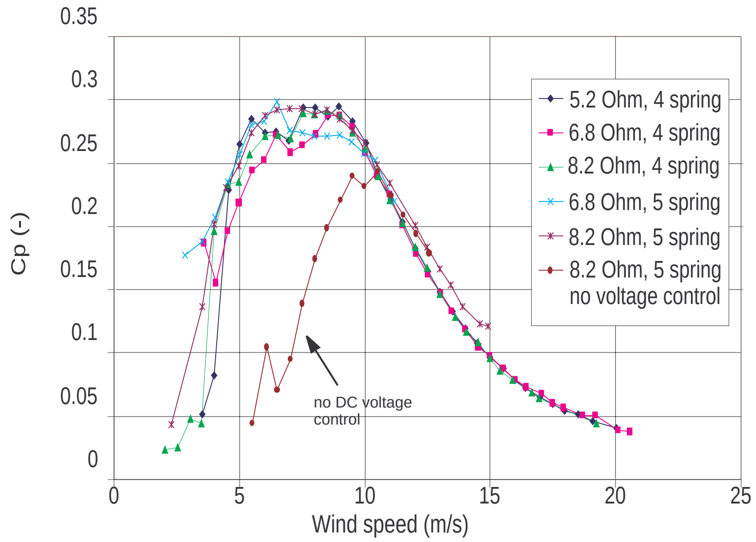

Figure 9: *Power coefficient vs wind speed at different load for the Proven turbine (4 or 5 rotor springs)*

Figures 8 and 9 further illustrate the observed behaviour. In systems with voltage control, the load is reduced at low rotor speeds to allow power production at these speeds. The overall aerodynamic efficiency of the rotor is increased by the load control.

2.2.3 Performance at end user

On completion of tests to define the turbine characteristics, the Proven wind turbine was deployed for the end user measurements on an exposed hilltop near Corrary Farm in Glenelg, Ross-shire, a remote part of the North West of Scotland. Figure 10 shows the load arrangement at this particular end user. Apart from the resistive loads and the voltage controller, two battery chargers and an inverter are connected at the DC side of the rectifier.

However when the turbine transferred the turbine to user site, the blade broke within a few days of operation because of the high wind speed coupled with high turbulence. The turbine could not be operated without modifications, which included:

- changes to controller settings;
- redesign and modification of blades;
- number of changes to the coning control springs and pretension.

Since it was demonstated in the previous section, that for systems with controlled DC voltage the load will not influence the power curve, the power curve of this system is expected to be identical to the one with only resistive loads. This is confirmed in figure 11, where the turbine was equipped with 4 springs.

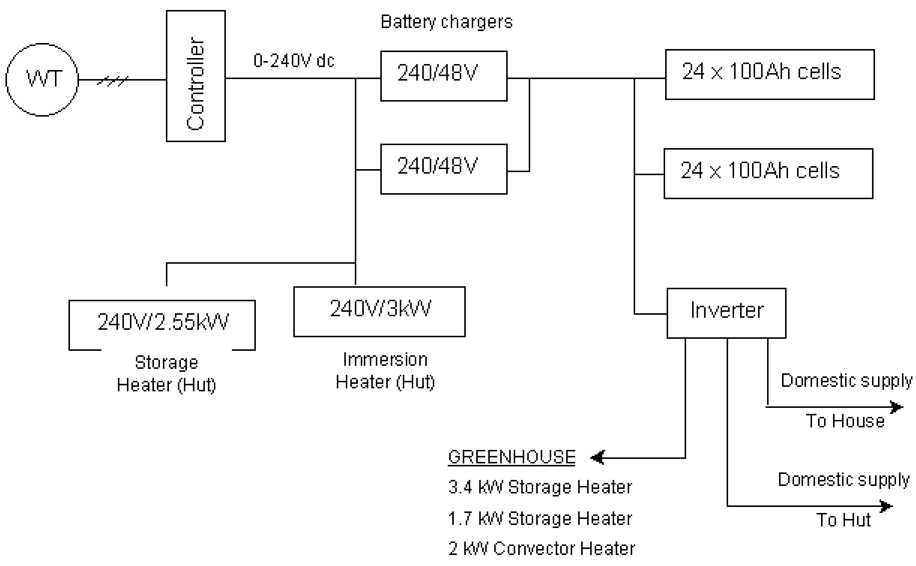

Figure 10: *End user load arrangement*

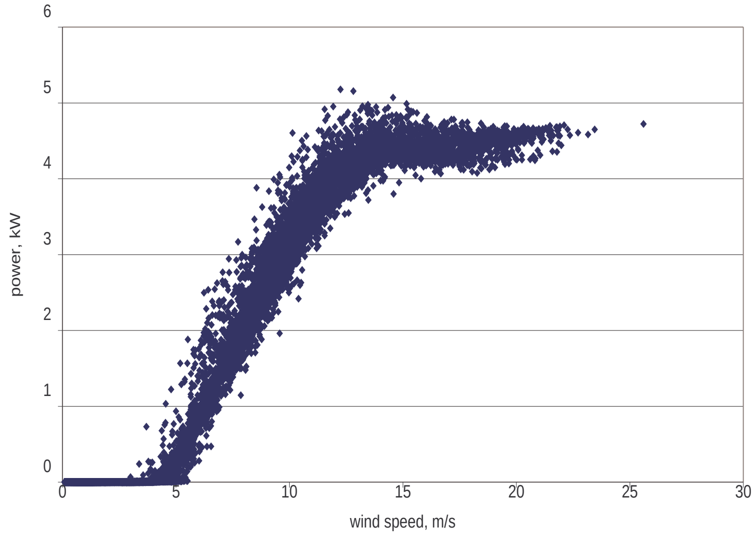

Figure 11: *Scatter plot of power versus wind speed at end user*

2.2.4 Recommendations for systems with resistive loads

Drawing from the findings of this study, the following performance evaluation methods are recommended for systems with Permanent Magnet generator, diode rectifier and a number of resistive loads at the DC side of the rectifier:

- for systems without voltage controller: perform a measurement of the power curve for the minimum and the maximum load. This will determine the best and worst performance of the system;
- for systems with voltage controller: document the setpoint(s) of the voltage control and measure the power curve for these setting(s). The load value and type is less relevant.

2.3 Systems with Permanent Magnet generator, rectifier and batteries

Figure 12: *Fortis Montana Turbine at ECN test site*

The Fortis Montana turbine (Fig. 12) tested at ECN is a three bladed, up-wind turbine with a rated power of 4 kW, a rotor diameter of 5 m and an inclined hinged tail vane to limit the aerodynamic power. The cut-in wind speed is 3.5 m/s and the rated power is reached at 12 m/s. The permanent magnet generator is direct driven. The three phase AC power is fed through a diode rectifier to a string of ten 12 V batteries (see figure 2). The battery charging is limited by a DC-voltage controlled FET which switches on a dumpload if the voltage reaches 143 V. The AC load is fed through a single phase IGBT inverter.

2.3.1 Effect of the DC voltage on the power speed curve

The DC voltage of the rectifier depends on the state of charge of the batteries and even more strongly on the direction of the current, viz. charging or discharging operation. Modeling has shown, that the power-speed curve of a wind turbine with diode recifier and batteries is shifted as the DC voltage increases (see figure 13). This will result in a change of aerodynamic efficiency of the turbine at a given wind speed, a different power curve and a different power performance. The changing voltage may also change the maximum power of the turbine by changing the maximum power of the generator. This effect is also influenced by the aerodynamic power limitation method of the turbine. These combined effects have been quantified by measurements on the Fortis Montana system (Fig. 12), to determine if and how it has to be taken into account in the power performance evaluation method.

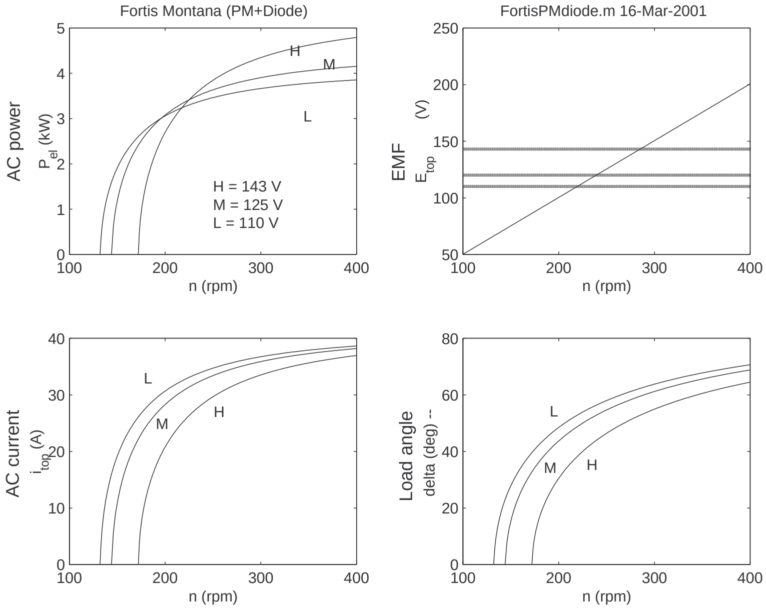

Figure 13: *Simulated power-speed curves, EMF, AC current and load angle of Fortis Montana for 3 DC voltages*

To evaluate the potential effect of the DC voltage on the power curve, measurement series of about 100 hours have been recorded with a sample frequency of 4 Hz. The measurements have been corrected for temperature and pressure and averaged over 30 seconds (section 2.5 explains the choice of the averaging period). The measurement conditions are identical to real load conditions: randomly changing AC load and wind power and randomly changing DC current and voltage. The range of operation of the DC voltage depends on:

- the maximum discharge current (in the Fortis system 47 A, equivalent to 5.2 kW). This results in a lower limit of about 112 V;
- the set point of the charge controller. The dumpload limits the DC voltage to 143 V.

The data has been binned against the DC voltage. Three bins were chosen: below 125 V, between 125 and 135 V and above 135 V. The data per voltage bin is binned a second time, now against the wind speed or the rotor speed. Different DC voltages will result in different power-wind speed, power-rotor speed and rotor speed-wind speed curves.

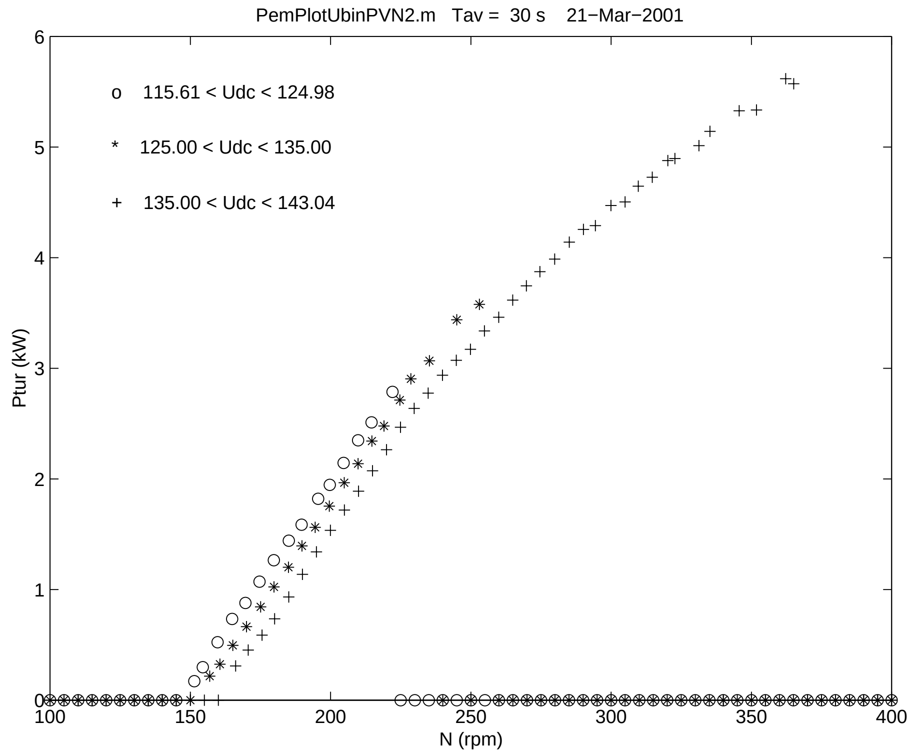

Figure 14: *Measured power-rotor speed curves for 3 DC voltage levels*

The power-rotor speed curves (Fig. 14) clearly show the effect of the DC voltage. At a lower DC voltage, the turbine starts delivering power at a lower speed and the power is higher. This corresponds to the prediction in figure 13. The effect should reverse at high rotor speeds. Since the combination of high rotor speed and low DC voltage does not occur, this effect is not present in the measurements however. High rotor speed and low DC voltage will not occur under real load conditions, therefore it is not relevant for the power performance.

The high rotor speed bins have an unsufficient number of data to draw conclusions. In the middle and low speed bins the numbers are sufficient to be representative. In this range the difference in power between the low and high voltage condition is about 0.5 kW, which is substantial.

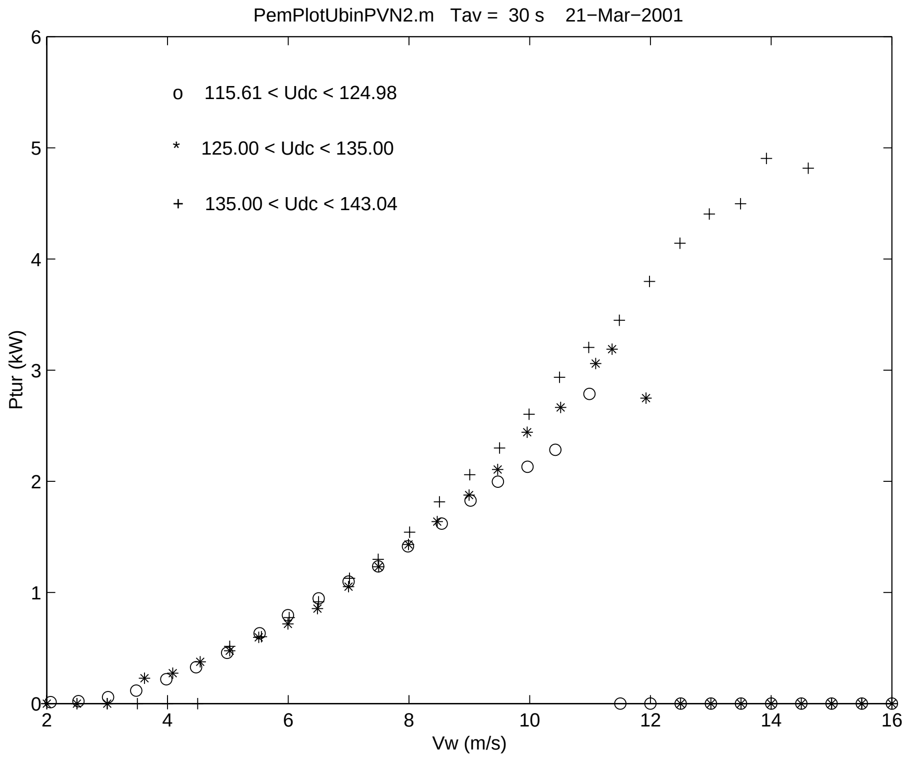

Figure 15: *Measured power-wind speed curves for 3 DC voltage levels*

Figure 15 plots the power-wind speed curves from the same data. The following observations are made:

- Below 5 m/s there is unsufficient data in the high voltage bin, which is logical since a high voltage is not likely to occur in combination with low wind speed. Any differences in the low region can be attributed to insufficient data.
- In the range from 5 to 8 m/s the amount of data is sufficient for all three voltage levels. In this range the differences in power for the 3 voltages are small.
- The range from 8 to 9.5 m/s also has sufficient data for all three voltage levels and shows a slight increase of power with voltage: about 0.2 kW.
- Above 9.5 m/s the number of data in the low voltage bin is unsufficient. This is also the case for the medium voltage bin above 10.5 m/s. Above this wind speed level it is not likely that the voltage will be in the two lower bins for a significant amount of time.

The measured effect of the DC voltage on the power-wind speed curve under real load conditions therefore is relatively small. It is surprising that substantial differences in the power-speed curve do not lead to significant differences in the power-wind speed curve. This can be explained by the strongly nonlinear behaviour of the rotor. Especially a flat $C_p(\lambda)$ curve will level out the effect on the power performance. For the turbine under investigation, the $C_p(\lambda)$ curve is not particularly flat however and still the effect of voltage on power performance is small. This justifies the conclusion that in many cases the effect of the DC voltage on the P(V) curve will not be very significant. This is an important argument for the recommendation of a simple method to determine the power performance of autonomous systems with batteries.

Conclusion: With regard to the effect of the load on the power performance it was shown that, although the influence of the load on the DC voltage is substantial (a 30% variation is not unusual) the effect on the power-windspeed curve is relatively small. The effect on the yearly averaged energy production, although dependent on the wind regime, is also expected to be small: in the range of 5%. This justifies a simplified method for the determination of the power curve for systems which fulfill the conditions in the measurements. The combined effects of the wind speed distribution and differences in P(V) curve on the actual energy production over a long period have been quantified as shown below.

2.3.2 Prediction of real load performance

Models are used to estimate the average yearly energy production of autonomous wind energy converter systems under various wind conditions. A distinction has to be made between the actually produced wind power and the power that can actually be used by a consumer. For grid connected systems the grid acts as an infinite buffer and all energy produced by the turbine is used by the consumers. This is generally not the case in autonomous systems: if the wind power exceeds the demand and the batteries are full, the power is dumped. This effect is influenced by the system lay-out (mainly the battery size) and the consumer demand pattern. For a standard power performance evaluation however, this effect is not taken into account.

Models to determine the power performance can either be statistical or time domain models. For power performance evaluation of grid connected systems only statistical models are used. To determine the amount of dumped power in an autonomous system with batteries, a time domain model is preferred, due to the difficulty to include the battery SOC in a statistical model [4, 1]. This type of model is sometimes referred to as logistic model, it estimates the system behaviour over a long period of time, for instance one year, by calculating the power balance at an interval of 1 hour or even better 10 or 1 minute. This type of model is especially useful to determine the optimal size of the system components and to evaluate the effect of different control strategies on the amount of power the consumer can use. In the time domain model the consumer load pattern has to be specified. The amount of dumped and useful power depend on this pattern. For the user of the system, the results from time domain models are very relevant.

For the determination of the standard power performance of an autonomous system, the dumped power and power lost by charging and discharging are counted as produced power (though not actually used). In other words the battery size and losses are not taken into account. For this power performance evaluation, a statistical model is sufficient.

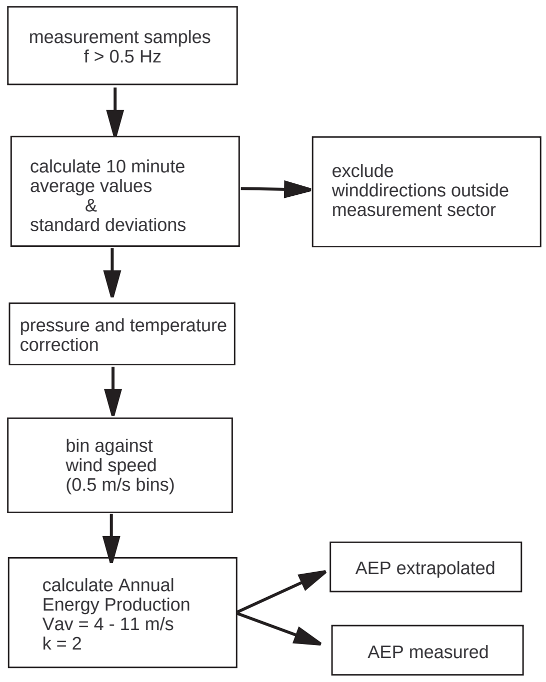

Figure 16: *Flow diagram of the power performance testing method in IEC 61400-12*

A flow diagram for predicting the annual energy generated, according to IEC 61400-12, is given in figure 16.

Power performance for different voltage levels

Based on the measured power curves for the three DC voltage levels used in section 2.3.1, the yearly average energy production is estimated for the wind speed range available in the power curves for all three levels: 5 to 11 m/s. In this region it is likely that all three voltage levels can occur and it is also the region which is most important for the total energy production. The differences in the power curves found in section 2.3.1 are small, and it will now be checked, whether the differences will be amplified by the wind speed distribution.

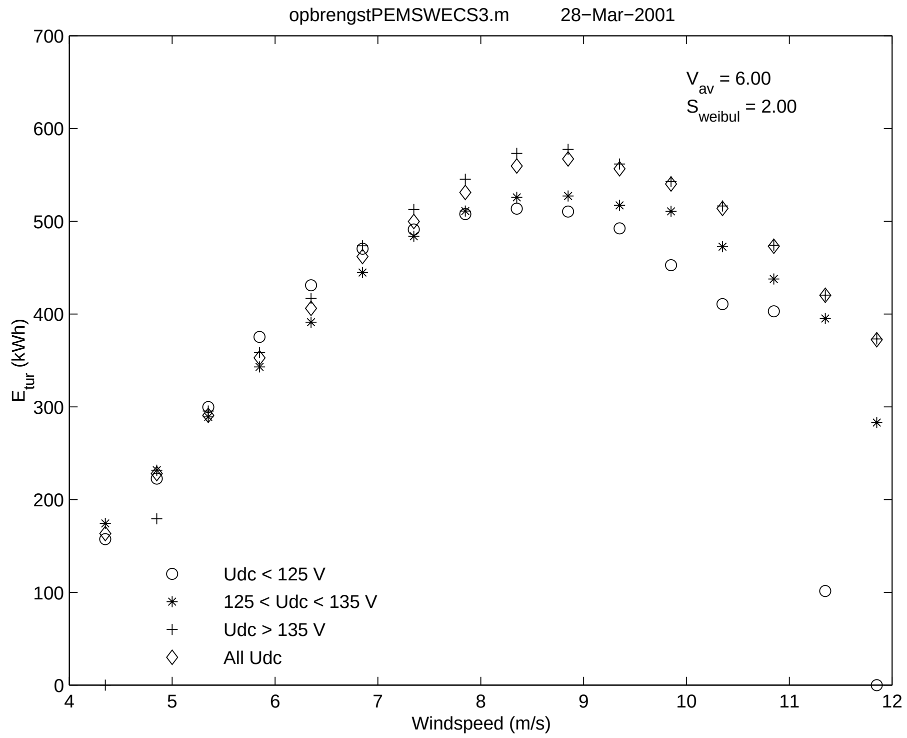

Figure 17: *Energy production for 3 DC voltage levels and the average over all voltages: Vav =6 m/s, k=2*

Figure 17 gives the energy production for 3 DC voltage levels and the average over all voltage levels for a Weibull distribution with an average wind speeds of 6 m/s and a shape factor of 2. Table 1 shows the cumulative results, also for 5 and 7 m/s average wind speed. The maximum deviation is 10%, under real conditions an average value of the listed deviations of about 5% is expected. This deviation present unsufficient justification for a complicated measurement procedure which takes the effect of DC voltage variations into account. Therefore, it is recommended to perform the measurements under real load conditions, implying randomly changing DC voltage, and make no correction for the DC voltage changes.

Table 1: *Yearly production in wind speed interval 5-11 m/s*

Weibull parameters			
$V_{w,av}$	5	6	7
k	2	2	2
Yearly energy production E (kWh/y)			
$U < 125V$	4087	5359	5959
$125 < U < 135V$	4093	5455	6128
$U > 135V$	4374	5849	6582
all U	4296	5753	6482
Deviations			
$\frac{E_{U>135}-E_{U<125}}{E_{U<125}}$	7%	9%	10%
$\frac{E_{U>135}-E_{allU}}{E_{allU}}$	2%	1.5%	1.5%
$\frac{E_{allU}-E_{U<125}}{E_{allU}}$	5%	7%	8%

2.3.3 Recommendations for systems with batteries

Measurement conditions for systems with permanent magnet generator, diode rectifier and charge controller directly connected to the batteries or through a downchopper:

- consult the manufacturer or perform a scoping measurement to quantify the variation, due to load changes, of the DC voltage at the diode rectifier;
- if the voltage deviations are 30% or less, voltage changes need not to be taken into account in the power performance measurement and evaluation procedure;
- if voltage variations are not taken into account, take measurements for the power-windspeed curve under random load conditions, comparable to end user conditions;
- if the voltage deviations exceed 30%:
  - either include voltage measurement in the data acquisition and bin measurements against 3 voltage levels and evaluate the effect on the power performance;
  - or measure power-wind speed curves at the two extreme values of the DC voltage and evaluate the effect on the power performance.

2.4 Systems with fixed speed or speed control

Figure 18: *Südwind turbine installed at DEWI test site*

The Südwind turbine tested by DEWI is a three bladed turbine with a diameter of 12.5 m and a rated power of 30 kW. The aerodynamic power is limited by a combination of stall and flapping of the hinged blades. The turbine is equipped with a synchronous generator and is designed for a constant speed operation at 71 rpm.

For the PEMSWECS project, the turbine was connected to a speed controller and resistive load to be operated at a number of fixed rotational speeds. The speed range investigated was 45-73 rpm. The speed controller keeps the speed constant irrespective of the wind speed. This type of operation is similar to operation on a utility grid or a constant speed wind-diesel grid. The voltage controller of the synchronous machine maintains a constant voltage for each speed, but does not compensate for speed differences. The voltage is proportional to the speed, indicating current compounding rather than feedback of the voltage value itself.

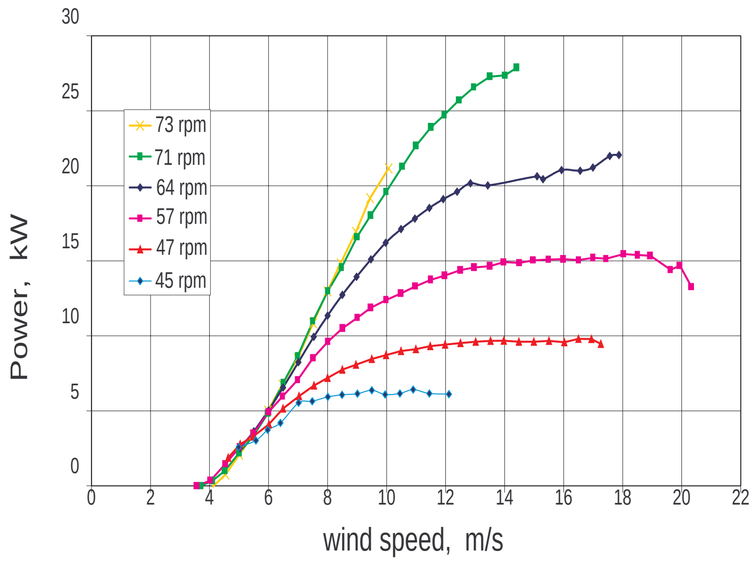

Figure 19: *Power curves for 6 rotational speed settings*

Figure 19 gives the power-wind speed curves for 6 rotational speeds. At lower speeds, stall regulation leads to a lower maximum power. The flapping of the blades in combination with centrifugal effects also influence the behaviour. Since the electric power is adapted according to speed changes, the load varies accordingly and the voltage does not have any effect on the system performance. Figure 20 shows the power coefficient for the different rotational speeds setpoints.

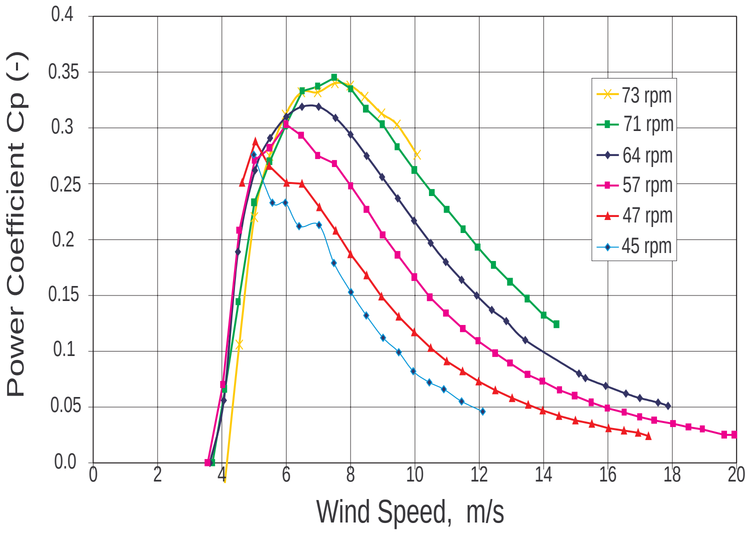

Figure 20: *Power coefficients for 6 rotational speed settings*

As could be expected, the speed set point will have a strong effect on the power performance of a system with speed control. Again, this is a matter of matching of the rotor characteristic with the load, as was demonstrated for the system with Permanent Magnet generator, rectifier and resistive load. However, constant speed operation of turbines is not often encountered in autonomous systems, unless the turbine is directly coupled to a diesel generator set with constant speed control.

Conclusion: Systems with synchronous generator, resistive load and speed control are similar to grid connected turbines and the same method for performance evaluation applies.

2.5 Effect of the pre-averaging time

There are three basic mechanism causing an imperfect correlation between the measured wind speed and electric power [3]:

- the time needed for the air to travel from anemometer to turbine rotor;
- the averaging effect of the rotor disc compared to a one-point measurement of the wind;
- the mechanical and electrical inertia of the system.

Time averaging reduces the effects of poor point-to-point correlation and inertial lag, acting as a low pass filter. High frequency wind fluctuations are filtered out and the inertial lag is masked if the pre-averaging time exceeds the response time constant. The averaging time should be chosen in relation to the system's response time. If it is chosen too short, the amount of scatter will be increased, which may result in misinterpretation of the measurements. If it is taken too long, important information may be filtered out and the measurement time is increased.

Hansen and Hausfeld [3] analysed this problem by deriving a transfer function for an arbitrary turbine. This transfer function is a low pass filter as well. Since a wind turbine is a highly nonlinear system and the measurement conditions will vary, the overall time constant is expected to vary as well. The analysis shows a variation of a factor 2-4 in calculated overall time constant. The size of the turbine also plays an important role, an increase in rotor diameter will shift the cutoff frequency of the low pass filter to a lower frequency.

Hansen and Hausfeld suggested to choose the averaging time of the measurements equal to the cutoff frequency of the turbine transfer function, since this will guarantee the best information transfer in the measurements. This frequency is defined by a decrease of -3 dB (a factor 0.5) in the turbine response. This method has been adopted in the PEMSWECS study.

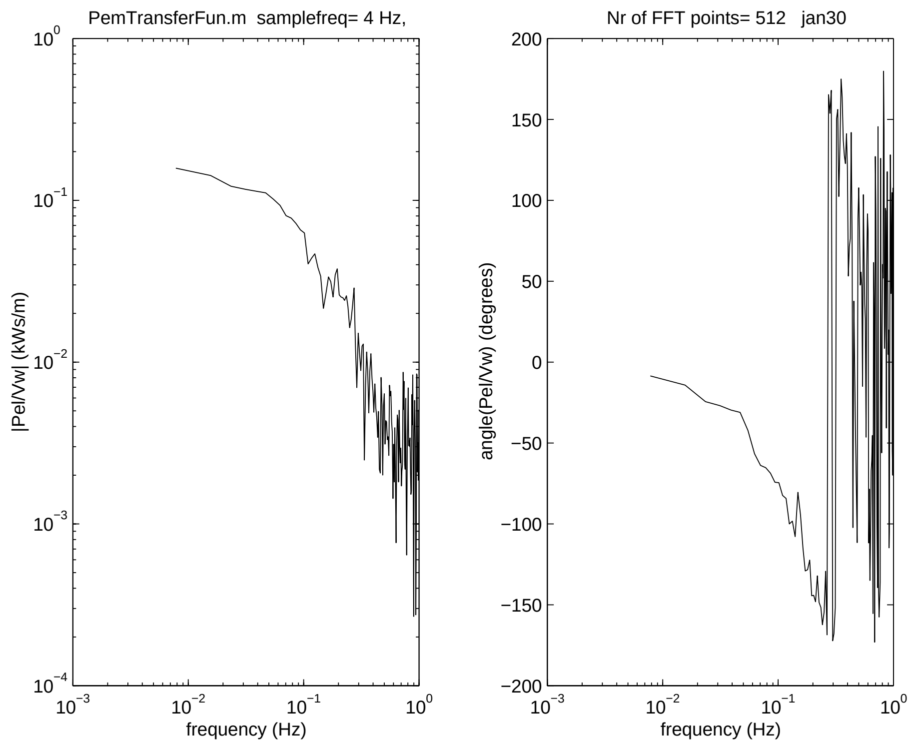

Figure 21: *Fortis Montana transfer function* $\mathrm{d}P_{el}/\mathrm{d}V_w$

Figure 21 gives the transfer function from wind speed to electric power for the Fortis Montana turbine, estimated from an 8 hour measurement with a sample frequency of 4 Hz and a length of the measurement sample used in the FFT of 512 data points (128 s). The static gain value $\Delta P_{el}/\Delta V_w$ is about 0.2 kW/(m/s), which corresponds to the value estimated from the P(V) curve. A reduction by a factor 2 of this value is reached at a frequency of 0.05 Hz, suggesting an optimal averaging time of 20 s. Compared to the values found in [3], it corresponds to those given for small turbines and favourable measurement conditions. However, the estimate should be taken as an indication, since it will depend on the operating conditions. To verify this result, the power curves of the Fortis turbine were determined for a number of sampling frequency and the differences were analysed.

2.5.1 Measured Fortis Montana Power Curves

To determine the power curves of the Fortis Montana turbine about 100 hours of measurement data were recorded at a sample frequency of 4 Hz. The measurement were taken under variable AC load, simulating real load conditions, and covering the full range of DC voltage: 115 to 143 V. The data was corrected for temperature and pressure, followed by averaging over 10, 30, 60, 120, 300 and 600 seconds. The averaged data was subsequently binned against wind speed and rotor speed to investigate the effect of the averaging time on the power-rotor speed and power-wind speed curve.

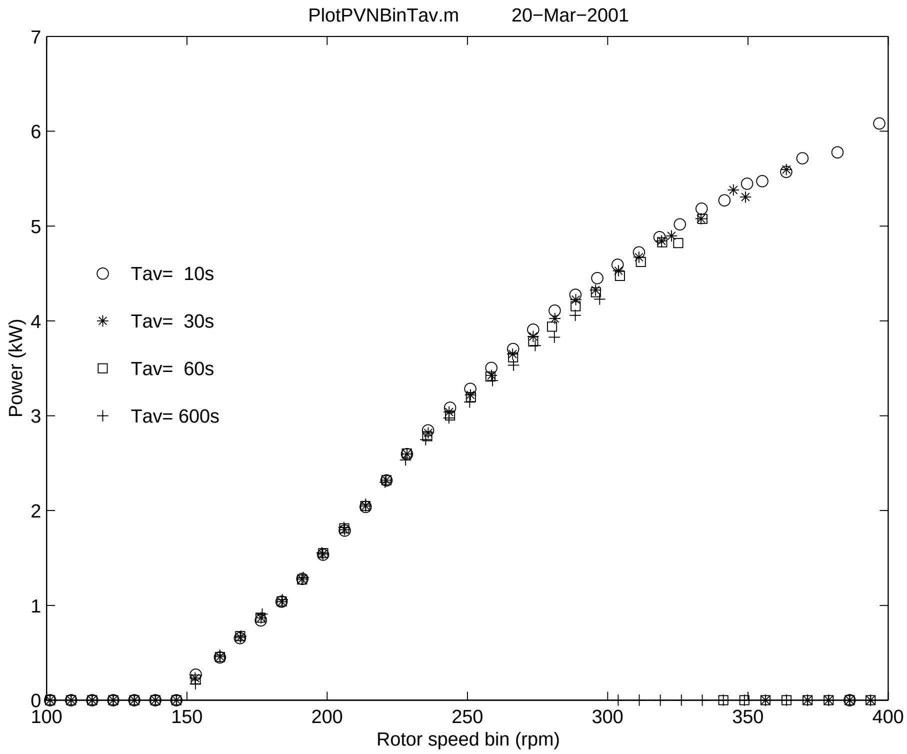

Figure 22: *Power-Rotorspeed curves for 4 averaging times*

Figure 22 gives the resulting power-rotor speed curves for 10, 30, 60 and 600 seconds. In the low speed region the differences are very small. Speeds above 260 rpm show small deviation which may be caused by the small number of data in the 600 s bins or insufficient filtering for the 10 s bins. The 30 and 60 s results are practically the same over the full range of operation. This is in agreement with the results in previous section.

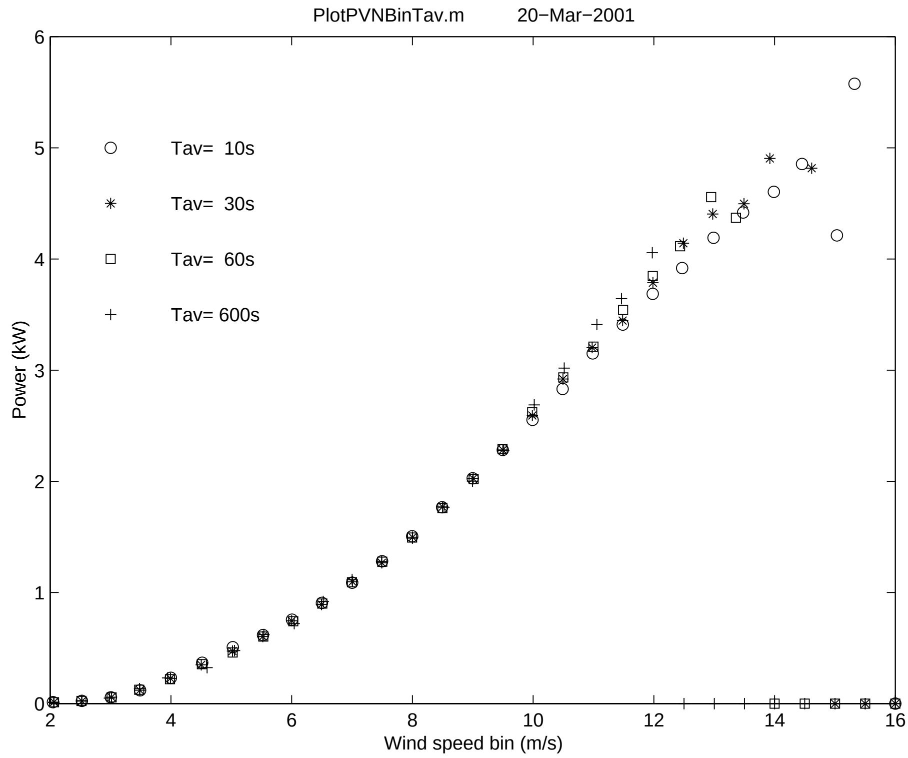

Figure 23: *Power-Windspeed curves for 4 averaging times*

Figure 23 shows the power-wind speed curves for 10, 30, 60 and 600 s averaging time. Again, the differences are small for all bins below 10 m/s, where all bins have enough data. This justifies the choice of a pre-averaging time of 30 s.

2.5.2 Measured Südwind Power Curves

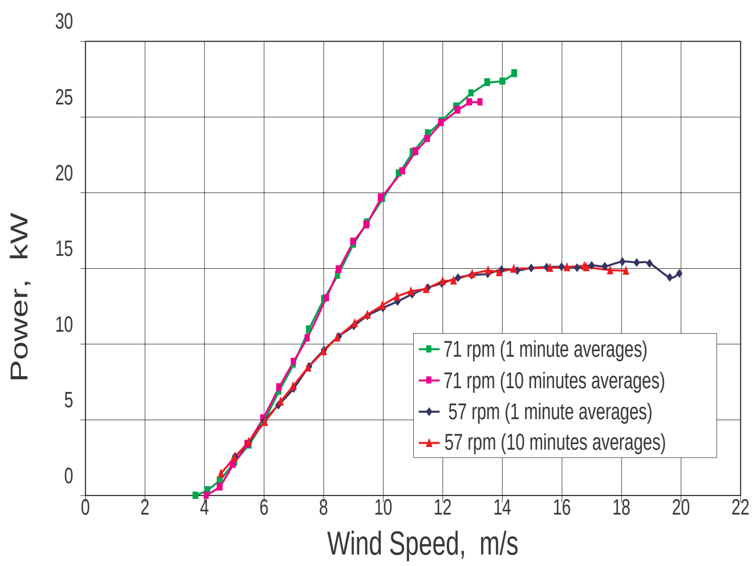

Figure 24: *Power curves at two rotor speeds for 1 and 10 minute averaging*

Figure 24 verifies the application of a 1 minute averaging time for the 12.5 m diameter Südwind turbine. It is shown that differences with the 10 minute average power-wind speed values is minimal.

Conclusion: An estimate of the optimal pre-averaging time for the 5 m diameter Fortis Montana was determined by calculating the transfer function $\mathrm{dP_{el}/dV_w}$. A value of 30 s appeared to be a good choice. This choice was verified by comparing the power curves for averaging frequencies of 10, 30, 60, 120, 300 and 600 s. The differences that were found are small or can be explained by an insufficient number of data in some of the bins. For the 12.5 m diameter Südwind turbine a 60 s pre-averaging time was verified.

2.6 Summary of recommendations

Measurements:

- Required measurements:
  - wind speed and direction;
  - electric power.
  - ambient temperature and pressure.
- Optional measurements:
  - DC voltage and current;
  - turbine rotational speed;
  - yaw angle.
- Use a sample frequency of 2 Hz or higher;
- Archive the raw 2 Hz data.
- Measured electric power should include wind power dissipated in a dump load.

Recommendations for systems with Permanent Magnet generator, diode rectifier and a number of resistive loads at the DC side of the rectifier:

- Without voltage control: perform a measurement of the power curve for the minimum and the maximum load. This will determine the best and worst performance of the system.
- With voltage control: document the setpoint(s) of the voltage control and measure the power curve for real load conditions. The load value and type is less relevant.

Recommendations for systems with permanent magnet generator, diode rectifier and charge controller directly connected to the batteries or through a downchopper:

- Consult the manufacturer or perform a scoping measurement to quantify the variation, due to load changes, of the DC voltage at the diode rectifier.
- If the voltage deviations are 30% or less, voltage changes need not to be taken into account in the power performance measurement and evaluation procedure.
- If voltage variations are not taken into account, take measurements for the power-windspeed curve under random load conditions, comparable to end user conditions.

- If the voltage deviations exceed 30%:
  - either include voltage measurement in the data acquisition and bin measurements against 3 voltage levels and evaluate the effect on the power performance;
  - or measure power-wind speed curves at the two extreme values of the DC voltage and evaluate the effect on the power performance.

Systems with synchronous generator, resistive load and speed control:

- These systems are similar to grid connected turbines and the same method for performance evaluation applies.

Recommendation for the evaluation of measurements:

- Use a pre-averaging time of 30 s for rotor diameters less than 6 m and 60 s for diameters of 6-12.5 m.
- Perform a pressure and temperature correction.

End user load prediction:

- For systems without batteries: use a statistical evaluation method.
- For systems with batteries: use a time domain model and include battery characteristics. A simple model was developed for this purpose [8].
- The effect of the battery size and battery losses is not included in the proposed measurement procedure for systems with batteries. It is proposed to evaluated this aspect separately, since it is dependent on the demand pattern of a given application.

3 ASSESSMENT OF RESULTS AND CONCLUSIONS

The conclusions drawn from this study are summarized below:

- The effect of the voltage control or voltage limitation was investigated using 2 system types. Recommendations were formulated based upon the power-wind speed curves determined from these two system types.
- The measurements and evaluations carried out in this study demonstrated the feasibility of a simple method for determining the power-wind speed curves for systems with voltage controls.
- For systems without voltage control, the size of the load will strongly influence the power performance.
- For systems with voltage control, the tuning of the controller will influence the power performance of the autonomous systems. However, the influence of the load on the power performance is small.
- With regard to the effect of the load on the power performance of the system with batteries, it was shown that, although the influence of the load on the DC voltage was substantial (a 30% variation is not unusual) the effect on the power-wind speed curve is relatively small. The effect on the yearly averaged energy production, although dependent on the wind regime, is also small: in the range of 5%. This justified the use of a simplified method for the determination of the power curve for this system type. This will satisfy the cost-effectiveness requirement of the measurements.
- The combined effects of the wind speed distribution and differences in P(V) curve on the actual energy production over a long period have been quantified.
- Systems with synchronous generator, resistive load and speed control are similar to grid connected turbines and the same method for performance evaluation applies.
- An estimate of the optimal pre-averaging time for the 5 m diameter Fortis Montana was determined by calculating the transfer function. A value of 30 s was found to be the optimum.
- This choice was verified by comparing the power curves, with averaging frequencies of 10, 30, 60, 120, 300 and 600 s. The differences were found were to be small. For the 12.5 m diameter Südwind turbine, a 60 s pre-averaging time was verified.
- Based on the results, recommendations have been made for the standardisation of power performance evaluation methods. If adopted by manufacturers and users, it is anticipated that the results of the project will give users more confidence in the performance of autonomous wind turbine systems and hence help the industry to develop. Each of the partners is using the results of the project to develop in-house test procedure and certification schemes.

4 ACKNOWLEDGEMENTS

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Abstract

This report summarizes the results of the PEMSWECS project: the development of methods for the power performance evaluation of autonomous wind turbine systems designed for electricity production. Three system types have been investigated. The emphasis was on the evaluation of the effect of the electrical load on the power production of the turbine. Measurements and simulations showed that, if certain conditions are met, a straight forward method similar to the method applied for grid connected systems is feasible.

Keywords

power performance, stand-alone wind turbines, wind energy, electric power, electrical models

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