PERFORMANCE EVALUATION METHODS FOR AUTONOMOUS, APPLICATIONS ORIENTATED WIND TURBINE SYSTEMS

J.T.G. Pierik [1], R.W. Dunlop [2], W.K. Lee [2], J. Gabriel [3]
[1] Energy research Centre of the Netherlands (ECN)
[2] National Engineering Lab (NEL), Scotland
[3] Deutsches Wind Institute (DEWI), Germany

ABSTRACT This paper describes 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: autonomous wind turbine systems, power performance evaluation, electrical systems.

1 INTRODUCTION

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 objective of the PEMSWECS project is to provide a technical basis for the standardisation of power performance evaluation methods of autonomous wind turbine systems for the generation of electricity, in the range of 100 W to about 30 kW. 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.

2 TEST SYSTEMS

The following stand alone wind turbine systems have been investigated:

- a 6 kW Proven system, 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;

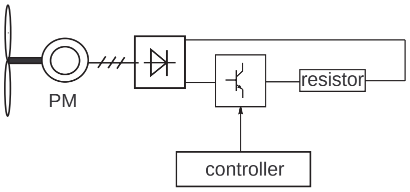

Figure 1: *Proven System with permanent magnet generator, rectifier, resistor and voltage controller*

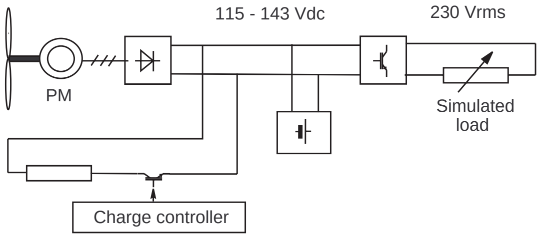

Figure 2: *Fortis system with permanent magnet generator, batteries, charge controller, inverter and AC load*

- a 4 kW Fortis Montana system with a permanent magnet generator, 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;

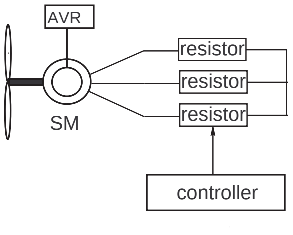

Figure 3: *Südwind system: synchronous generator, resistive load, voltage and speed control*

- a 30 kW Südwind system 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.

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

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

3 SYSTEMS WITH PM GENERATOR, RECTIFIER AND RESISTIVE LOAD

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

The Proven turbine at NEL 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 passive pitching/coning can be tuned by applying either 4 or 5 springs. 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, which is controlled by the generator 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. 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.

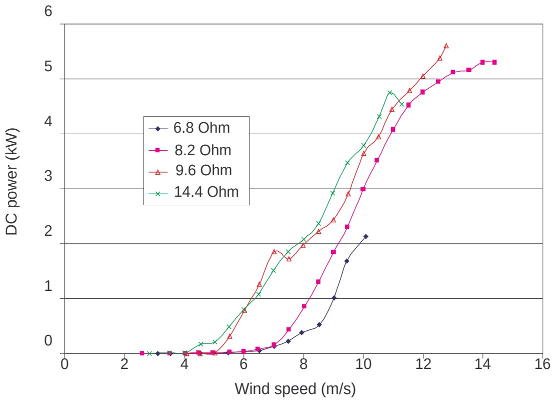

Figure 5: *DC power vs wind speed at different loads for the Proven turbine (no control of the DC voltage)*

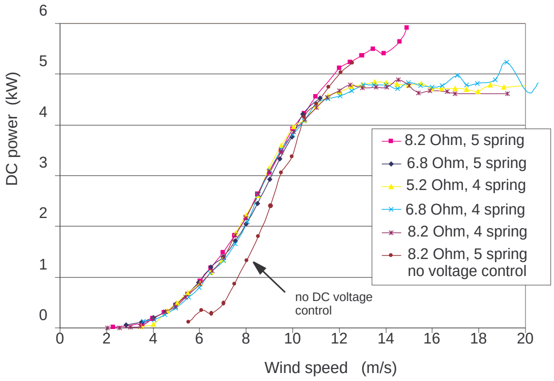

Figure 6: *DC power vs wind speed at different load for the Proven turbine (4 or 5 rotor springs)*

The effect of controlling the DC voltage is demonstrated in figure 6. 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. In systems with voltage control the tuning of the controller will influence the power performance of the autonomous system, while the influence of the load on the power performance is small.

4 SYSTEMS WITH PM GENERATOR, RECTIFIER AND BATTERIES

The Fortis Montana turbine 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 (figure 7). The three phase AC power is fed through a diode rectifier to a string of ten 12 V batteries (see figure 2). Battery charging is limited by a FET which switches on a dumpload if the DC voltage reaches 143 V. The DC voltage depends on the DC current and direction and varies between about 115 V and 143 V. The AC load is supplied by a single phase IGBT inverter.
With regard to the effect of the load on the power performance figure 8 shows that, although the influence of the load on the DC voltage is substantial, the effect on the power-windspeed curve is relatively small. In the range

Figure 7: *Fortis Montana Turbine at ECN test site*

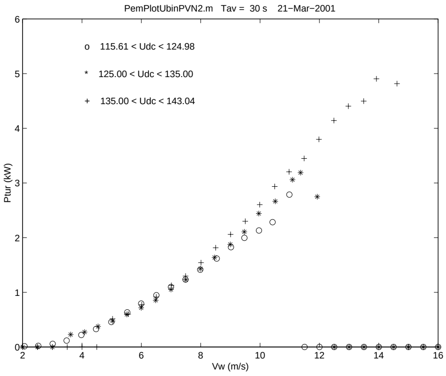

Figure 8: *Measured power-wind speed curves for 3 DC voltage levels*

above 10 m/s there is some difference, but the number of values per bin was relatively small. The small effect suggests the feasibility of a simplified method for the determination of the power curve for systems with batteries which fulfill the conditions in the measurements. The combined effect of the wind speed distribution and differences in P(V) curve on the actual energy production over a long period will now be quantified.

Figure 9 gives the energy production for the 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. The deviations from the average over all voltages is small. 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 seems to 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.

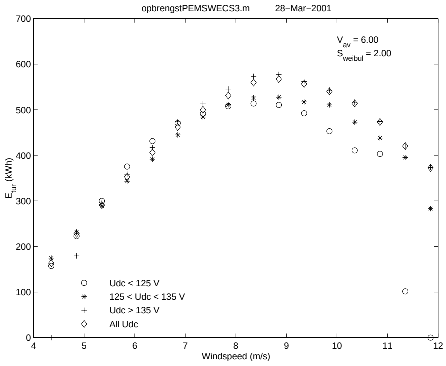

Figure 9: *Energy production for 3 DC voltage levels and the average over all voltages: Vav =6 m/s, k=2*

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%

5 EFFECT OF THE PRE-AVERAGING TIME

IEC 61400-12 suggests a pre-averaging time of 10 minutes for the evaluation of grid connected wind turbines. For small autonomous systems, this is probably too long. 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. Hansen and Hausfeld [1] analysed this problem by deriving a transfer function for an arbitrary turbine. This transfer function is a low pass filter as well. They suggest 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.

Figure 10 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). A reduction by a factor 2 is reached at a frequency of 0.05 Hz, suggesting an optimal averaging time of 20 s. This 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 have been determined for a number of sampling

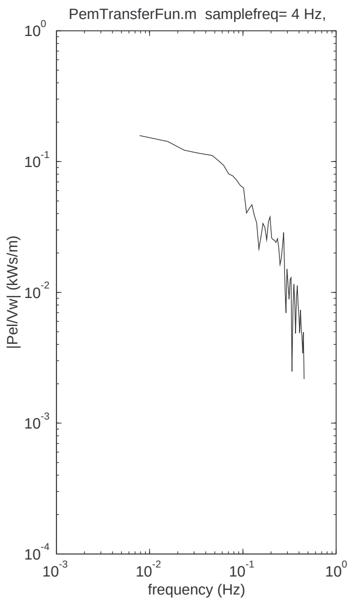

Figure 10: *Fortis Montana transfer function* $\mathrm{d}P_{el}/\mathrm{d}V_w$

frequencies and that confirmed the result.

6 SUMMARY OF RECOMMENDATIONS

Measurements for the power performance of autonomous systems:

- 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.

Systems with PM generator, diode rectifier and resistive loads at the DC side:

- 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 are less relevant.

Systems with permanent magnet generator, diode rectifier and charge limitation:

- 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-wind speed 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.

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 performance 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 [2];
- 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;

ACKNOWLEDGEMENTS

This work has been executed in the JOULE programme on Renewable Energy, on a partial grant of the European Commission and Generic R&D programmes financed by the participating countries.

REFERENCES

[1] A.C. Hansen and T.E. Hausfeld. Frequency response matching to optimize wind-turbine test data correlation. *Transactions of the ASME*, pages 246, Vol. 108, 1986.

[2] J.T.G. Pierik. Pemswecs - performance evaluation methods for autonomous, applications orientated wind turbine systems - systems with batteries. Technical Report ECN-C-01-032, ECN, 2001.