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VERIFICATION OF DESIGN LOADS FOR SMALL WIND TURBINES

FINAL REPORT
Joule 2 Project CT93-0423

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SUMMARY

The work described in this report has been carried out within the framework of the European Community Joule project JOU2-CT93-0423: Experimental verification of design loads for small wind turbines. The objective of the project was to validate the simplified calculation method in IEC 1400-2, and to formulate recommendations towards standardization bodies for the development and improvement of standards for small wind turbines.

The work was done in an international team, coordinated by ECN. Participants were CRES, DEWI, NEL and Risø.

In order to validate the method, measurements of mechanical loads have been carried out on three small wind turbines at three different test stations:
- a LMW 1003 machine, installed and tested by CRES (Greece);
- an Inventus 6 wind turbine at the test station of DEWI (Germany);
- a Proven WT2200 wind turbine installed at the test station of NEL (UK).

A similar test programme has been executed on the three machines in order to measure the loads in the six load cases, defined in IEC 1400-2. Furthermore some comparative calculations have been performed by Risø in order to check the similarities and differences with the code for small wind turbines under development in Denmark.

Within the limited project period, the majority of load cases have been investigated. From the results and experiences obtained it appears that the simplified method given in IEC 1400-2 in general is easy to use and gives a reasonable approximation. However, the applicability of the method is quite limited, and the formulation should be improved. Specific recommendations for the use of the method, necessary additions and improvements and further work to undertake have been made. These recommendations are primarily intended for IEC and European Standardization Bodies. The results are also useful for certifying bodies and wind turbine manufacturers / designers.

List of symbols

Symbol	Description	Unit
A	section area	$[m^2]$
A_{proj}	area projected on to a plane perpendicular to the wind direction.	$[m^2]$
B	number of blades	[-]
c_d	drag coefficient	[-]
e	distance between rotor and tower centre	[m]
e_r	distance from the centre of gravity of the rotor to the rotation axis	[m]
F	force	[N]
F_{xB}, F_{yB}, F_{zB}	forces on blade at the blade root	[N]
$F_{x\text{-shaft}}$, $F_{y\text{-shaft}}$, $F_{z\text{-shaft}}$	forces on the rotor shaft at the rotor attachment point	[N]
g	acceleration due to gravity	$[ms^{-2}]$
h	height above ground of the rotor shaft	[m]
I_B	blade moment of inertia	$[kgm^2]$
l_{rb}	distance from rotor centre of gravity to first bearing	[m]
M_{brake}	nominal torque of mechanical brake	[Nm]
M_{xB}, M_{yB}, M_{zB}	moments on the blade at the blade root	[Nm]
$M_{x\text{-shaft}}$	torsion moment on the rotor shaft at the first bearing	[Nm]
$M_{b\text{-shaft}}$	bending moment on the rotor shaft at the first bearing	[Nm]
m_B	mass of a blade	[kg]
m_r	mass of the rotor	[kg]
m_n	mass of the nacelle	[kg]
n	speed of the rotor	[rpm]
n_{max}	maximum speed of the rotor	[rpm]
n_R	rotor speed at rated wind speed	[rpm]
P_R	SWTGS rated power	[W]
Q_R	rotor shaft torque at rated wind speed	[Nm]
R	radius of the rotor	[m]
R_{cgB}	distance blade centre of gravity to blade root - hub junction	[m]
R_{char}	characteristic material strength	$[Nm^{-2}]$
V_{in}	cut in wind speed	$[ms^{-1}]$
V_{out}	cut out wind speed	$[ms^{-1}]$
V_{hub}	wind speed at rotor shaft height	$[ms^{-1}]$
V_R	lowest wind speed at which the wind turbine delivers the installed generator power	$[ms^{-1}]$
V_{exr}	reference 50 years wind speed at hub height	$[ms^{-1}]$
W_b	section modulus	$[m^3]$
γ	safety factor	[-]
η	efficiency	
λ_R	tip speed ratio at V_R	[-]
ρ	density of air	$[kgm^{-3}]$
σ	stress	$[Nm^{-2}]$
σ_d	design stress (calculated from design loads)	$[Nm^{-2}]$
σ_{eq}	equivalent stress	$[Nm^{-2}]$
τ	shear stress	$[Nm^{-2}]$
ω	angular rate of yawing	$[s^{-1}]$

1. Introduction

1.1 Background

The scope of the project described in this report encompasses wind turbines with a swept area less than 40 m^2 (rotor diameter < 7 m) and a maximum rated power of about 10 kW. Wind turbine technology of this size can play an import role in the energy supply in remote areas, also in combination with other renewable energy sources (e.g. hybrid PV - wind energy systems). The present market for small wind turbines seems to be quite substantial. The actual number of small wind turbines is of the estimated order of magnitude 10^5 machines installed worldwide, and the growth rate amounts to approximately 10^4 units per year. The market relies on the supply by mostly small manufacturers. A drawback often encountered is that these have limited possibilities and support for research and product development, as compared to manufacturers of larger wind turbines. Sometimes this results in poor product quality and limited machine life-time. An adequate method to ascertain the safety and quality of small wind turbines certainly would be their verification and certification according to recognized standards. Manufacturers can obtain valuable feedback for optimisation of product quality and reliability by the certification process. Inferior products are more likely to be excluded from the market. However, to use the same standard as developed for larger wind turbines (IEC 1400-1) would put a too heavy burden on the designer because of the complexity of design calculations involved and would lead to an unnecessary increase of the engineering costs. The following considerations lead to the establishment of a separate standard for small wind turbines:

- in contrast to the larger machines, there is a need to demonstrate the engineering integrity primarily by testing;
- the machines are purchased by the general public for installation on unprotected access locations for private users;
- the equipment is seldom interfaced to a utility grid;
- the systems may include a storage system (batteries).

With these arguments, the technical committee TC88 of the International Electrotechnical Commission (IEC) formed a working group (IEC-TC88-WG4) in 1992 and prepared a standard IEC-1400-2 for small wind turbines with swept area less than 40 m^2 [1]. Structural design requirements have been formulated in this standard that do not involve extensive and costly calculation procedures. A method is specified which allows the calculation of design loads and the design stresses in a simplified way. The project described in this report has been set up in order to check the validity of this simplified method of IEC 1400-2 by load measurements on small wind turbines.
During the course of the present project, which started early 1994, a demonstration programme was initiated in Denmark to support the introduction of so-called household wind turbines in Denmark. Within this programme, an approval procedure was included in which the implemented technologies are assessed according to a set of technical regulations. As a part of these regulations specific rules for the calculations of the loads have been established. It has been considered useful in this project to also look at this development and to compare the Danish approach with the IEC method.

1.2 Objectives of the project

The long term objective is to promote the utilization of small wind turbines as an ecologically benign technology for power generation in remote areas. A necessary step towards this objective is a consolidation of the technology. For this goal, adequate (international) standards should be available. The aim of the present project is to obtain experimental evidence in order to validate and if necessary improve the existing (international) standard for small wind turbines.

The immediate objectives of the project are:
- to compare the design loads of small stand alone wind turbines, calculated by the IEC 1400-2 standard for small wind turbines, ref.[1], with load measurements carried out on different types of machines installed on different site types,
- to contribute to the development of standards and uniform test methods for small stand alone wind turbines within the EC.

1.3 Project information (principal, partners etc.)

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Project partners:

Centre for Renewable Energy Sources CRES (Greece);
National Engineering Laboratory NEL (UK);
Deutsches Windenergie-Institut DEWI (Germany);
Risø National Laboratories (Denmark).

The project has been carried out within the Joule 2 programme (Contract JOU2-CT93-0423)

The project started in January 1994. The planned project period was 18 months. Due to delays in contracting of partners and procurement of wind turbines and due to abnormal low wind conditions in 1995, an extension of the end date has been granted by the European Commission to the end of 1995.

Additional information about this project can be found in references [6], [7], [8] and [9].

1.4 Project organization

The involvement of the main participants in the various project tasks is outlined below:

Phase I	Task		ECN	CRES	DEWI	NEL	RISØ
	I.1	kick-off meeting	●	●	●	●	●
	I.2	site preparation		●	●	●	
	I.3	installation of WT		●		●	
	I.4	instrumentation		●	●	●	
	I.5	organization of data flow	●	●	●	●	●
	I.6	progress meeting	●	●	●	●	●
Phase II	II.1	IEC calculation	●	●	●	●	
	II.2	measurements + data processing		●	●	●	
	II.3	progress meeting	●	●	●	●	●
Phase III	III.1	preparation data comparison format	●				
	III.2	comparison calculations / measurements	●	●	●	●	●
	III.3	evaluation	●	●	●	●	●
	III.4	final meeting	●	●	●	●	●
	III.5	final report	●	●	●	●	●

1.5 This report

This report contains the overall description of the project, and the main results, conclusions and recommendations. Details of applied methods and measurement results are given in appendices. Where possible reference has been made to publications and other project documents.
The report first gives an overview of the method followed (Chapter 2), containing description of the wind turbines tested, the measurement method used and the calculation procedure followed. In Chapter 3 the results of measurements and calculations are presented per tested wind turbine. In Chapter 4 an overall discussion is given of the results based on the comparison of measurements and calculations. In Chapter 5 recommendations are formulated based on the experience of testing and calculations towards users of the method specified in IEC 1400-2. Chapter 6 contains recommendations for IEC and European Standardization bodies on how to improve the present version of the standard for small wind turbines.

2. Description of the project method

2.1 General

In this chapter, the method for carrying out the verification is presented in detail. For the purpose of verification of the simplified method in IEC 1400-2, a load measurement programme has been carried out on three small wind turbines at different test sites in Europe. The selection of machines reflects the variety of available types. Wind turbine sizes from 3 to 6 m diameter and various concepts have been selected, procured and installed at the test sites. Measurement systems have been designed, procured and implemented for the load measurement programme.

The three test locations reflect various types of terrain:
- a complex terrain site: the CRES test site at Lavrio (Greece);
- a site with very high wind speeds: the NEL test site at East Kilbride (Scotland) ;
- a flat terrain site: the DEWI site at Wilhemshaven (Germany)

For each of the three wind turbines a similar set of measurements has been carried out. The measuring period was approximately 12 months. The principal mechanical loads have been measured in selected sections of the blades, shaft and the supporting structure at various average wind speeds in the operational range of the wind turbine in order to validate the load cases defined in the simplified method given in the IEC 1400-2 standard [1].

The measured loads have been compared with the corresponding calculated values based on the method described in the IEC 1400-2 document. Furthermore the measurements and calculations have also been compared with the results of calculations based on alternative methods, such as a Code developed in Denmark for small wind turbines. This comparison is presented in Chapter 4.

Based on the results of this comparative analysis, conclusions are formulated with respect to the validity and applicability of the method. These aspects are discussed in Chapters 5 and 6.

2.2 Description of the test wind turbines

2.2.1 General

The main characteristics of the wind turbines are summarized in Table 2.1.

Table 2.1 *Main characteristics of the selected wind turbines used for the verification.*

Measuring institute	CRES	NEL	DEWI
site	Lavrio (Greece)	Myres Hill (Scotland)	Wilhelmshaven (Germany)
manufacturer	LMW (NL)	PROVEN (UK)	WENUS (D)
type	LMW 1003	WT 2200	Inventus 6
diameter (m)	3.0	3.4	6
rated power (kW)	1	2.2	5 (el.) 1) 2.5 (mech.) 2)
number of blades	3	3	4
yawing	passive (hinged) tail vane	passive down wind orientation	passive (fixed) tail vane
rotor type	rigid hub, cantilever blades	flexible blade root flap + zebadee hinge	rigid hub supported blades
power regulation	horizontal furling	passive blade pitch regulation + rotor coning	passive blade pitch regulation
conversion system	pm generator variable speed stand-alone operation	pm generator variable speed for stand-alone operation	asynchronous generator 2-speed grid connected
hub height (m)	9	6.5	13
type of tower	tubular steel free standing	tubular steel free standing	tubular steel guyed

1) operated with asynchronous grid connected generator
2) mechanically connected to heat pump compressor

As can be seen the machines are quite different from each other, both in size and type of design. From the start of the project it was clear that not all the turbines are appropriate for the application of the calculation method of IEC. Especially the Proven WT2200 with its flexible rotor blades does not comply to the requirement: rigid hub, cantilever blades.

The advantage of this wind turbine selection however is that it can be checked if the method is applicable or not, allowing some conclusions about the useablility of the method, and giving practical indications for further elaboration of the standard.

2.2.2 Details per wind turbine

LMW 1003

General description

The wind turbine is a 3-bladed upwind horizontal axis machine directly driving a permanent magnet alternator. The variable frequency, variable voltage output of the alternator is rectified to DC by a voltage control system which also regulates the charging current depending on the battery state of charge. Turbine overspeeding is controlled automatically by turning the rotor out of the wind at high wind speeds. An electrical brake is used to bring the rotor to a standstill by short-circuiting the alternator terminals (only for low wind speeds).

Fig. 2.1 *The LMW 1003 at Lavrio test station of CRES*

The tower and foundation

The tower has been constructed according to the initial LMW design, but a modification was found necessary in order to install the strain gauges for the tower bending moment measurements. At the bottom part of the tower, a tubular section of 40 cm height has been added. This section is connected to the main part via nuts and bolts and has the same dimensions with the main part (30 cm diameter and 3 mm thickness). All the parts of the tower have been hot dip galvanised and finished in white colour. The foundation consists of a reinforced concrete block B225 of 2 x 2 x 1 m^3. A special construction has been provided near the tower bottom to support the housing of the measurement equipment.

Remarks to applicability for the project

The rotor type allows the application of the simplified method. The behaviour of the yaw system however (for power control) is difficult to model and calculate. The tower has been specially adapted in order to measure directly the bending moments. The omission of the guy wires however results in freedom for excitation of the tower and tail vane natural frequencies in the operational range of rotor speeds.

Table 2.2 : *Technical specifications of LMW 1003 from manufacturers information*

Max. output	:	1100 W
Rated output	:	600 W
Wind speed		
cut in	:	2.5 m/s
rated	:	7 m/s
survival	:	60 m/s
Rotor		
number of blades	:	3
diameter	:	3.0 m
swept area	:	7.07 m^2
airfoil	:	NACA 4418
tip speed ratio	:	6.08
material	:	glass-fibre reinforced polyester
hub type	:	rigid
Generator:		
type	:	brushless permanent magnet 12-pole
rated rpm	:	320
max. rpm	:	775
voltage	:	24 VDC
frequency	:	0-70 Hz
Other:		
braking mechanism	:	turning tail 90^o / electrical brake
rotor speed control	:	inclined hinged vane
output control	:	voltage control with dump load.
rectifiers	:	built inside controller.
yaw system	:	tail vane
tower	:	steel tubular, height 9 m

Proven WT2200

General description

The Proven turbine is of three-bladed, downwind design, with a rated power of 2.2 kW. The conceptual design and manufacture of the rotor and generator have been carried out in-house by Proven Engineering at their factory in Kilmarnock, Scotland along with the fabrication and assembly of the remainder of the turbine.

The main feature of the turbine is the rotor which is of both novel construction and concept. The generator, which is driven directly by the rotor, outputs to an electronic control system which can be configured to manage a number of possible electrical loads. In practical terms, operation of the turbine is not restricted by wind speed as the passively regulated rotor will continue to protect the systems up to the design maximum wind speed. A hand-operated disk brake is provided to park the rotor during lowering and raising of the tower. A detailed description of the wind turbine and the principles behind the rotor design is given in [4].

Description of the rotor

The rotor blades are manufactured in one piece from polypropylene sheet using a purpose built tool to apply heat and vacuum to form the aerofoil section. Two hinges are formed at the root of each blade by compressing the polypropylene sheet to a very small depth. The orientation of the hinges is such that one is parallel to the blade chord line hence allowing a pure flap deflection of the blade whereas the other is at an angle to the chord line and causes a flap and pitch change to be coupled. The hinge region is strengthened by sandwiching the blade area between the two hinges between a pair of triangular steel plates. The steel plates also provide a hard point for attachment of one end of a spring which constrains the deflection of the hinges to the desired limits. The other end of the spring is attached to a point on the hub. The hinge arrangement ensures coarse pitch to assist start-up which gradually reduces to fine pitch under the action of centrifugal forces as the rotational speed increases. Therefore, during each phase of operation, the instantaneous rotor geometry results from a balance between aerodynamic, centrifugal and spring forces. In high wind speeds, the rotor power is regulated by stalling as any increase in aerodynamic torque is accompanied by an increase in rotor speed which feathers the blades further into stall.

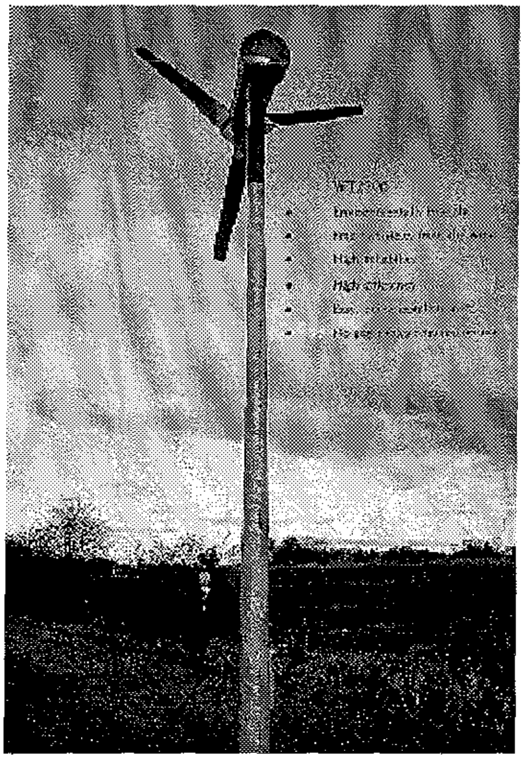
Remarks to applicability for the project

The rotor is not of rigid hub type. Therefore the simplified IEC method is not applicable in principle. Especially for the blade root moments calculations are not relevant. Moreover they cannot be measured in a straightforward way. An attempt has been made to measure the displacements in the blade root and to establish a method to correlate those to load values. The results of this attempt are further discussed in Chapter 3.

Some of the loads e.g. shaft loads and tower loads can be measured and calculated even for this concept. It has been considered useful to perform these calculations in order to check the limits of applicability of the IEC-method.

Table 2.3 *Technical specifications of Proven WT2200 from manufacturer's information*

Rated Power	2200 Watts
Rotor Diameter	3.4 m
Number of Blades	3
Blade Material	Polypropylene
Rotor Orientation	Horizontal axis, down wind
Rotor Power Regulation	Passive coupled coning and pitch
Nominal Rotor Speed	300 rpm
Rotor Bearings	Sealed-for-life self-aligning ball bearings
Generator Type	Permanent magnet 120V
Transmission	Direct drive
Yaw System	Free yaw / downwind
Yaw Bearing	PTFE bush and ball bearing
Tower Height	6.5 m
Tower Construction	Cantilevered, hollow, tapered, galvanised steel
Tower Diameter	150 mm at top, 300 mm at bottom
Rotor Safety Brake	Disc brake operated by cable from tower base
Mass of Turbine & generator	200 kg
Design Survival Wind speed	75 m/s



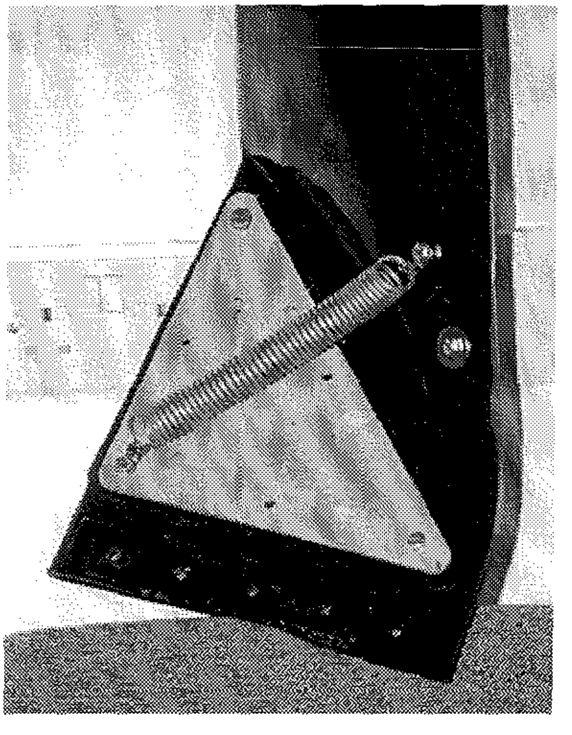


Fig. 2.2 *The Proven WT2200 and detail of it's rotor blade*

Inventus 6

General description

The wind turbine Inventus 6 (13) S is of 4-bladed up-wind design, rotor diameter 6 m, and with a rated electrical power of 5 kW. The wind turbine is built by the manufacturer Wenus Windenergie-Nutzungs-Systeme in Erftstadt (Germany). The electrical system consists of a two stage asynchronous generator, connected to the grid. The first power stage produces 1.5 kW at a generator speed of 1000 min^{-1}. The second power stage is laid out for a generator speed of 1500 min^{-1} and produces a maximum electrical power of 5 kW. The machine can also be supplied with a mechanical output (rotating shaft to down-tower) via a bevel gearbox. The Inventus is standing on a tiltable steel tower with four guy wires.

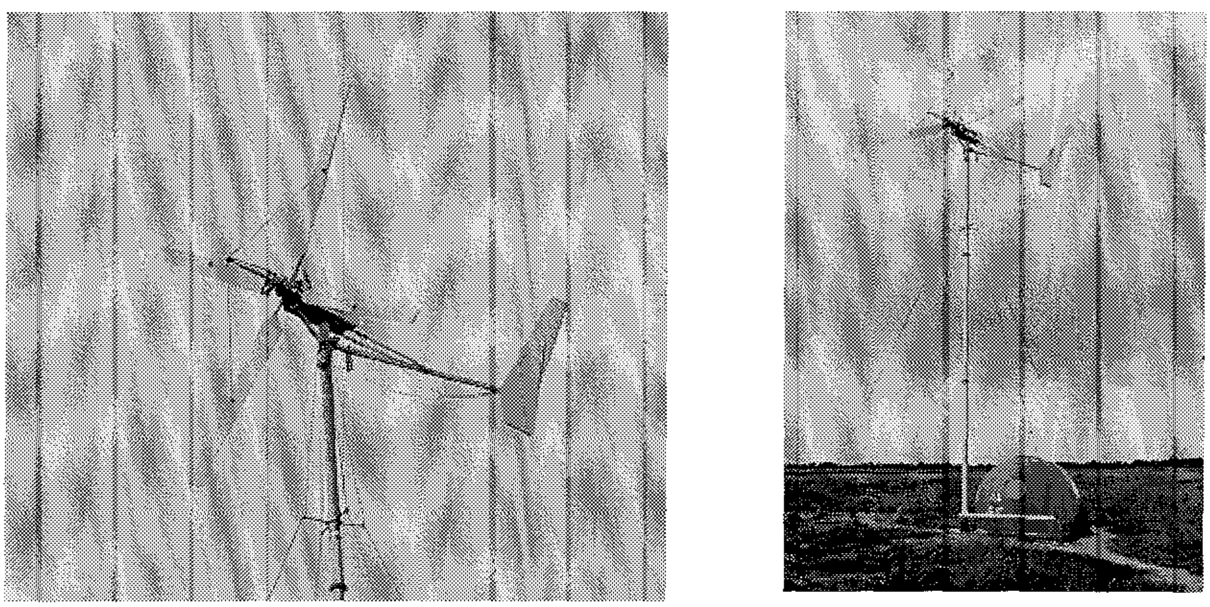


Fig.2.3. *The Inventus 6 wind turbine at the test station of DEWI.*

Control and safety systems

The aerodynamic power regulation of the turbine is realized by passive blade pitch control, using the aerodynamic forces to pitch the blades. With increasing wind speed the lift forces and the resulting pitching moment are reduced through the increased pitch angle of the blade, resulting in a constant moment and power of the rotor.

For yawing, the Inventus 6 has a tail vane. The vane is made of a straw composite sandwich construction. It has a surface of 2.34 m^2 and weighs only about 20 kg. The material has been developed at the Wilhelm-Klauditz-Institute (work group for wood research).

The wind turbine is equipped with a vibration protection system that disconnects the generator from the load and activates the mechanical brake. The fail-safe mechanical brake is pneumatically released and spring force applied. The brake can only be released when the fault current breaker is disactivated manually.

Remarks to the applicability for the project

The rotor blades of the wind turbine are connected by struts to a rod protruding from the hub (the so-called pitch rod). Part of the loads on the blades is carried by these struts. As such, the blades are not completely cantilevered. In the interpretation of the load measurements, this effect has to be taken into account.

Table 2.4 *Technical specifications Inventus 6 from manufacturers information*

rotor	
diameter	6 m
number of blades	4
airfoil	NACA 4415
rotor type	upwind (negative cone angle 7°)
rated rotational speed	128 min^{-1}
construction of the blades	composite of steel and GRP
tower	
hub height	13 m
construction	tubular guyed steel tower
control / safety systems	
power regulation	passive mechanical blade pitching
yawing	tail vane
braking system	fail-safe disk brake
drive train	
gear	2-stage / transmission ratio 1:12.11
generator	asynchronous generator
power rating	
rated power	5 kW
cut-in wind speed	app. 3.5 m/s
rated wind speed	app. 10.5 m/s

2.3 Calculations

2.3.1 General

The loads calculated by the simplified method, recommended in IEC 1400-2 have been evaluated. For reference purposes also a method used in Denmark has been evaluated. A brief explanation of the calculation methods applied follows in this paragraph.

2.3.2 IEC method

The IEC standard 1400-2 for small wind turbines [1] contains a recommended practice for a simplified load calculation procedure on small wind turbines. In general the method is only valid for horizontal axis wind turbines with rigid hub and cantilever blades. To reduce the number of calculations and to simplify the calculations to be performed, only a limited number of load cases have to be considered in this procedure. If this method is applied, the influences of dynamics are assumed to be incorporated in the conservatism of the calculations. The conservatism is considered to be both in load assumptions and in safety factors.

In contrast to the IEC1400-1 [2], only two wind turbine classes are defined i.e. a normal class and a special class. Only one wind speed value is design driving for the normal class: the so-called reference wind speed V_{exr} of 35 m/s.

Six load cases have to be assessed by means of equations calculating the relevant extreme and fatigue loads for the most critical sections: blade root, shaft and tower. Rather than using a complicated wind model, the operational loads are based on the rated power and rated rotational speed of the machine. The load cases are listed in Table 2.5. Contrary to the approach in IEC 1400-1, a single safety factor has to be applied to the calculated load (ranges) in order to evaluate the design stresses in the relevant construction sections.

For the load case *normal operation* it is assumed that the design load is a fatigue load. To determine the range of the forces and moments in the root of the blades it is assumed that:
- the aerodynamic forces act on the blade at 2/3 R and on the z-axis of the blade;
- the electrical power output varies cyclically between $1.5 * P_R$ and $0.5 * P_R$, where P_R is the rated electrical power;
- the rotor speed varies cyclically between $1.5 * n_R$ and $0.5 * n_R$

The ranges are to be considered in the fatigue assessment as peak to peak values.

The ultimate loads are assumed to occur in the following load cases:
- yawing at maximum yaw speed, at V_R;
- loss of electrical connection : calculations have to be done with the maximum rotational speed at $V = 35$ m/s;
- normal shut-down with a mechanical brake (not relevant for many small machines);

- parking at 49 m/s with minimum exposed area, and at 35 m/s with maximum exposed area due to faulty feather or yaw control.

The method consists of a set of equations. For information, these are given in Appendix 1. For the purpose of a common calculation method, these equations have been programmed in a spreadsheet.

Table 2.5 *Design load cases for the simplified load calculation method of IEC standard for small wind turbines [1].*

DESIGN SITUATION	LOAD CASE		WIND INFLOW	TYPE OF ANALYSIS	REMARKS
Power production	A	Cyclic wind loading during normal operation	Cyclic varying wind speed around V_R	Fatigue	Power alternates cyclically between $1.5 * P_R$ and $0.5 P_R$ Rotor speed alternates cyclically between $1.5 * n_R$ and $0.5 n_R$
	B	Yawing	$V_{hub} = V_R$	Ultimate loads	maximum possible yaw speed
	C	Loss of electrical connection	$V_{hub} = V_{exr}$	Ultimate loads	measure the rotor speed at normal wind speed and extrapolate to V_{exr}
Shut-down	D	Normal shut-down	$V_{hub} = V_R$	Ultimate loads	braking torque
Parked	E	Minimum exposure	$V_{hub} = 1.4 * V_{exr}$	Ultimate loads	normal parking position
	F	Maximum exposure	$V_{hub} = V_{exr}$	Ultimate loads	maximum attack area

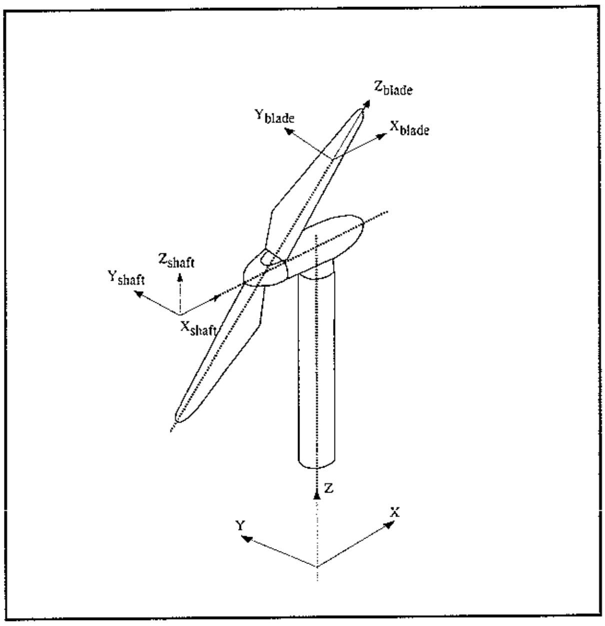


Fig. 2.4 *System of axes used in calculations and measurements*

2.3.3 Other methods

2.3.3.1 Danish demonstration programme for small wind turbines

In 1994 the Danish Energy Agency has initiated a demonstration programme for small wind turbines (so called household wind turbines). The programme is set up for wind turbines within the following dimensions:

2 m < rotor diameter < 13 m
Maximum power < 25 kW
Maximum height to blade tip < 25 m

About 50-80 turbines were expected to be erected during 1995 under this demonstration programme.

To put some quality demands on the manufacturers, a new simple set of rules for calculation of loads has been developed. The demonstration programme offers the opportunity to validate the calculations for a broad range of concepts. A major problem is to take into account in a simple manner the structural response of the complete turbine.
The basis has been a simplification of the method in DS-472 [3], which is verified through measurements on several wind turbines of different sizes. A complication is that the method is only valid for the "Danish concept".

This so-called "reference concept" of DS 472 implies:

3 Blades
Rigid hub
Active yawing
Constant speed
Stall regulated
Cut-out wind speed 25 m/sec

Load calculations for different concepts are executed by multiplying by a factor associated to the specified concept. The determination of the factors has been carried out by calculation with the aeroelastic code JTP-HawC.
Equivalent loads for the different concepts have been compared with those from the reference concept. The factors are expected to be verified during the demonstration period, where profound measurements will be carried out on each new concept.

During 1995 the Danish rules for small wind turbines have been applied to assess the design documentation of 5-6 wind turbines from 4 kW to 22 kW, with rotor diameter from 5 m to 13 m. In connection with the demonstration programme a measuring project has been prepared. The project includes collection of statistical data on all turbines, such as energy production, availability, faults and repair as may arise. On one representative turbine of each type more intensive measurements are carried out, i.e. power curve, yaw stability, noise, and brake efficiency. On turbines which differ from the "reference concept" blade loads and rotor loads are measured too.

2.3.3.2 Some details of the Danish code for small wind turbines

Load case A, normal operation

As basis for the load calculations a characteristic aerodynamic load value p_0 is evaluated. p_0 is defined as the x-component of the aerodynamic line load at 2/3 blade radius.

The load distribution along the blade is supposed to be triangular i.e. p_0*r/R.

$$p_0 = 0.5 * \rho * W^2 * c_{2/3} * C_{lmax}$$

W	:	relative windspeed = $((\omega_{rated} * 2/3 * R)^2 + V_{rated}^2)^{0.5}$
$c_{2/3}$	:	chord at 2/3 radius
C_{lmax}	:	max. lift coefficient at V_{rated}

In DS 472 this expression is used together with a function for the wind speed distribution to create a load spectrum. In the rules for the small turbines the highest level from this spectrum is used as an equivalent load for the entire life (20 years). This implies a certain amount of conservatism, which is decreasing for smaller turbines.

Concerning turbine concepts which differ from the "reference concept" loads are adjusted by means of "concept factors" multiplied on each load component. The "concept factors" are calculated with the aerodynamic code JPT-HAWC. Only factors applied to actual turbine concepts on the Danish market are calculated at present. In the loads are included load components from gyroscopic loads, gravity loads and to some extent dynamic response.

The safety factors to be applied are given in Table 2.6 and compared to the IEC 1400-2 values.

Table 2.6 *Safety factors in IEC 1400-2 and Danish code*

DK code			**IEC code**		
Safety factor		remark	Safety factor		remark
γ_l	1.0		γ_l	1.0	
$\gamma_{m\ steel}$	1.72	blades,hub, main shaft	$\gamma_{m\ steel}$	10.0	including conversion from ultimate tensile strength to fatigue strength of 10
$\gamma_{m\ steel}$	1.56	other structures			
$\gamma_{m\ wood}$	1.87	blades,hub, main shaft	$\gamma_{m\ wood}$	10.0	including conversion from ultimate tensile strength to fatigue strength of 8
$\gamma_{m\ wood}$	1.70	other structures			
$\gamma_{m\ GRP}$	1.87	blades,hub, main shaft	$\gamma_{m\ GRP}$	10.0	
$\gamma_{m\ GRP}$	1.70	other structures			

2.4 Measurements

2.4.1 Measured quantities

The measured quantities are listed in Table 2.7.

Table 2.7 *Measured quantities at the different test wind turbines*

Measurement location	PARAMETERS	LMW (CRES)	INVENTUS (DEWI)	PROVEN (NEL)
ROTOR / BLADES	edgewise bending moment	○	●	○
	flapwise bending moment	●	●	○
	cone angle	○	○	●
	pitch force	○	●	○
SHAFT	torque	○	● fast shaft	●
	rotational speed	●	●	●
NACELLE	yaw angle / yaw speed	●	●	●
TOWER	tower collar bending	○	●	○
	tower bottom bending	●	○	●
ENERGY CONVERSION SYSTEM	electrical power output	●	●	●
	generator frequency	●	○	○

Legend: ●: implemented
○: not available / not applicable

2.4.2 Measurement programme

The measurement programme has been set up systematically in order to collect the load data in the load cases defined in IEC 1400-2. The equation numbers refer to the equations in ref.1, also given in Appendix 1.

DETERMINATION OF TIP SPEED RATIO AND RATED TORQUE

In order to be able to calculate λ_R and Q_R (equations 1) the power curve of the machine has to be measured. From the power curve and the rotational speed characteristic P_R, v_R, and the rotational speed at v_R have to be derived.

LOAD CASE A (FATIGUE)

For comparison with calculations, **load ranges** should be measured, i.e. load differences within load cycles (peak to peak values). The calculation method assumes a constant range, which should result in stresses below the fatigue limit.
In reality the ranges are variable and should be measured throughout the entire operational wind speed range of the machine. In order to cover the windspeed range, four wind speed classes are defined

I	$5 < v < 10$ m/s
II	$10 < v < 15$ m/s
III	$15 < v < 20$ m/s
IV	$v > 20$ m/s

In each of the four classes 10 samples of 1 minute have to be measured. In order to obtain equally divided data throughout the class, the mean wind speeds of the samples should be equally divided throughout the class. In total 40 samples should be measured.

To get representative fatigue data the turbulence intensity level of the windspeed in the 1 minute sample should be between 0.1 and 0.2.

Four times the standard deviation of the measured data within the class will be determined as the representative load amplitude to compare with the calculated value.

From these measurements, 4 numbers result for the 3 blade quantities (ΔM_{xB}, ΔM_{yB} and ΔF_{zB}) and the 3 shaft quantities ($\Delta M_{x\text{-shaft}}$, $\Delta M_{y\text{-shaft}}$ and $\Delta F_{x\text{-shaft}}$).

In order to determine the influence of the yaw loads, for each of the 40 samples the average yaw speed and the maximum yaw speed should be registered. (See also load case B).

LOAD CASE B (YAWING)

The assumed loads (see IEC method) are mainly based upon inertia loads of which the uncertainty is rather low. On the other hand the loads are difficult to measure. The individual terms in the equations are difficult to evaluate. The measurements therefore are concentrated on the determination of the maximum yaw speed, to be used as design parameter in equations 6,7 and 8.
The **maximum yaw speed** ω_{MAX} has to be determined from measurements for the 4 wind classes and compared with the value specified by the manufacturer and also by the IEC method.

LOAD CASE C (LOSS OF LOAD)

Similar considerations as for load case B can be made here. The measurements concentrate on the determination of the maximum rotational speed.
The **maximum rotational speed** should be determined from measurements in the four wind classes and should be extrapolated to v_{out}. The experiment should be done e.g. at the lowest wind speed value of each class (5, 10, 15 and 20 m/s) by disconnecting the load. If possible, measure F_z.

LOAD CASE D (SHUT DOWN)

The brake loads, if applicable, should be measured in the four wind classes (lower class limit).

LOAD CASES E AND F (PARKED)

The loads on the parked turbine should be measured on the tower (foot or collar) in the four wind classes (lower class limit), both for minimum and maximum exposure of the rotor to the inflowing wind.

The form to be completed by the measuring institutes is given in Appendix 2.

2.4.3 Detailed description of the measurement method per test site

2.4.3.1 The LMW 1003 turbine at the CRES site in Lavrio

Site

The location of the wind turbine is situated 40 m SSE from the 100 kW Wincon machine on the Lavrio site of CRES. The prevailing wind direction is NNE. Annual average wind speed 6.5 to 7.0 m/s. Wind measurements are taken from a 10 m mast, at a distance of 10 m from the wind turbine in the prevailing wind direction. Other meteo parameters (temperature, air pressure) are taken from existing instruments on the 30 m mast.

Instrumentation

Blade flapwise bending moment
Full bridge strain gauge on the root of one blade and 350 ohm bridge amplifier of HBM. The signal is transmitted via HBM telemetry FM transmitter with DC excitation housed in the rotor hub, to the receiver on the wind turbine. A 6.0 Volts rechargeable battery system is used for power supply.

Yaw meter
Pulse output rotation encoder mounted on the top of the tower, driven by means of a small gear coupled via belt to another gear on the rotating part of the machine. Additionally, a proximity sensor has been installed, to set up the zero yaw position.

Rotational speed and power output
Rotational speed is calculated from direct measurement of frequency at the AC part of the controller, while power output is calculated from current and voltage at the DC part.

Tower bottom bending moment
Two full bridges of 350 ohm of KYOWA.

Meteo parameters
A set of calibrated wind speed-direction sensors (NRG) and a set of temperature and pressure sensors.

All data from signals are recorded by means of two CR10 data logger units of CAMPBELL Inc. and shown in Table 2.8. The sampling rates have been specified with the criterion of at least 6 points per full load cycle. For that reason, the first eigenfrequency of the blade was measured and found to be 9.0 Hz, using an accelerometer.

Calibration

The calibration of strain gauges on the blade root has been carried out in the laboratory. The instrumented blade has been mounted on the rotor hub in horizontal position and bending moments up to 150 Nm acted on it. The unloaded point (zero b.m.) was set up with the blade being in vertical position. The calibration of tower bottom has been carried out on site. The 3.0 m lower part of the tower, instrumented with the strain gauges, has been loaded horizontally using load cells in two perpendicular directions. The calibration is described in Appendix 3.

Table 2.8. *Measured parameters and calibration LMW 1003*

SIGNALS	DESCRIPTION, ANNEX OR REFERENCE
ROTOR / BLADES flapwise bending moment	 Appendix 3 Strain gages at blade root. 350 ohm bridge HBM amplifier FM telemetry transmission from hub to receiver on WT. Power supply 6 V replacable battery.
SHAFT	No measurements
NACELLE yaw angle / yaw speed	 Pulse output encoder on tower top. Driven by belt and gear.
TOWER tower bottom bending	 Appendix 3
ENERGY CONVERSION SYSTEM electrical power output generator frequency	 Voltage x current at DC part. F to V converter at AC part of controller
METEOROLOGICAL SIGNALS wind speed wind direction ambient temperature atm. pressure	 NRG wind speed / direction sensors at 10 m/mast signal taken from 30 m mast signal taken from 30 m mast

Data acquisition

The measurement period started in March 1995 and was completed in November 1995. The measurements are divided into two categories:

a. Normal measurements where the measured parameters were sampled with various ranges and stored every one minute.

b. Fast measurements of wind speed, yaw direction, blade flapwise bending moment and tower bottom bending moments.

Normal measurements were monitored by two CR10 data loggers and data was stored in two ordinary casette recorders connected to the loggers. Data was continuosly recorded until the cassets overflowed after about 6 days. These data then were transmitted in a PC using appropriate software.

Fast measurements were executed using the LABTECH data acquisition system and a portable PC. The parameters have been monitored with 160 Hz sampling rate for a time period of 15 seconds. The procedure was applied for various wind speeds in the prevailing wind direction.

2.4.3.2 The Inventus turbine at the DEWI site in Wilhelmshaven

Site

The Inventus wind turbine is situated at the DEWI test site in the north of Wilhelmshaven, Germany, nearly 5 km west of the North Sea coast. The meteorological data is measured by means of a meteomast of 41.5 m height. The wind speed is measured at five heights: 10 m (average 1995: 5.0 m/s), 20 m, 30 m (1995: 6.0 m/s), 40 m (1995: 6.3 m/s) and 41.5 m (1995: 6.5 m/s). Two further metmasts of 10m, rsp. 13m height are located at the test site for special measurements. In the north of DEWI's test site a 130 m met mast is operated by DEWI (average wind speed 1995 at 92 m: 7.9 m/s).

Instrumentation and calibration

The measured parameters and a short description of the measurement system are listed in table 2.9. A general overview of the instrumentation and details about the instrumentation and calibration are given in Appendix 4.

Data acquisition

The data acquisition system is described in detail in Appendix 4. The measurement programme was controlled by an integrated PC with a software called TorturDAC. The data is stored on an external hard disk with a capacity of 2 Gbytes. Only those time series were stored which are necessary to fit the matrix or is triggered by a special event. For the measurements within load case A a measurement matrix was developed. The wind speed classes were divided into 2.5 m/s bins and the turbulence intensity classes into 5 % bins. So a maximum of 40 time series can be recorded in the demanded classes I, II, III and IV instead of only 10 time series. During the evaluation attention has been paid to the fact that not all the used measuring values for the average value are measured in just one row of 10 minutes. Furthermore the measured time series should be equally divided over the whole wind speed range of 5 m/s. For this purpose a detailed measuring matrix has been developed.
During the whole measurement period from 16.11.1995 to 21.02.1996 seven such matrices were recorded by reading the data from the hard disk and resetting the matrix. Due to problems with the telemetry signals not all the measured time series were usable.

Table 2.9. *Measured parameters Inventus 6 at DEWI test station.*

SIGNALS	DESCRIPTION, ANNEX OR REFERENCE
ROTOR / BLADES edgewise bending moment flapwise bending moment tension in pitch rod	 double strain gages (full bridge, 1000 Ω) linear strain gages (full bridge, 1000 Ω)
SHAFT torque rotational speed	 45 degr strain gages Inductive sensor on high speed shaft
NACELLE yaw angle / yaw speed	 Absolute pulse output encoder on tower top. Megeatron M 500, 12 bit Gray Code Driven by belt and gear.
TOWER tower collar bending	 double strain gages (full bridge, 350 Ω) (N-S, E-W)
ENERGY CONVERSION SYSTEM electrical power output	 see measurements shaft
METEOROLOGICAL SIGNALS wind speed wind direction ambient temperature atm. pressure	 calibrated cup anemometer (Combi wind speed/ wind direction sensor) test station standard instrument "

2.4.3.3 The Proven WT2200 at the NEL site in Myres Hill

The Test Site

The wind turbine is installed at NEL's wind turbine test site at Myres Hill. This is located on high moorland approximately 10 km south west of the large town of East Kilbride and 5 km south of the village of Eaglesham. The Firth of Clyde coast lies approximately 30 km west of the site and is visible on a clear day. The site is some 330 m above sea level.

At the time of the measurements there were three grid connected turbines on site; a 300 kW WEG turbine, a 400 kW WEG turbine and an old 15 kW IRD turbine. There are also a number of small turbines dispersed around the site. The Proven WT2200 turbine is located on a universal foundation on Pad No.2 with its own dump load.

Instrumentation

Some special instrumentation was required to suit the novel features of the Proven rotor. As the rotor is very flexible at the root, it is not possible to measure strains; instead, deflections of the hinges must be determined (on one blade only due to limitations on the number of channels on the slip rings and data logger). To fully define the blade geometry in terms of pitch change and coning angle the deflections of both hinges on a blade are measured. It has not been possible to measure both yaw angle and yaw speed. An estimate of the yaw speed has been made off-line using the high frequency yaw angle data as input. A full list of the measurement transducers is presented in table 2.10.
A 6-way, mercury contact slip ring assembly is being used to supply power to and remove signals from the transducers on the rotating components of the system. This has been mounted on the end of the shaft on the upwind side of the generator.

Data Logging

Data acquisition is being handled by a Campbell Scientific CR10 data logger interfaced to the serial port of an IBM PC AT. The CR10 is the slave whilst the PC is the master controller. Ordinarily the CR10 would be used in a stand-alone mode, however in this instance the PC is being used to decide from the wind data logged by the CR10 whether or not the wind conditions coincide with a desired load case. If conditions are appropriate, then the CR10 is interrupted from its normal task of logging performance data at a relatively low sample rate and storing the statistics and a high sample rate load monitoring program is downloaded from the PC to the CR10 and run for several minutes. At the end of this short period the PC retrieves the load data from the CR10 and stores it on the hard disk and re-loads the CR10 with the performance measurement program. A matrix file on the PC has been used to determine which load cases have been obtained and how many so that excessive repetition is avoided. At the end of each day the PC initiates archiving of all data from the hard disk to tape for easy retrieval back to the lab.

The performance program samples the 12 channels of Table 2.10 at a frequency of 2Hz and calculates and stores the statistics listed in Table 2.12.
The load program samples all channels except temperature and pressure. A sampling frequency of 62Hz is being used, this being the maximum reliable sampling frequency the data logger can handle with ten input channels. Raw sampled data are streamed from the CR10 to the solid state Campbell Scientific storage module interfaced to the CR10.

Table 2.10. *Measured parameters Proven WT2200 at NEL test station.*

SIGNALS	DESCRIPTION, ANNEX OR REFERENCE
ROTOR / BLADES	
cone angle	linear displacement transducer
zebadee angle	linear displacement transducer
SHAFT	
torque	strain gauge full bridge
rotational speed	pulse counter (generator frequency)
NACELLE	
yaw angle	Belt driven Servo Potentiometer
yaw speed	must be done in software (numerical differentiation)
TOWER	
tower bottom bending NS	strain gauge N-S half bridge
tower bottom bending EW	strain gauge E-W half bridge
ENERGY CONVERSION SYSTEM	
electrical power output	depends on controller output
METEOROLOGICAL SIGNALS	
wind speed	anemometer
wind direction	wind vane
ambient temperature	PRT
atm. pressure	barometer

Table 2.11. *Calibration of parameters Proven WT2200*

SIGNALS	DESCRIPTION, ANNEX OR REFERENCE
ROTOR / BLADES	
pitch angle	Measurement of transducer link-arm geometry
cone angle	Measurement of transducer link-arm geometry
SHAFT	
torque	Calibrated masses suspended from horizontal blade with brake on. Done in laboratory.
rotational speed	Calculated from generator frequency.
NACELLE	
yaw angle / yaw speed	Yaw angle determined by manually yawing the nacelle through 360° and noting transducer output. Yaw speed from time derivative.
TOWER	
tower bottom bending	loads applied using winch and calibrated load cell.
ENERGY CONVERSION SYSTEM	
electrical power output	calibrated power transducer used.
generator frequency	calibrated frequency transducer used.
METEOROLOGICAL SIGNALS	
wind speed	anemometer calibrated in NEL wind tunnel.
wind direction	set-up using compass on site.
ambient temperature	not calibrated.
atm. pressure	not calibrated.

Table 2.12. *Performance Program Statistical Calculations Proven WT2200.*

Channel	1 Minute average	spot reading	maximum	minimum	standard deviation
Wind Speed	x		x	x	x
Wind Direction	x				x
Power	x		x	x	x
Rotor Speed	x		x	x	x
Temperature		x			
Pressure		x			
Flap Angle	x		x	x	x
Zebadee Angle	x		x	x	x
Shaft Torque	x				
Yaw Angle	x		x	x	
Yaw Speed					
Tower Bend 1	x		x	x	
Tower Bend 2	x		x	x	

3. Results of measurements and calculations

3.1 General

This chapter is devoted to the results of the calculations and measurements. Per wind turbine the main measurement and calculation results are presented. Details about the measurements where relevant are given in appendices 4-6.

3.2 LMW 1003

3.2.1 Measurements LMW 1003

3.2.1.1 Design parameters from power curve

The power output was measured at the output of the battery charger (DC part), measuring directly the charging current and voltage. It should be noted that the power output not only depends on the wind speed, but also on the charging level of the batteries. Since no electrical load was connected to the system, as soon as the batteries were fully charged, all the production was consumed by the dumpload. The output was significantly higher when the batteries were not fully charged.

The power curve determined according standard procedure is illustrated in figure 3.1. The windspeed and power data are given in Table 3.1. The dashed part of the power curve is based on measurements with probably incorrect wind speeds which are not included in figure. Correct or not, the power output was always limited at 800 watt level. Above 14 m/s, the power output is increasing only very slightly with windspeed. For that reason and in order not to end up with a very high rated windspeed value, it has been decided to determine the rated windspeed at 95% of the rated power, i.e. 14 m/s.

The rotational speed characteristic is given in Appendix 5. From this curve, it appeared that the rotational speed at rated windspeed was limited to about 700 rpm.

From the measured power curve and speed characteristics the following design values for the operational parameters are derived:

rated wind speed V_R	14 m/s
rated power P_R	0.8 kW
rated rotational speed n_R	700 rpm
tipspeed ratio at rated windspeed λ_R	7.85
torque at rated windspeed Q_R	12.96 Nm

Table 3.1 *Power curve LMW 1003*

wind speed m/s	power output, watt
3.47	26
4.59	103
5.71	225
6.43	316
7.55	453
8.49	536
9.45	614
10.42	659
11.49	705
12.49	732
13.57	763
14.57	773
15.50	785
16.48	793
17.45	791
18.55	799
19.50	795

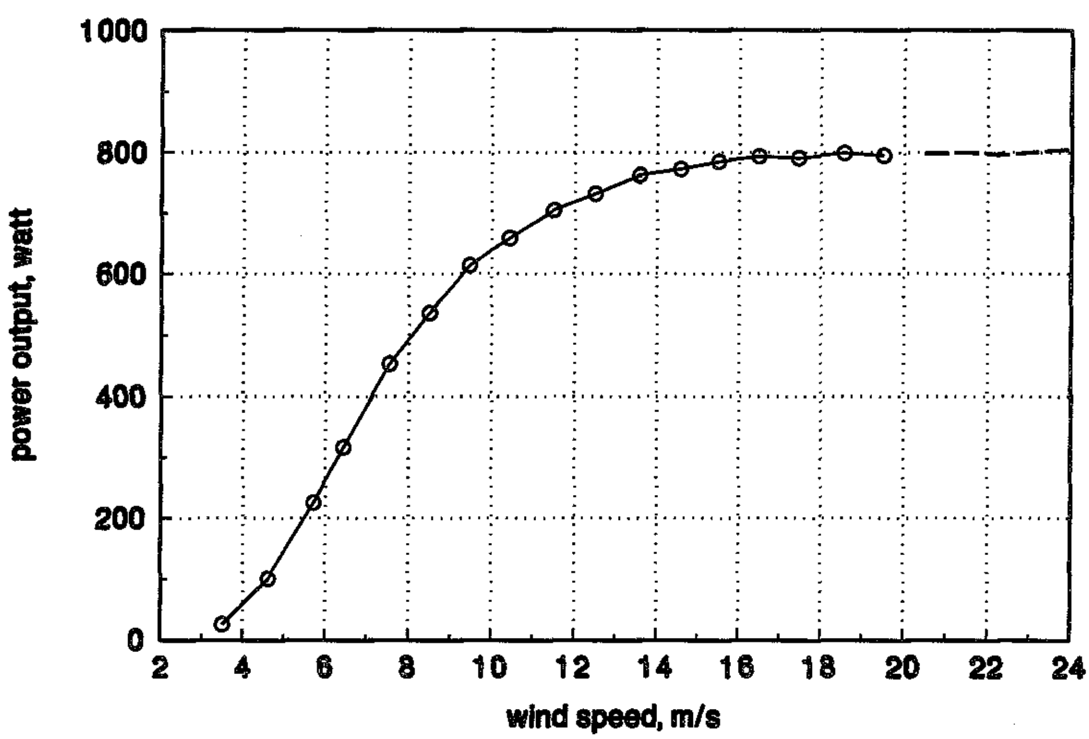


Fig. 3.1 *Measured power curve LMW 1003*

3.2.1.2 Load measurements LMW 1003

The measurement results are summarized in Table 3.3 (paragraph 3.2.3). More details are given in Appendix 5.

The mechanical loads measured were the two components of the tower bottom bending moment and the blade flapwise bending moment. The edgewise moment was not measured due to the particular shape of the blade root. Shaft loads measurements were also excluded because the hub is directly coupled to the alternator's shaft. Since the tower loads are not considered as fatigue loads, the bending moment in the flapwise direction remains the only measured parameter for comparison with the calculations for the load case A (fatigue).

Several problems appeared during the measurement period. The major problem in the beginning was the fact that the wind speed measurement was strongly influenced when the batteries were fully charged and the dump load was energized. In that case the dump load is connected and disconnected with very high frequency and the wind speed measurement is influenced by the harmonics. Because the wind speed is the reference quantity for all the measured parameters, the relevant measurements were totally with no use. The problem has been solved by connecting the dump load directly to the batteries. It was then observed that the measured power output slightly depended on the charging condition of batteries.

A serious damage occured after a short period of measurements and the machine was taken down for the necessary repairs. One of the support legs of the tail vane was broken. The repair included strenghtening of the whole support. After that, the machine was only allowed to run when the measurement system was in operation and the wind direction was appropriate. The blade bending moment was then recalibrated and a significant variation of the offset constant was mentioned, while the slope remained unchanged. The same problem was observed at the strain gauges of the tower loads also. Since the range of the CR10 data loggers is limited to +-2.5 Volts, a half reduction of the output voltage was applied. The offset which was always changed, was simply taken into account during data analysis, where the relevant constants were estimated from data taken during calm.

The failure of the tail vane support was a result of high vibrations at high rotational speeds due to resonance at the 2nd eigenfrequency of the tower. After the failure, load case C (loss of load) never has been tried out even at low wind speeds, although the relevant open-circuit switch had already been foreseen.

Due to absence of any mechanical brake, the load case D (shut down) was not relevant. The machine is shut down by short-circuiting the alternator, but this is successful only at low wind speeds. From windspeeds of approximately 10 m/s or higher, the machine cannot be stopped, unless it is first decelerated turning the rotor opposite to the wind. A piece of rope applied at the tail vane was used for the above procedure.

For the LMW 1003 machine, the critical parked + fault load case is the failure of the hinged tail vane mechanism (stuck hinge). Any other failure such as loss of one blade or loss of the tail vane, will lead to non-critical load cases. Since the above situation is almost impossible, the aforementioned load case was not considered.

3.2.1.3 General observations measurements LMW 1003

Small wind turbine systems are rather complex structures to analyze due to the tail vanes and other protection mechanisms. The problems relevant with load and other measurements are not in proportion with their nominal size.

First of all, the operational parameters such as power and voltage, rotational speed, yaw speed etc. often are not exactly specified and have to be measured. In the case of LMW1003, the power output but also the rotational speed was found to be dependent on the battery charging conditions. Some of the first measurements of these parameters showed that they were significantly increased, since the batteries were not fully charged. These two cases can be easily distinguished in the relevant figures illustrating the raw data (see Appendix 5). For power curve measurements on small battery chargers, it is recommended to discharge the batteries connecting additional loads.

The yaw behaviour seems to be a complex phenomenon with two major components. It has been observed that rotor unbalances, even small, cause small but measurable yaw fluctuations (see Appendix 5). On the other hand yaw fluctuations due to wind direction changes can be observed. The relevant maximum yaw speed never exceeded 10 deg/sec, which is a very low yaw speed. But this is also reasonable, if one takes into consideration the high inertia due to rotation. But the most important limitation of the maximum yaw speed is the damping due to the soft coupling of the tail vane to the main structure.

For the dynamic load measurements, both standard deviation and maximum values are strongly depending on the sampling rate. This is recommended to be 6 times the load frequency. For the normal measurements, the first eigenfrequency of the blade was measured in the laboratory and found to be about 9.6 Hz in flapwise direction. The sampling rate for the blade root bending moment was then set equal to 60 Hz. For the tower bending moments, a sampling rate of 20 Hz was choosen. Fast measurements with 160 Hz sampling rate showed the first and second eigenfrequencies equal to 1.2 and 5.1 Hz respectively. The latter is greater than the 1/6 of the sampling rate and thus the maximum tower bending moment relevant to the normally parked load case is probably slightly underestimated.

It is recommended to execute initially fast measurements to find out the frequency of cyclic loads and to put the sampling rate 6 to 8 times of the above, concerning critical load measurements.

The measurement campaign went on for about 8 months. During this period, fatigue and ultimate loads up to wind speed of 20 m/s were measured in various conditions. Fatigue loads tend to increase as the wind speed is increasing. But since the infinite number fatigue criterium is considered and since wind speeds above this value are not usual even for considerably high wind regimes, we can state that the measurement campaign for the fatigue load case is more or less completed. The only load case, which is probably the most critical, is that of parked in storm conditions. The ultimate loads appear at the extremely high wind speed (49 m/s) which may not occur even as gust wind. On the other hand, extrapolation for the estimation of these ultimate loads, based on the measured values at lower wind speeds includes great uncertainty, since the geometry of the machine is variable due to hinged tail vane. At such high wind speeds, the rotor turns parallel to the wind direction and additional lift forces act on the blades as well as on the tail vane. But these are not expected to be critical as ultimate loads for the blades. Calculations result in values for the lift forces of about 270 N on each blade.

For all the load cases, both fatigue and ultimate loads are increased at higher wind speeds. Loads on the blade however, seems to limit out at high wind speeds. This is reasonable because the blade does not stall but turns progressively out of the wind.

3.2.2 Calculations LMW 1003

The input data for the IEC calculations are given in Table 3.2.

Table 3.2. *Input for the calculations LMW 1003*

Rotor radius	1.565 [m]
Hub height	9.650 [m]
tip chord	0.110 [m]
Root chord	0.175 [m]
Radius to root chord	0.330 [m]
Tip angle	2.0 [^{o}]
Blade twist	6.5 [^{o}]
Hub type	rigid
number of blades	3
mass of blade	2.5 [kg]
Mass of total rotor	14.5 [kg]
Distance from cg. Blade to center of hub	0.670 [m]
Distance from center of hub to tower center	0.200 [m]
Rated power	0.8 [kW]
rated wind speed	14.0 [m/s]
Rated rpm	700 [rpm]
Range of rpm	300-800 [rpm]
Tail vane area	0.360 [m2]
Distance from tower center to tail vane center	2.300 [m]
Moment of inertia for blade	1.950 [kgm2]
Maximum yaw rate	0.1745 [rad/s]
Dist. From center of hub to 1st main bearing	0.100 [m]

The calculation results are summarized in the Table 3.3. The calculations were done according to the equations in the IEC 1400-2 standard.

Without any comparison, the calculated values appear reasonable. The only exception is the load ΔF_{zB}= 18000 N, which is additionally considered as a fatigue load. This load was not measured, but being an inertia load and considering that all the quantities involved in the relevant formula were carefully measured, a measurement is not really necessary. There are however some remarks to be made about the calculation assumptions. First of all, the formula is based on the assumption that the wind turbine runs at 50% higher rotational speed and produces proportionally more power. This is not the case for the LMW machine, since both power and speed are limited by the protection mechanism. But the most important is that this load is assumed to be a fatigue load with an infinite number of cycles and a safety factor as high as 10 is to be applied. The above combination may be too conservative. However the stresses due to centrifugal and thrust loads are of the same order of magnitude.

Load case E (normally parked) was excluded because it was difficult to estimate the component area perpendicular to the wind direction. On the other hand, the load case F is expected to be more critical, assuming that the hinge mechanism of the tail vane is failed. In that case, the rotor is always perpendicular to the wind and has the maximum exposure. The calculations of the ultimate loads for this load case were based on the above assumptions.

3.2.3 Results and discussion LMW 1003

Table 3.3. *Summary of measurement and calculation results LMW 1003*

Equation	Parameter	Dim.	Measured value	Calculated value	Measured / calculated
	P_{rated}	kW	0.8	-	
	V_{rated}	m/s	14		
	n_{rated}	rpm	700		
1	λ_R	-		7.85	
1	Q_R	Nm		12.96	
Load case: A	FATIGUE - NORMAL OPERATION				
2	ΔF_{zB}	N	n.m.	18000	
3	ΔM_{xb}	Nm	n.m.	37.4	
3	ΔM_{yb}	Nm	115	34.7	3.31
4	$\Delta F_{x\text{-}shaft}$	N	n.m.	99.7	
5	$\Delta M_{x\text{-}shaft}$	Nm	n.m.	13.6	
5	$\Delta M_{y\text{-}shaft}$	Nm	n.m.	32	
Load case: B	YAWING				
	w_{max}	rad/s	0.17		
6	$M_{yb,max}$	Nm	80	66.52	1.2
7/8	$M_{b\text{-}shaft,max}$	Nm	n.m.	115	
Load case: C	LOSS OF LOAD				
	n_{max}	rpm	n.m.	1100	
9	$F_{zB,max}$	N	n.m.	22225	
10	$M_{b\text{-}shaft,max}$	Nm	n.m	30.9	

The load quantities to be compared are limited to blade flapwise bending moment for load cases A (normal operation) and B (yawing). However, the blade is a critical component and the above load cases are representative in normal operation. The calculated value for load case A is 34.7 Nm, while the measured value is extrapolated to 115 Nm. The difference is quite substantial. Explanations can be found in effects of yaw misalignment and dynamic amplifications, which are not taken into account in the calculations

For the load case B (yawing), the measured value 80 Nm is very close to the calculated, which is 66.5 Nm. In this case, no additional assumption is made and the value is extracted directly from measurements.

3.3 Inventus 6

The Inventus 6 can be equipped with different types of conversion systems as desired by the customer. Possible options are a directly mechanically driven heat pump or a grid connected electrical generator. In the first part of the project the mechanical version has been examined, but the measurements have only been carried out to a limited extent. This was due to severe vibration problems experienced at wind speeds above rated wind speed. After modification of the machine in order to cope with this problem, the machine has been rebuilt as an electricity producing machine. The data presented in this report only relate to the last version. Some measurements and calculations of the mechanical version can be found in [5].

3.3.1 Measurements Inventus 6

3.3.1.1 Design parameters from power curve

During the measurement campaign it was necessary to adjust the control system of the wind turbine because of low initial power performance. During the first measuring period (10.10.95 - 28.11.95) the turbine was just performing 4.2 kW at 15 m/s wind speed. After adjustment of the control system by the manufacturer the output of the turbine was even worse: the maximum power output was now about 3 kW at a wind speed of 13 m/s. So the power control system was changed once again. Maximum power output now was about 4.8 kW at 15 m/s windspeed.

The power curves for all three measuring periods are shown in the figure.3.2.

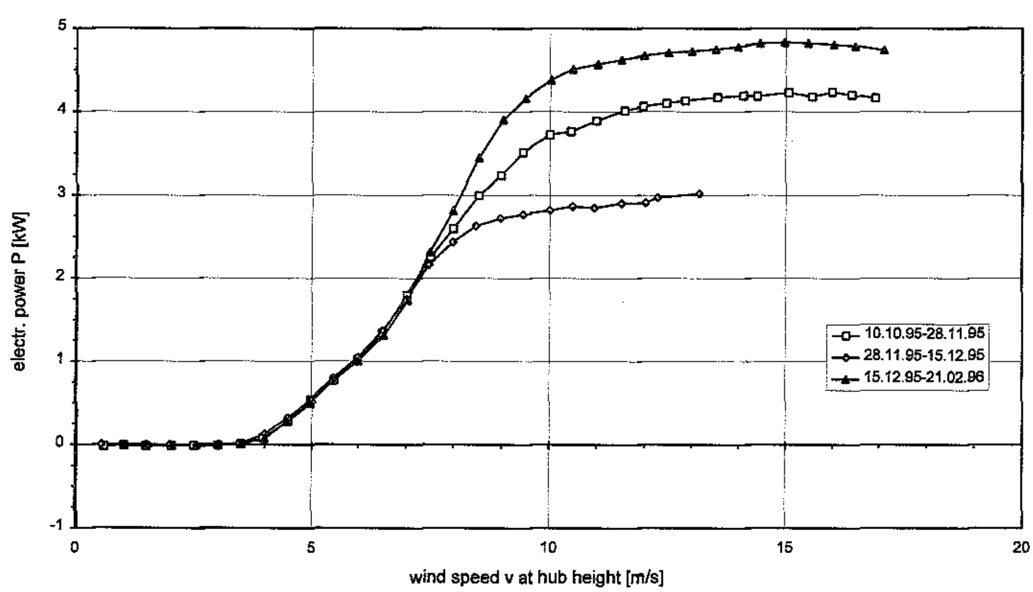


Fig. 3.2: *Power curves for the three measuring periods Inventus 6*

The rotational speed characteristics of the Inventus 6 with its two power stages are independent of the power control system. The wind turbine essentially operates at constant speed. This was confirmed by the measurements.

From the measured power curve and rotational speed characteristics, the following data have been derived:

rated wind speed V_R	12 m/s
rated power P_R	4.8 kW
rated rotational speed n_R	128 rpm
tipspeed ratio at rated windspeed λ_R	3.35
torque at rated windspeed Q_R	448 Nm

3.3.1.2 Load measurements

For load case A the maximum amplitudes (peak to peak values) were derived for the edgewise and the flapwise moments. So the influence of the pitch rod on the flapwise moment is not calculated.

In order to determine the ultimate loads (gyroscopic forces and moments) at maximum yaw speed, it is possible to use the values from the normal operation, but with a yaw error. In addition the turbine was forced to yaw artificially. This was possible by throwing a rope across the wind vane mounting and pulling the turbine out of the wind direction (appr. 45 degrees). After releasing the rope, the turbine began to move back in the correct direction. The values for maximum yaw speed are taken from these actions and from the normal operation mode.

Load case C (loss of electrical load) and load case D (shut-down) are the same. The shut down of the Inventus 6 is carried out by switching off the electrical connection, forcing the brake to be activated.

The measurements in the load cases B and D could only be done at low wind speeds (between 10 and 15 m/s i.e. below rated wind speed).

For the evaluation just the files are analysed that have been recorded at a mean windspeed of at least 5 m/s and at a turbulence intensity between 10 and 20%.

Because of transmission problems between the rotating system and the stationary system errors in the measured data appeared, so that the files had to be checked manually. A second source of error was the humidity, which affected especially the "N-S" measuring position of the tower.

The evaluation was carried out as follows. Every usable file was checked with regard to errors, which caused failure peaks. All the files without errors were used in the further evaluation.

Because of the relative low hub height (13m) and the low wind speeds during the measurement period, no values have been measured in the wind class > 20 m/s.

The values extracted from the measurements to be compared with the calculations have been derived by extrapolation from the measurements at different windspeeds. This extrapolation is described in detail in Appendix 4.

3.3.2 Calculations Inventus 6

The entry data for the calculation of the loads on the Inventus 6 are given in table 3.4. The data are based on manufacturers specifications and measurements of the power curve.

Table 3.4 *Input for calculations Inventus 6*

rotor radius	3 m
rotor speed at rated wind speed (stage 1 / 2)	89/128 rpm
rated wind speed	12 m/s
rated power	4.8 kW
efficiency (assumed value)	0.8
mass of one blade	12 kg
distance from cg of a blade to the blade root - hub junction	0.986 m
number of blades	4
distance from rotor center of gravity to first bearing	0.15 m
maximum angular rate of yawing (assumed value)	0.71 rad/s
distance between rotor and tower centre	0.7 m
blade moment of inertia	26 kgm^2
maximum speed of the rotor	179 rpm
mass of the rotor	75 kg
distance from the center of gravity of the rotor to the rotation axis	0.003 m
nominal torque of mechanical brake	1816.5 Nm

The results of the calculation are summarized in Table 3.5. The calculations of the loads have been done with various assumptions. Results of the different calculations are presented in Appendix 4. In this summary report only the calculations are relevant for the finally adjusted version, yielding in the power curve presented in figure 3.2.

3.3.3 Results and discussion Inventus 6

Table 3.5 *Summary of measurements and calculation results Inventus 6*

Formula	Parameter	Units	Measured value	Calculated value	Measured / calculated
	P_{rated}	W	4800		
	V_{rated}	m/s	12		
	n_{rated}	rpm	128		
1	λ_R	-		3.35	
1	Q_R	Nm		448	
Load case: A	FATIGUE - NORMAL OPERATION				
3	$\Delta\ M_{xb}$	Nm	448	344	1.30
3	$\Delta\ M_{yb}$	Nm	302	375	0.81
4	$\Delta\ F_{x\text{-}shaft}$	N	n.m.	750	-
5	$\Delta\ M_{x\text{-}shaft}$	Nm	360	448	0.80
5	$\Delta\ M_{y\text{-}shaft}$	Nm	n.m.	596	-
Load case: B	YAWING				
	ω_{max}	rad/s	0.71		-
6	$M_{yb,max}$	Nm	(275)	499	(0.55)
7/8	$M_{b\text{-}shaft,max}$	Nm	-	1879	-
Load case: C	LOSS OF LOAD				
	n_{max}	rpm	n.m.		-
9	$F_{zB,max}$	N	n.m.	4157	-
10	$M_{b\text{-}shaft,max}$	Nm	n.m.	122	-
Load case: D	SHUT DOWN				
11	$M_{x\text{-}shaft,max}$	Nm	n.m.	2264	-
12	$M_{xB,max}$	Nm	(477)	682	(0.70)

3.4 Proven WT2200

3.4.1 Measurements Proven WT2200

3.4.1.1 Design parameters from power curve

Rated Power

The power curve has been measured according to IEC standard and is given in Figure 3.3. The electrical power and windspeed data are given in Table 3.6.

Table 3.6 *Power curve Proven WT2200*

number of data	wind speed m/s	power Watt	rpm
4	4.57	10.26	31.1
37	5.06	11.88	164.7
100	5.53	15.74	238.7
136	6.01	39.33	288.6
148	6.48	100.25	315.2
114	7.00	198.14	315.0
137	7.52	312.37	310.3
102	8.00	424.54	304.5
80	8.49	537.47	302.6
76	9.02	678.10	306.0
61	9.47	813.28	310.0
45	9.98	984.62	314.8
42	10.49	1149.96	321.6
22	10.96	1292.73	340.0
11	11.45	1452.47	345.2
10	11.98	1487.59	356.3
8	12.42	1545.09	366.2
2	13.02	1788.65	369.0
4	13.43	1687.25	375.8
4	13.92	1710.88	381.8

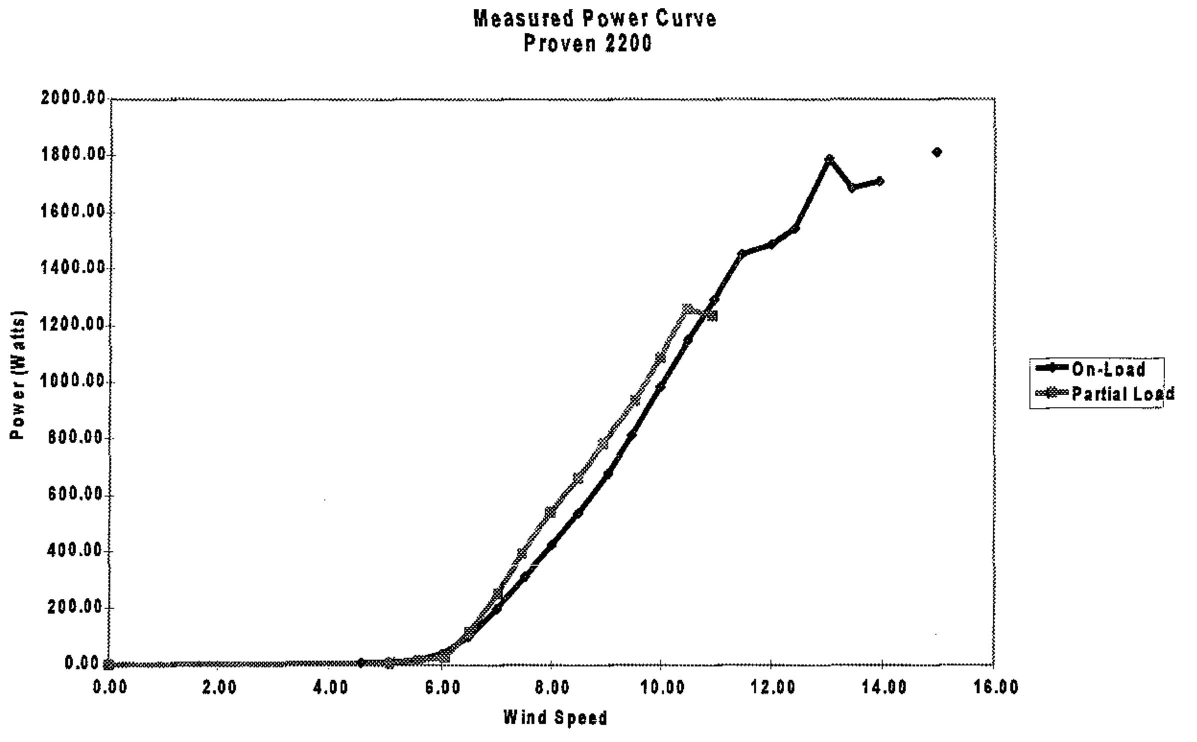


Figure 3.3 *Power curve Proven WT 2200*

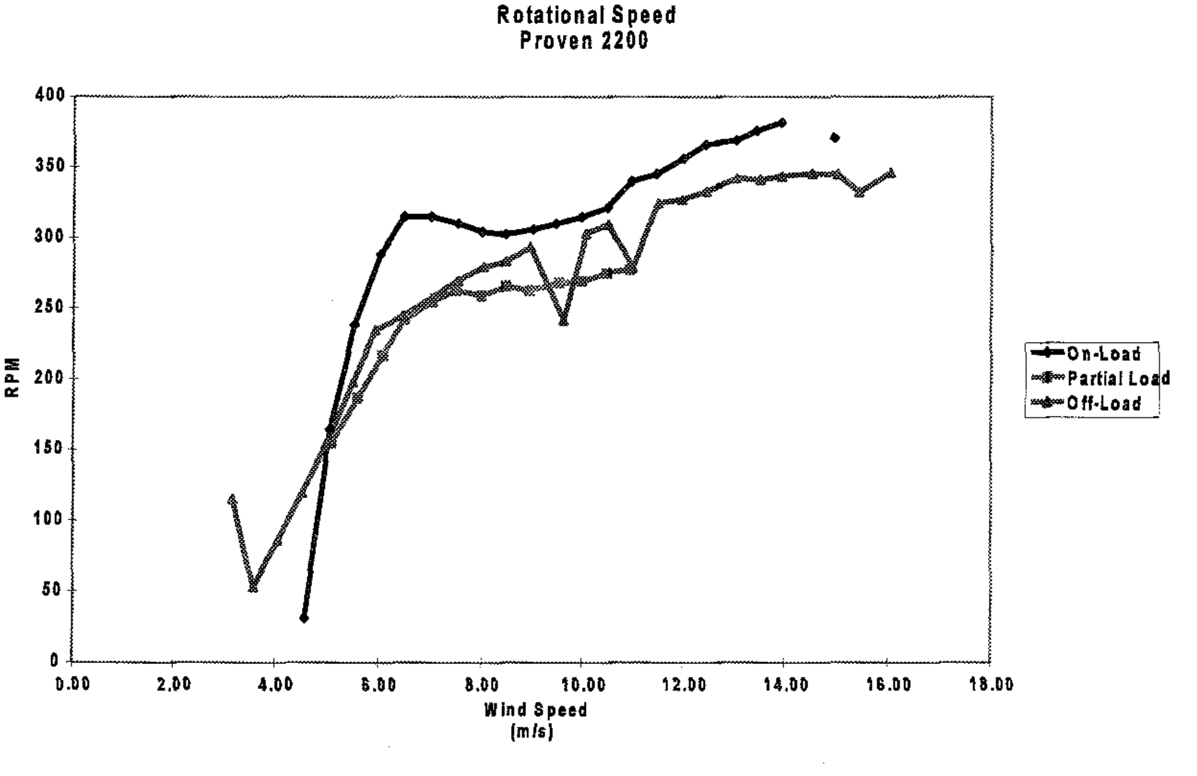


Figure 3.4 *Rotational speed characteristic Proven WT 2200*

Only a nominal figure of 300 rpm is quoted for the wind turbine by the manufacturer. However, on load, the control system regulated the rotational speed between 280 and 350 rpm up to the highest recorded 10-minute average wind speed of 20 m/s. The rpm wind speed curve - see figure 3.5 - indicated that the rotational speed had stabilised at this wind speed and showed no signs of increasing further.

Rated Torque

This value was taken as the measured shaft torque at the measured rated power. By using the nominal power rating and rotational speed it is possible to derive a higher value for this torque.

From the measured power and rotational speed characteristics the following values have been derived. Based on equation 1, the torque Q_R = 82.39 Nm.

rated wind speed V_R	13 m/s
rated power P_R	1.7 kW
rated rotational speed n_R	320 rpm
tipspeed ratio at rated windspeed λ_R	4.38
torque at rated windspeed Q_R	63.4 Nm

3.4.1.2 Load measurements

LOAD CASE A

Blade Flap and Edgewise Load Ranges

These values could not be measured or derived from the measured data due to a transducer failure early in the measurement campaign. The flap/pitch angle transducer may have provided a clue to the forces acting on the blades, however, the severe activity of this blade hinge meant that the transducer lasted only a few weeks. The Proven turbine blade roots are flexible so that an equilibrium blade position is reached by passive means which implies that the blade root flap moment is close to zero.

The edgewise blade root moments combine to generate the shaft torque. Therefore, the edgewise root moment range has been approximated by assuming that 1/3 of the measured shaft torque range is attributable to each of the three blades. Also the moment range caused by the blade weight has to be added.

Rotor Thrust Range

The rotor thrust range was determined by assuming a linear relationship between the measured tower base bending moment and rotor thrust. Although this is a good approximation for the mean loads, it is not correct for the dynamic loads. The standard deviation of the tower bending is magnified considerably by the tower dynamic characteristics leading to a significant but unquantifiable over-estimate of the rotor thrust range.

Shaft Torque Range

This figure was taken directly from the measurements of the shaft torque.

LOAD CASE B

Maximum Yaw Speed

The yaw speed was determined by differentiating the yaw position data with respect to time. The maximum yaw speed was then extracted from each of the resulting yaw speed time series for each wind speed bin. The maximum yaw speed was then extrapolated to the agreed maximum wind speed of 35 m/s.

LOAD CASE C

Maximum Rotational Speed

As there is no upper limit to the operational wind speed in the Proven specification, the agreed value of 35 m/s was used. Measurements were taken with the turbine off load and a curve of rotational speed against wind speed plotted. This was then extrapolated to 35 m/s to give a value for the maximum rotational speed. The rotational speed of the Proven rotor is passively governed by the deflection of the blades about the flap and flap/pitch hinges. The figure 3.4 shows that this passive regulation is very effective.

LOAD CASE D

Maximum shaft torque

This figure was taken directly from the measurements of the shaft torque.

3.4.1.3 General observations measurements Proven WT2200

The measured rated power was somewhat below the nominal rated power in the turbine specifications. However, it is believed that this was at least partially due to the characteristics of the electrical load used by NEL. The control system is designed to operate with an immersion heater in a water tank. However, it was not possible to provide a tank of water at the test site. Therefore, a bank of three halogen floodlights with a power rating equivalent to the standard immersion heater was used instead. As the rotational speed of the rotor increases from rest, the generator winding voltage increases. The turbine is initially off-load. When the voltage reaches a certain level, the electronic controller begins to switch the electrical load in and out of the circuit intermittently so that on average, the generator only sees a fraction of the total load. As the rotational speed and voltage continue to increase, the load is switched in and out more frequently such that the average electrical load approximately matches the turbine rotor power.

However, it is believed that the current and voltage characteristics of the halogen lights used were slightly different from those of an immersion heater and hence the switching of the load according to rpm and voltage was not well matched to the turbine characteristics. Unfortunately winds at rated and higher speeds were not experienced until relatively late in the measurement campaign revealing this short fall in power, by which time it was not sensible to adjust the controller characteristics to compensate. The sensitivity of the turbine performance to the load characteristics was further highlighted when one of the three halogen lights failed towards the end of the measurement campaign. The resulting modified rotational speed/generator voltage relationship resulted in the power curve shifting to the left, producing more power than before in light winds. This dependancy of the performance on the load characteristics strengthens the case for the development of a standard methodology and test set-up for the power performance testing of small, non-grid connected wind turbines.

3.4.2 Calculations Proven

The Proven turbine presented major problems when attempting to apply the simplified calculation methodology. A qualitative assessment per load case based upon the experiences is given below.

Load Case A: Normal Operation

Loads in the Blade Root:

The design load is a fatigue load in the blade root. A calculation procedure is given to determine the range of forces and moments in the blade root. The root of each Proven blade contains a pair of hinges with minimal stiffness. Although the centrifugal forces and edgewise bending at the point where the blade is bolted to the steel hub could conceivably be calculated using the simplified procedures, the flapwise loading could not be adequately defined for the Proven turbine. Fatigue of the hinge materials in flap is potentially the most important design load case for the Proven blades, but the design is not compatible with the simplified calculation procedures.

Loads on the Rotor Shaft:

These loadscould be calculated using the simplified procedures. The only problem could be defining the effective rotor radius as the rotor is intended to cone freely in high wind speeds.

Load Case B: Yawing

The calculations of blade and shaft loads are explicitly restricted to a rigid hub and therefore exclude the Proven design. The Proven design is down wind with free yaw and therefore could be subject to high yaw speeds and loads and this is therefore an important design case, especially with regard to blade deflections.

Load Case C: Loss of Electrical Load

Loads in the Blade Root:

This is an ultimate load case and is defined by the maximum centrifugal load. Assuming the geometry adopted by the rotor was known (or a worst case geometry assumed) on loss of load this could be calculated for the Proven turbine.

Loads on the Rotor Shaft:

In this instance the loads arise due to rotor imbalance. Due to the passively varying geometry of the individual blades on the rotor this would be difficult to specify for the Proven turbine.

Load Case D: Shut-Down

As the Proven turbine has a mechanical, manually operated brake, these calculations are partly possible.

Loads on the Rotor Shaft:

This calculation is possible.

Loads in the Blade Root:

The difficulty arises in determining the contribution of the blade inertia to the edgewise bending moment. The blade will probably deflect about the pitch hinge rather than transmit the full moment to the blade root.

Load Case E: Normally Parked

Load on each Component:

Without the benefit of centrifugal stiffening, the Proven rotor becomes very flexible and deflects to a position of minimal wind loading when parked in strong winds. Calculation should be possible in this instance.

Load Case F: Parked + Fault

Load on each Component:

This should be possible, although some assumptions would have to be made about the geometry adopted by the rotor.

Taking into account the above considerations, calculations have been performed for the various load cases applicable. The results are given in Table 3.8. The input for the calculations is given in Table 3.7.

Table 3.7. *Input for the calculations Proven WT2200*

Rotor radius	1.7 [m]
Hub height	6.5 [m]
Hub type	not rigid
number of blades	3
mass of blade	2 [kg]
Mass of total rotor	14.5 [kg]
Distance from cg. blade to center of hub	0.5670 [m]
Rated power	1.7 [kW]
rated wind speed	13.0 [m/s]
Rated rpm	320 [rpm]
Distance from yaw bearing to rotor	0.7025 [m]
Moment of inertia for blade	1.927 [kgm2]
Maximum yaw rate	0.52 [rad/s]
Dist. from center of hub to 1st main bearing	0.235 [m]

3.4.3 Results and discussion

Given that the IEC calculation could not accurately represent the loading of the flexible Proven rotor, an attempt was made to investigate the integrity of the rotor using the measured data directly in conjunction with the known material properties. An intuitive guess was made to identify the likely weakest point of the rotor which was then analysed for structural integrity. The weakest feature was believed to be the blade hinges as this was where the blade cross-section was constrained to be at it's narrowest and where the largest cyclic deflections of the blade material occurred.

There are two hinges on each blade, one giving a pure flap deflection and the other giving a flap/pitch coupling. The flap/pitch hinge is unconstrained and therefore experiences the greatest range of deflections. If either hinge was going to fail, this one was expected to fail first. However, a transducer failure due to the severe operating motion of this hinge meant that only a very limited quantity of measured data were available for the flap/pitch hinge. Therefore, the analysis concentrated on the flap hinge where the larger quantity of measured data made the analysis more meaningful.

A cycle counting algorithm was applied to examples of time series from each of the predefined wind classes. Using data obtained from the blade material manufacturer, a damage histogram was then established for each time series. The damage histograms were then weighted according to an assumed duty cycle for the turbine during it's life time and then the lifetime to failure of the hinge was then extrapolated.

Although the procedure was followed rigorously, an unbelievable value of the lifetime of the hinge was obtained. It is thought that the assumptions regarding the blade material behaviour were not valid for the actual behaviour of the hinge. The blade is capable of a wide range of angular deflection during operation, subjecting the hinge material to strains beyond those documented in the material manufacturer's literature. The extrapolation of the S-N curve to these higher strains was obviously unrealistic.

The tower was subjected to a similar analysis and appears to be over-designed. However, ignoring the specifics of the Proven turbine, the most interesting aspect of general relevance to small wind turbines highlighted by this analysis was the proportion of damage caused to the tower by the dynamic interaction of the tower and turbine. This was particularly evident in light winds where insufficient yaw moment could result in a temporary yaw misalignment hence causing momentary tower resonance (see Appendix 6). The point is that with a small wind turbine, which will generally be variable speed, there are a range of frequencies likely to be excited by the turbine rotor during normal operation and hence the support structure must be designed to avoid having the fundamental structural frequencies close to the operating range of the turbine.

The Proven turbine standard tower seems to be sufficiently over-designed that the minor tower resonance wittnessed does not present a safety problem, however there are other examples where tower resonance is a problem. For example, the CRES turbine has a custom built tower which suffers from considerably more severe tower resonance than the Proven turbine. Also, the Proven turbine can be supplied without a standard tower if the customer wishes to supply one to their own design. There are cases where such customer supplied towers have experienced dangerous levels of vibration, threatening the integrity of the turbine. The standard deals with the design of the tower in a rather superficial way (section 6.2). There should probably be a specific mention of dynamic effects in this section to highlight the problem to the turbine designer.

Table 3.8 *Summary of measurements and calculation results Proven WT2200*

Formula	Parameter	Dim.	Measured value	Calculated value	Measured / calculated
	P_{rated}	kW	1.7		
	V_{rated}	m/s	13		
	n_{rated}	rpm	320		
1	λ_R	-		4.38	
1	Q_R	Nm	63.4	80.79	
Load case: A	FATIGUE -NORMAL OPERATION				
2	ΔF_{zb}	N	-	2542	
3	ΔM_{xb}	Nm	45.8	43.36	1.06
3	ΔM_{yb}	Nm	n.a.	92.6	
4	$\Delta F_{x\text{-}shaft}$	N	1490	245.2	6.07
5	$\Delta M_{x\text{-}shaft}$	Nm	71.0	63.4	1.12
5	$\Delta M_{y\text{-}shaft}$	Nm	-	136.3	
Load case: B	YAWING				
	ω_{max}	rad/s	0.52		
6	$M_{yb.max}$	Nm	-	(80.34)	
7/8	$M_{b\text{-}shaft.max}$	Nm	-	153.6	
Load case: C	LOSS OF LOAD				
	n_{max}	rpm	413		
9	$F_{zB.max}$	N	-	2121	
10	$M_{b\text{-}shaft.max}$	Nm		36.1	
Load case: D	SHUT DOWN				
11	$M_{x\text{-}shaft.max}$	Nm	191.7		
12	$M_{xB.max}$	Nm		(75.014)	

A lot of the uncertainty is to be expected from making conclusions based on this comparison. This results from the concept of the Proven turbine, which is not compatible with the simplified calculation methods.

4. Conclusions based on comparison / validation

In this chapter the measuring and calculation results of the three test wind turbines will be summarized, and an attempt is made for a comparison / validation of the equations of the simplified method as applied for these particular machines.

4.1 Design parameters λ_R and Q_R

There are substantial differences in values of design parameters specified by the manufacturers and the ones derived from the actual measured characteristics : power curve and rpm curve. The overview of the differences is given in table 4.1. The table gives the measured and specified values. It also gives the ratio between measured and specified parameter for P_R, V_R and n_R, and the derived quantities λ_R and Q_R.

Table 4.1 *Comparison of measured and specified values for the design parameters*

			LMW 1003			Inventus 6			Proven WT 2200		
	symbol	units	spec	meas	m/sp	spec	meas	m/sp	spec	meas	m/sp
rated power	P_R	kW	600	760	1.27	5000	4800	0.96	2200	1800	0.77
rated windspeed	V_R	m/s	7	14	2.00	10.5	12	1.14	12	13	1.08
rated speed	n_R	rpm	320	700	2.19	128	128	1.00	300	320	1.07
torque	Q_R	Nm	22.38	12.96	0.58	466	448	0.96	87.54	67.14	0.73
tip speed ratio	λ_R		7.18	7.85	1.09	3.83	3.38	0.88	4.45	4.38	0.98

Using measured instead of specified values has consequences for the calculated loads. From the comparison of the values for the three measured machines it is apparent that if actually measured values are used, some of the calculated loads can be substantially lower than if the manufacturers specified values are used. This is particularly the case for the loads which are a product of torque and tipspeed ratio: the flapwise blade root bending moment and the thrust force in the rotor shaft. In all the three cases measured, the values of product of lambda and torque are lower than specified. The consequence is that in these cases the loads will be overestimated, if calculating them from manufacturers specified values.

The effect is quantified in table 4.2. This table first shows the ratio's of measured and specified values for rated power, rated wind speed and rpm at rated power. It then gives the relative values (measured divided by specified) of tipspeed ratio and torque at rated wind speed, as calculated by the equations [1] of IEC 1400-2. Finally it gives the ratio's of the product of tipspeed ratio and torque (measure for thrust load and blade root flapwise bending load). From the table it is apparent that in the case of these test wind turbines, load values for blade flapping moment and thrust force are up to 35% lower when measured values for the design parameters are taken from the power curve. In these particular cases, the calculation of the loads based on wind turbine characteristics specified by the manufacturer yields higher values. But the effect can also play in the other direction, and measurements show that the specified values can deviate a lot from the actual wind turbine characteristics. For this reason it is recommended to base the calculations on measured values anyway.

Table 4.2 *Ratio measured / specified values for the three test wind turbines*

parameter	LMW 1003	Inventus 6	Proven 2200
P_R	1.27	0.96	0.77
V_R	2.00	1.14	1.08
n_R	2.19	1	1.07
λ_R	1.09	0.88	0.99
Q_R	0.58	0.96	0.73
blade flap-load and thrust force	0.63	0.84	0.69

4.2 Summary ratio measured / calculated loads

In Table 4.3 the summary is given of the ratio's between measured and calculated values for the three machines as far as available. Although the amount of experimental evidence is rather limited, for almost all load cases some values are available.

The numbers printed in bold indicate the cases in which the measured values are higher than the calculated values.

Based on the experience collected, a further discussion of the results per load cases is given in the following paragraphs.

Table 4.3 *Summary of ratio's measured / calculated load quantities*

Formula	Parameter	LMW1003	Inventus 6	Proven
Load case: A	NORMAL OPERATION			
2	ΔF_{zb}	n.a.	n.a.	n.a.
3	ΔM_{xb}	n.a.	**1.30**	**1.06**
3	ΔM_{yb}	**3.31**	**1.01**	n.a.
4	$\Delta F_{x\text{-}shaft}$	n.a.	n.a.	**6.07**
5	$\Delta M_{x\text{-}shaft}$	n.a.	0.80	**1.12**
5	$\Delta M_{y\text{-}shaft}$	n.a.	n.a.	n.a.
Load case: B	YAWING			
6	$M_{yb,max}$	**1.20**	(0.55)	n.a.
7/8	$M_{b\text{-}shaft,max}$	n.a.	n.a.	n.a.
Load case: D	SHUT DOWN			
11	$M_{x\text{-}shaft,max}$	n.a.	n.a.	n.a.
12	$M_{xB,max}$	n.a.	(0.70)	n.a.

4.3 Comparison per load case

4.3.1 Load case A: power production (fatigue loads)

Loads in the blade root

Equation 2:

Centrifugal loads.

Measurements of this load have not been executed. However, the uncertainty of the determination by calculation is low. The validity of the result depends highly on the correct specification of the rotational speed n_R and a correct interpretation of the rotational speed variations.

Equations 3:

Blade root edgewise bending moment

Compared to measurements on the Inventus 6 wind turbine, the measured value is 30% higher than the calculated value. For the Proven WT2200, the edgewise load has been derived from the measured torque and the blade weight. This value was - quite expectedly - almost equal to the edgewise load calculated from equation 3. The approximation seems acceptable.

Blade root flapwise bending moment

In the case of LMW 1003, the measured value is much higher than the calculated. For the Inventus, the calculated and measured values are similar. However, since at the rotor of the Inventus some of the loads are being carried by the blade struts, the calculation overestimates the blade root loads, because it does not take into account this load alleviating effect. So, it can be concluded that for both machines, the calculation is not conservative.

Possible reasons for an underestimation in the calculation are:

- effects of yaw misalignment, which are in particular prominent for the LMW machine are not taken into account in the calculation method;
- dynamic amplifications of the loads (e.g. by the tower) are not taken into account.

From the measurements and calculations on both machines it can be concluded that the simplified method is not conservative in the case of predicting the fatigue loads in the blade root.

Rotor shaft loads

Equation 4:

Thrust force

It appeared that this load is difficult to measure directly. Only in one experiment, it has been tried to derive the shaft loads from the tower bending moment (Proven). The difference however between measured value and calculated value is very large. This can possibly be explained by the dynamic effects of the tower. These effects do not necessarily affect the components in the tower top.

Equations 5: Torsion and bending moments

The measured torsion loads are in one case lower (Inventus) and in another case higher (Proven) than the calculated values, but the differences are not really significant. The IEC method gives a reasonable approximation.

The bending moments could not be verified by measurements.

4.3.2 Load case B. Yawing

Blade root loads

Equation 6:

Flapping moment

The measured blade load value is slightly higher than the calculated value for the LMW machine. The measured value for the Inventus is only available for low wind speeds (far below V_{rated}), so experimental evidence is too limited for conclusions from that machine. This is to be expected because of the effect of the blade support rods (see load case A flapwise loads).

It could be stated that equation 6 gives a reasonable approximation.

Shaft loads

Equation 8:

Bending moment

The shaft bending loads have not been measured. The verification was not possible in this experiment.

4.3.3 Load case C: Loss of load

The determination of the maximum rotational speed, which could cause very high centrifugal loads and unbalance loads, is essential. It appeared to be not easy to carry out this experiment, in case of the LMW1003 mainly because of safety considerations. Due to the dynamic behaviour of the free standing tower severe oscillations occurred in the tail vane support especially at high rotor speeds. The Inventus 6 on the other hand is automatically stopped by the fail-safe mechanical brake when loss of load occurs. In the design a maximum rpm of 179 is assumed, it is not clear on what basis this assumption has been made. In case of the Proven the maximum speed measured was 413 rpm (extrapolated from measurements to 35 m/s). The unbalance loads calculated in the rotor shaft are well below the fatigue load range (load case A) and below the loads during yawing.

In view of the importance of the value of maximum rotational speed in the design, it is recommended to have this value tested in any case. Appropriate and safe test methods must be developed.

The relevant loads (blade centrifugal load and shaft bending) have not been measured, because of earlier mentioned reasons.

4.3.4 Load Case D: Shut-down

Equations 11 and 12

This load case is relevant for machines with a mechanical brake, such as Inventus and Proven.

At the Inventus, the measured shaft load during braking was lower than the calculated value, but only measurements at low wind speeds are available. For the Proven wind turbine, it was not possible to obtain the manufacturers specification of the rated value of the brake torque. Essentially it is a hand operated disk brake, and only meant for parking. From the measurements however it was observed that the loads during braking actions are rather high. It is recommended for the standard to specify default loads for the mechanical brake, if no actual data are available. Alternatively a test programme should be specified to derive the brake torque experimentally.

4.3.5 Load cases E and F: Parking

The validation of the calculated loads by measurements has not been carried out within this project. The complexity and relevance of the calculation of these loads is very machine / concept specific. In the case of concepts such as LMW1003, this load is quite difficult to evaluate analytically because of the non-linear dependency of yaw angle with wind speed. The best way to determine the relationship between yaw angle and wind speed is by experiment.

In the case of Inventus, the loads during parking in storm can be determined quite easily, because the rotor is always following the wind.

In case of the Proven, the rotor is designed in such a way that the loads are diminished in storm by folding the rotor blades.

4.4 Summary

Table 4.4 *Summary of conclusions from the comparison per equation*

equation	Parameter	Remarks and conclusions
Load case: A FATIGUE		
2	ΔF_{zb} Blade root centrifugal load range	Not evaluated. Because of strong dependence of rotational speed, it is recommended to use the measured value of n_R.
3	ΔM_{xb} Blade root edgewise moment range	Evaluated on two of the three wind turbines (Inventus and Proven) Measured value close to calculated value.
3	ΔM_{yb} Blade root flapwise moment range	Evaluated on two of the three wind turbines (LMW and Inventus). Calculations seem to underestimate this parameter. Better approximation must be worked out. Guidelines for supported or guyed blades should be worked out.
4	$\Delta F_{x\text{-shaft}}$ Thrust force range	Only measured on one turbine - even not directly (Proven). Calculated value depends strongly on Q_R. It is recommended to derive Q_R from the measured power curve.
5	$\Delta M_{x\text{-shaft}}$ Shaft torsional moment range	Measured at two of the three wind turbines (Inventus and Proven). Measured value close to calculated value.
5	$\Delta M_{y\text{-shaft}}$ Shaft bending moment range	This parameter has not been validated. In practice very difficult to measure on small wind turbines. Calculated values low in comparison to values during yawing.

equation	Parameter	Remarks and conclusions
Load case: B YAWING		
6	$M_{yb,max}$ Blade root flapwise moment	Evaluated on two of the three wind turbines (LMW and Inventus). Experimental evidence insufficient for firm conclusion. Order of magnitude OK.
7/8	$M_{b\text{-}shaft,max}$ Shaft moments	This parameter has not been validated. In practice very difficult to measure on small wind turbines
Load case C: LOSS OF LOAD		
9	$F_{zB,max}$ Blade root centrifugal load	Not evaluated. Very dependent on value of maximum rotational speed. This should be measured appropriately.
10	$M_{b\text{-}shaft,\ max}$ Shaft bending	Not evaluated. The calculated value is small in comparison to the bending during yawing and not really design driving.
Load case D: SHUT DOWN		
11	$M_{x\text{-}shaft,max}$ Shaft torsion	Not evaluated. Values for M_{brake} not always available. Shaft loads can be very high, design driving load. Determination by calculation possible, uncertainty low. Accurate assumptions on M_{brake} and Q_{rated} needed.
12	$M_{xB,max}$ Blade root edgewise moment	Only evaluated for one turbine (Inventus). Same remarks as for 11 on shaft loads. The loads in the blades can be design driving. Accurate assumptions on M_{brake} and Q_{rated} necessary.
Load case E: NORMALLY PARKED		
13	F Force on all components	Not evaluated. Uncertainty / complexity of calculation depends on concept. With ecliptic regulation rather difficult to evaluate. Measurements of yaw angle recommended.
Load case F: PARKED + FAULT		
14	F Force on all components	Not evaluated. Uncertainty / complexity of calculation depends on concept.

In practice it appeared that this validation could not be done for all the load cases and load quantities. It is recommended to validate some of the equations with help of a validated design code.

4.5 Comparison Danish method / IEC method

Comparative calculations have been made to evaluate the differences between the Danish Code (described in par. 2.3.3) and the IEC method. The calculations have only been done for the LMW1003 and the Inventus. The characteristic fatigue loads (load case A) have been calculated. Based on assumptions on material fatigue design values and these characteristic loads, the required moments of resistance and dimensions have been calculated for blade root, main shaft and tower bottom.

The summary results are presented in table 4.5, giving the ratios between values calculated by DK and IEC method. Details are given in Appendix 6.

Table 4.5 *Ratio of DK / IEC calculated load values for LMW1003 and Inventus 6 (Load case A)*

	load quantity	LMW 1003	Inventus 6
characteristic blade loads	ΔM_x	4.9	1.8
	ΔM_y	11.3	2.4
characteristic rotor loads	ΔF_x	15.4	3.2
	ΔM_y	15.3	2.4
	ΔM_x	1.0	1.0
moments of resistance	blade root	1.36 / 1.37	0.88 / 0.90
dimensions	main shaft (diameter)	1.58	1.02
	tower bottom		
	unwelded	8.3	1.72
	fillet weld	18.5	3.83

As can be seen the Danish code and IEC method results are quite different. The discrepancies are larger in case of the LMW wind turbine. Especially the required blade root and tower bottom dimensions of the LMW resulting from the Danish code are much heavier than from the IEC method. Also in the case of the Inventus 6, the resulting tower bottom dimensions as calculated by the Danish method are heavier.

It is obvious that the DK rules and the IEC rules are based on quite different philosophies. Calculations with the DK rules cause rather high characteristic loads, taking in account the high degree of uncertainty in site and operational conditions as well as lack of knowledge on loads and behaviour of this very different turbines. Besides it was a request to use the same safety factors as in DS 472 which correspond to the values given in the codes for the relevant materials.

The IEC rules seem to cause rather low characteristic loads, on the other hand the safety factors are high.

It should be remarked however that these are the fatigue design values. Ultimate loads could result in different design dimensions. This has not been checked within the project.

The conclusions from this comparison indicate a similar tendency as was observed fom the measurements i.e. the IEC method seems to underestimate blade flapping moment and the rotor thrust load.

5. Guidelines for interpretation of the IEC-standard

5.1 General

From the findings in this validation project, some guidelines are formulated on how to use the method specified in IEC1400-2. It should be understood that the verification only has been done on the level of loads determination, so the recommendations on the interpretation are limited to this aspect of the design process.

The philosophy of load determination however is strongly linked to the system of safety factors specified in the standard 1400-2. No attempt has been made on evaluating this system of safety factors for now.

Further it should be remarked that the recommendations are based upon the evaluation of a limited sample of the large variety of existing small wind turbine designs.

The guidelines for interpretation given here are distinguished in:

- recommendations how to use the specific equations in the defined load cases;
- recommendations on the application of the method for various wind turbine concepts.

5.2 Specific guidelines per load case

5.2.1 Operational design parameters

For the determination of the design values of rated power, rated wind speed and from there the derivation of the quantities rated torque and tip speed ratio at rated wind speed to be used in equations 1, it is strongly recommended to measure the power curve and the rotational speed characteristics of the wind turbine according to standardized practices.

5.2.2 Load case A

Equation 2: Centrifugal loads / blade

- use measured values of n_R;
- in case of constant speed wind turbines, do not use this equation;
- the equation over-estimates the loads of wind turbines with a functional regulation of the rotational speed; for these cases a more accurate method should be used, based on the real variations of the rotational speed.

Equations 3: Blade bending moments

a) edgewise bending moment

- the equation gives a good approximation;
- use measured value of P_R to determine Q_R.

b) flapwise moment

- the equation is not appropriate: it underestimates the loads;
- use by preference a different method (aerodynamic code) to determine this quantity;
- alternatively, when using the present equation, it is recommended to apply an additional load factor; the estimation of the magnitude of this factor is strongly dependent on the wind turbine type configuration, especially when obvious effects of yaw misalignment and dynamic amplifications occur; in any case also use measured values of P_R, n_R and V_R to determine Q_R and λ_R;
- the equation is not applicable as such in the case of non-cantilevered blades (such as Inventus). When using it, the contribution of supporting members has to be taken into account appropriately.

Equation 4: Shaft thrust load

- use measured values of P_R, n_R and V_R to determine Q_R and λ_R
- when using the value of the thrust force for tower design, take into account possible dynamic amplifications. In the case of a free-standing tower, a check on coincidence of exciting and natural frequencies has to be made (e.g. by use of Campbell diagram).

Equations 5: Shaft moments

a) torsion moment

- the equation gives a good approximation;
- use measured value of P_R to determine Q_R.

b) bending moment

- use measured values of P_R, n_R and V_R to determine Q_R and λ_R.

5.2.3 Load case B: Yawing

Equation 6: Blade root bending moment

- the equation gives a good approximation;
- use measured value of n_R;
- the equation is not applicable as such in the case of non-cantilevered blades (such as Inventus). When using it, the contribution of supporting members has to be taken into account appropriately.

Equations 7/8: Shaft loads

- use measured value of n_R;
- this bending load is important for dimensioning the shaft for ultimate loading.

5.2.4 Load case C: Loss of load

General

Before calculating, a system analysis should be performed in order to determine the design situations that will occur in case of loss of load.

Equation 9: Blade centrifugal load

- the equation can be used;
- use appropriately determined value of n_{max}, a simple calculation might not be sufficient. A proper extrapolation from measured values to value at wind speed = 35 m/s should be made.

Equation 10: Shaft bending moment

- the equation can be used, but might appear to yield values substantially lower than equations 7/8; it is always recommended to balance the rotor carefully; if done so, this load is not relevant for design.

5.2.5 Load case D: Shut-down (for machines with mechanical brake)

Equation 11: Shaft torsion loads

- the equation can be used, however a careful determination of M_{brake} and Q_R (from measurements) is recommended. If the braking moment is not available from manufacturers data, a test will be necessary to determine the value.

Equation 12: Blade edgewise loads

- the equation can be used, however a careful determination of M_{brake} and Q_R (from measurements) is recommended. If the braking moment is not available from manufacturers data, a test will be necessary to determine the value.

5.2.6 Load cases E and F: Parking

Equation 13: Storm loads on each component

- a distinct approach should be made between wind turbines with and without a cut-out wind speed; accurate calculations can be made for wind turbines which are blocked/stopped at high wind speeds. In case of turbine concepts with variable exposure surface depending on the wind speed e.g. ecliptic regulation, the relevant parameters like yaw angle and/or main shaft tilt angle as function of the wind speed should be measured.

Equation 14: Storm loads on each component

- first perform a system failure analysis to define possible fault states;
- make calculations, same remark as sub 13.

5.3 Guidelines on the application for wind turbine concepts

In general it appears that parts of the simplified method also can be used for deviating concepts. The scope of the project however was too limited in order to allow for making generalisations based upon the experiences with calculations and measurements. It is strongly recommended to initiate further research in order to investigate the applicability of the method for the most important concepts available now or in the near future.

6. Recommendations for IEC / Cenelec

6.1 General observations

Small wind turbines are quite diverse in typology and technologies used. For that reason, to develop a general simplified design method covering the whole range of existing concepts requires a lot of effort. Such a method cannot be formulated by now. It is therefore of utmost importance to indicate very clearly the restrictions in application of the design method prescribed in the standard IEC 1400-2.

In general the simplified method specified in IEC 1400-2 is easy in use. No major difficulties have been encountered in implementing the method for designs for which it is suited (rigid hub, cantilever blades). The calculations can be performed rapidly with a simple spreadsheet. The input parameters are rather easy to collect, at least for the concepts for which the method applies.

Some extra attention was required for:

- determination of the rated torque of the mechanical brake : this value is not always readily available, e.g. in case of use of non-standard industrial equipment;
- determination of the exposed area as a function of wind speed in case of an ecliptic regulation.

6.2 Recommendations for improvement on the method

1. **Fatigue loading due to centrifugal loads**

   Equation 2 can lead to an overestimation of the loads, specifically in the case of wind turbines where the rotational speed is carefully limited above rated value. A more accurate definition should be worked out, depending on the way of control of the rotational speed.

2. **Fatigue loads in blade root - flapwise moment**

   Significant discrepancies between measurements and calculations have been observed. This is also confirmed by comparison with the 'Danish approach'. An improved model should be developed. The measurements indicate that some physical effects are not taken into account - e.g. horizontal wind shear and dynamic effects. These effects should be included in the calculation method. There is experimental evidence that the present equation underestimates the loading.

3. **Fatigue loading in shaft: thrust force**

   The tower dynamics should be taken into account, when the thrust load is used for dimensioning the tower. An addition should be made in the standard for wind turbines with free standing tower where dynamic amplification of the loads can occur.

6.3 Recommendations for improvement of the formulation

1. The standard should more clearly specify how to derive the design values P_R, V_R, and n_R from the measured power curve. This can be done by reference to the chapter 9. Testing. This chapter should give clear guidelines on how to measure the power curve and how to derive the design values from the measured curve.

2. For equation 2 (centrifugal loads) the standard should specify more clearly that the measured value of n_R shall be used. The standard also should state that in case of constant speed machines, this load is not to be calculated.

3. For equation 3 (blade edgewise bending moment) the standard should specify clearly to use the measured values of P_R and V_R to determine Q_R.

4. For equation 4 (shaft thrust load) the standard should specify clearly to use the measured values of P_R, n_R and V_R to determine Q_R and λ_R. The standard should give also clarifications for taking into account tower dynamics in the calculation.

5. For equations 5 (shaft moments), the standard should clearly state to use the measured values of P_R, n_R and V_R to determine Q_R and λ_R.

6. For load case B yawing, the standard should specify that the measured value of n_R shall be used. The standard should furthermore give guidelines on how to carry out the experimental determination of ω_{max} in a proper way, in Chapter 9. Testing.

7. For load case C: loss of load, the standard should prescribe to determine first the machine states that can occur at loss of load. The standard should specify also to use the appropriately measured values of the maximum rotational speed n_{max}. The standard should furthermore give guidelines on how to carry out the experimental determination of n_{max} in a proper way, in Chapter 9. Testing.

8. For load case D: shut-down, the standard should specify what to do if manufacturers data for nominal brake torque are not available. The standard should give clear guidelines on how to determine this value of M_{brake} experimentally (Chapter 9. Testing) or analytically in such cases.

9. For load cases E and F, the standard should give guidance on the approach to follow in case of ecliptic regulations.

10. The standard should formulate in an appropriate way the limitations of the applicability of the simplified load calculation method. Some of the load cases also can apply to the deviating concepts. This should be mentioned per load case. A better description of wind turbine systems for which the method is valid should be added.

6.4 Recommendations for additional specifications

1. The standard should give more clear guidelines for the design of supporting structures, as small wind turbines are often installed on non-standard towers.

2. The standard should give more clear specifications on how to perform tests. Specifically the standard should give very clear guidelines on how to measure the power and rotational speed characteristics (possibly by referring to other standards), and how to derive the values at rated wind speed from the measured characteristics. Furthermore the standard should give more clear guidelines on how to perform the extrapolations in the determination of maximum rotational speed and maximum yaw speed to high wind speeds from measurement at normal wind speeds.

6.5 Recommendations on the applicability of IEC 1400-2

As for now, IEC 1400-2 gives guidance for only a limited number of wind turbine types. In the case of concepts deviating from the one specified, more complex design methods have to be used. It would be desirable to have more specific guidelines in 1400-2 on the simple but reliable design methods to apply for other concepts.

As a good starting basis the method developed in Denmark can be followed and further developed. At the moment however no proper documentation of this method is available in English.

The standard should also give a classification of wind turbine concepts, based on configurations of commercially available machines. For each class specified, appropriate design methods should be specified. In the case where appropriate methods do not exist, preliminary approaches to follow should be indicated.

7. Conclusions & recommendations for further work

7.1 Conclusions

A comparative evaluation of calculations and measurements of principal loads on small wind turbines has been made, with the objective to assess the validity of the simplified method specified in the standard IEC 1400-2.

The evaluation has been limited to the comparion of measured and calculated loads and has not attempted to evaluate the method on the level of stress reserve in the construction.

As a summary some general conclusions are formulated below:

- Although a quite substantial evaluation programme has been carried out, not all load cases specified in 1400-2 could be measured. Some loads are difficult to measure, e.g. main shaft bending moments, due to the technological concept. Also the appropriate wind conditions are not available in the limited project time. Due to low wind conditions in the second half of the project, the measurement period had to be extended, causing delay in the project execution.

- The selection of the machines showed to be advantageous because it reflected the diversity of existing concepts and gave a feeling for the limits of the applicability of the IEC method. The disadvantage of limitation to only three machines, and moreover different design concept is that generalizations based on quantitative results are not justifiable because of lack of statistical evidence.

- Apart from practical execution details, the procedures for measurements of mechanical loads on small machines are not easier for small machines than for large machines. This is an additional argument in favour of the development of good design standards based on fundamental research, not to be undertaken by individual wind turbine manufacturers / designers.

- The evaluation of loads has mainly concentrated on the determination of the fatigue loads. Parking loads have not been evaluated.

- Conclusions have been formulated per load case. In general the simplified method yields loads in the same order of magnitude as measured for the verified cases. Essential modifications of the IEC method seem to be necessary for modeling of blade fatigue loads (flapwise bending) and shaft loads. Recommendations for a better specification on how to use measured values of operatioanal parameters have been given per load case.

- The amount of work involved for improving the IEC 1400-2 standard based on the findings of this project justifies the initiation of a new work item within IEC TC-88, to be carried over later on within Cenelec.

7.2 Recommendations

The following recommendations for further work can be made:

1. Elaboration of methods for various concepts

   It would be desirable to have more specific guidelines in 1400-2 on the simple but reliable design methods to apply for other concepts. As a good starting basis the method developed in Denmark can be followed and further developed. The standard should also give a classification of wind turbine concepts, based on configurations of commercially available machines. For each class specified, appropriate design methods should be specified. In the case where appropriate methods do not exist, preliminary approaches to follow should be indicated.

2. Verification of the latter by measurements / sophisticated design codes

   A research project - similar to the present one - should be set up in order to validate the more diversified methods by measurements and calculations with more sophisticated design codes as well.

3. Establishment of clear guidelines for measurements on small wind turbines, after developing the necessary measurement techniques and procedures, especially suitable for small machines. Essential requirements for the measurement techniques are simplicity, low cost and reliability.

8. References

[1] IEC 1400-2 Wind turbine generator systems. Part 2. Safety of small wind turbines (1996)

[2] Last-, sikkerheds og konstruktions forskrifter for husstandsmoller ; Technical basis for certification of small wind turbines in Denmark (in danish) December 1994

[3] Danish Standard DS 472 "Loads and safety of wind turbines".

[4] Regulation and application of the Proven 2kW Wind Turbine.
G. Proven, A. Derrick , Presented at BWEA Conference 1994

[5] Experimentelle Belastungsuntersuchung kleiner Windkraftanlagen.
R. Kruckenberg, D. Lüttermann. Diplomarbeit. Fachhochschule Wilhelmshaven
Summer 1994.

[6] Standardization and certification of small wind turbines.
F.J.L. Van Hulle. Paper presented at EWEC'94 Conference, Thessaloniki, Greece, October 1994

[7] Validation of design criteria for small wind turbines.
F.J.L. Van Hulle. Paper presented at 1996 EU Wind Energy Conference, Goteborg, Sweden May 1996

[8] Mechanical loads monitoring on a small wind turbine in complex terrain.
P.N. Zorlos e.a. Paper presented at 1996 EU Wind Energy Conference, Goteborg, Sweden May 1996

[9] Experimental verification of design loads of small wind turbines.
F.J.L. Van Hulle. Proceedings of Wind Energy Contractors Meeting, East Kilbride
Feb. 1995. Report EUR 16875 EN

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Title Verification of design loads for small wind turbines.

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Abstract

The work described in this report has been carried out within the framework of the European Community Joule project JOU2-CT93-0423: Experimental verification of design loads for small wind turbines. The objective of the project was to validate the simplified calculation method in IEC 1400-2, and to formulate recommendations towards standardization bodies for the development and improvement of standards for small wind turbines.

The work was done in an international team, coordinated by ECN. Participants were CRES, DEWI, NEL and Risø.

In order to validate the method, measurements of mechanical loads have been carried out on three small wind turbines at three different test stations:

- a LMW 1003 machine, installed and tested by CRES (Greece);
- an Inventus 6 wind turbine at the test station of DEWI (Germany);
- a Proven WT2200 wind turbine installed at the test station of NEL (UK).

A similar test programme has been executed on the three machines in order to measure the loads in the six load cases, defined in IEC 1400-2. Furthermore some comparative calculations have been performed by Risø in order to check the similarities and differences with the code for small wind turbines under development in Denmark.

Within the limited project period, the majority of load cases have been investigated. From the results and experiences obtained it appears that the simplified method given in IEC 1400-2 in general is easy to use and gives a reasonable approximation. However, the applicability of the method is quite limited, and the formulation should be improved. Specific recommendations for the use of the method, necessary additions and improvements and further work to undertake have been made. These recommendations are primarily intended for IEC and European Standardization Bodies. The results are also useful for certifying bodies and wind turbine manufacturers / designers.

Keywords wind energy, small wind turbines, design loads, standards

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