EXPERT GROUP STUDY
ON

RECOMMENDED PRACTICES FOR WIND TURBINE TESTING AND EVALUATION

6. STRUCTURAL SAFETY

Review of (draft) standards/code of practice

PREPARATORY INFORMATION

Submitted to the Executive Committee
of the International Energy Agency Programme
for
Research and Development
of Wind Energy Conversion Systems

RECOMMENDED PRACTICES
FOR WIND TURBINE TESTING

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FOREWORD

The evaluation of wind turbines must encompass all aspects of a Wind Energy Conversion System (WECS) ranging from: energy production, quality of power, reliability, durability and safety, through to cost effectiveness or economics, noise characteristics, impact on the environment and electromagnetic interference. The development of internationally agreed evaluation procedures for each of these areas is now needed to aid the development of the industry while strengthening confidence and preventing chaos in the market.

It is the purpose of the proposed recommendations for wind turbine testing to address the developent of internationally agreed test procedures which deal with each of the above noted aspects for characterizing wind turbines. The IEA expert committees will pursue this by periodically holding meetings of experts, to define and refine consensus evaluation procedures in each of the following areas:

1. Power Performance;
2. Cost of Energy from WECS;
3. Fatigue Evaluation;
4. Acoustics;
5. Electromagnetic Interference;
6. Structural Safety;
7. Quality of Power;
8. Glossary of Terms.

For items, 1, 2, 3, 4 and 7 documents have been issued during the years 1980–1984. However, items 5 and 6 have turned out to be difficult to treat within the same framework as items 1–4 and 7. The documents which address item 5 and 6 therefore are presented as Preparatory Information only. The document which addresses Electromagnetic Interference was published in February 1986. The present document on Structural Safety completes the series although updated versions of all the documents will be issued as the need arises.

In spite of the limited scope it is felt that the information contained in this paper can be of great value to planning authorities, manufacturers and users of wind turbines and therefore justifies the presentation of the document in this series of Recommended Practices.

Due to the widening appeal of wind energy it was considered that a Glossary of Terms, expressed in simple language, would serve to introduce consistency into future publications of the IEA as well as be of use to those with an interest in wind energy. For this reason in march 1987 an additional publication No. 8 'Glossary of Terms' was published in the series.

Contents

INTRODUCTION

During the preparation of this document on structural safety, considerable problems were faced, due to the complexity of the subject and the lack of good documentation. Meanwhile in several countries (USA, Netherlands, Denmark, Canada, Federal Republic of Germany, UK and Sweden) draft standards were being prepared on the safety of wind turbines. The application and the formal frame work in which the standards were developed varied considerably in most cases. In most European countries for instance, the standards were developed for horizontal axis machines of limited dimension, whereas the Canadian standard was aimed particularly at vertical axis machines.

To prepare recommendations independently of the work which was going on in the different countries was not considered prudent. Since standards and codes of practice were being formulated in different countries quite independently of each other, it was considered that the best approach would be to collect and review the available material. The aim of this document is to compare the (draft) standards and codes and to comment on their similarities and their differences. The conclusions drawn from this is intended to be of help for national standards committees (both present and furute) in formulating a consistent set of safety standards as well as to stimulate international standardization.

In order to try to obtain as concise a document as possible it was decided to limit the documents to be reviewed to those prepared by official standards committees and not to include other related documents, such as design specifications. It was also decided to limit the scope of the work to those aspects which are not subject to national laws and regulations such as electrical aspects, operation and maintenance requirements and existing safety. As a result, only structural aspects concerning the components of wind turbines are dealt with.

The review is based on documents that were collected until the begining of 1988 and since the development of standards is a rapidly progressing process, it must be borne in mind, that the information could become outdated very rapidly.

THE DEVELOPMENT OF SAFETY STANDARDS IN DIFFERENT COUNTRIES

Official activities to establish standards for wind turbine safety were reported from: Canada (Can), Denmark (DK), the Federal Republic of Germany (D), the Netherlands (NL), Sweden (S), the United States of America (USA) and the United Kingdom (UK). In January 1987 a European Community project was initiated to draft a conceptual European safety standard on the basis of the best elements of existing European (draft) standards. For this document the Dutch, Danish and the German standards have been considered as the building stones.

The approach taken by each country is described very briefly, partly on the basis of official documents and partly on the basis of unpublished material and personal communications. The official documents which were considered are listed in the reference list (Annex 2).

Canada

The Canadian standard [4] was developed under the auspices of the Canadian Standards Association (CSA). The document was prepared by the subcommittee on Safety of Small Wind Energy Conversion Systems under the jurisdiction of the Technical Committee on WECS and the Standards Steering Committee on Solar and Wind Energy. The first edition of the CSA Preliminary Standard (F416) was published in May 1985. Like all other CSA standards this standard is subject to periodical review.

Denmark

Under the auspices of the Danish Engineering Society (Dansk Ingeniørforening - DIF) a standards committee has been established in which along with others the Risø National Laboratory, specialists from universities and industry are represented. The committee finalized its work in July 1987 after having collected critical comments from specialists [6]. At present (May 1988) adjustments are being made so as to harmonize the code with other similar Danish codes. The process is expected to be finished by the end of 1988.

The Federal Republic of Germany

In Germany the state of Schleswig Holstein has been the most active in setting up rules for the use of wind turbines. On behalf of the Ministry of the Interior of Schleswig Holstein, Germanischer Lloyd has issued guidelines for the design, installation and operation of wind turbines up to 100 kW rated power [7]. Furthermore guidelines for testing, commissioning and supervising have been issued. At the beginning of 1987 the Institute for Building Technology (Institut für Bautecknik), Berlin, which was appointed to develop rules for larger wind turbines, called a coordinating meeting, with the aim of completing the criteria for safety and reliability and to set up uniform rules for the whole of the Federal Republic of Germany. The initiative was attended by the state authorities responsible for the building codes and Danish and Dutch representatives participated in the meeting.

The Netherlands

The Dutch standard [5] was prepared by a committee of the Netherlands Electrotechnical Committee (NEC 96) in which representatives of the wind turbine industry, the wind turbine owners, utilities, the Netherlands Energy Research Foundation ECN, several R&D institutes and government bodies participated. NEC is a formal branch of the Netherlands Standards Institute (Nederlands Normalisatie Instituut - NNI). The first version of the standard was published in September 1985. The suggestions for improvements which were received up to November 1986 will be incorporated in a revised version together with the results of a research project on design criteria for small machines. The publication of the final version is planned for the last quarter of 1988.

Sweden

The Aeronautical Research Institute of Sweden (FFA) has been entrusted by the Building Division of the National Swedish Board of Physical Planning and Building to prepare a document [8] containing guidelines for the structural design of wind turbines. The Board is responsible for issuing of the Swedish Building Code (SBN). A national committee is planned to carry on the work on rules for installing wind turbines.

The United States of America

Most of the work on wind turbine Standards is being carried out under the auspices of the American Wind Energy Association (AWEA). The board of directors of AWEA appoint a Standards chairman who appoints a Standard's coordination committee representing manufacturers, researchers, product end users, financial interests and government and other institutions. There are currently nine sub-committees working on different standards.

These are:

1. Design Criteria,
2. Site assessment (including site measurement procedures and effects of micro siting and arrays),
3. Acoustics,
4. Wind Diesel Systems,
5. Performance,
6. Electric Power Subsystems (including wind farm interconnects and small system interconnect to the utility),
7. Terminology,
8. Operations and Maintenance, and
9. Installation.

Documents dealing with electrical interconnection are being developed jointly with IEEE and AWEA.

Issues of safety are covered in four of the Standard's documents:

1. Design Criteria - covers structural aspects both static and dynamic, braking systems and electrical components.
2. Installation - covers safety aspects associated with the installation of a wind turbine such as site preparation, equipment handling, foundations, anchors, erection and electrical interconnections.
3. Electrical Power Subsystems - These two documents address the electrical design and safety aspects of the electrical infra-structure from the wind turbine generator to the utility.
4. Operations and Maintenance - addresses the safety issues associated with the operation and maintenance of a wind park.

AWEA has joint agreements with the American Society for Testing and Materials (ASTM) concerning the development of a performance testing code and with Institute of Electrical and Electronic Engineers (IEEE) with respect to interconnection of small wind turbines to the grid and windfarm interconnection. The relation between AWEA and ASTM will be replaced by a working agreement between AWEA and the American National Standards Institute (ANSI).

The United Kingdom

Work has been initiated leading towards the formulation of standards in the UK. This work which will be coordinated by the Department of Trade and Industry through the National Wind Turbine Centre of the National Engineering Laboratory (NEL), Glasgow, will initially address the problems of safety, noise and electromagnetic interference. The work will be guided by a committee made up of representatives from manufacturers, utilities, users, technical institutions and government departments. The present philosophy on safety aspects is to encompass all machine sizes from the smallest battery charger to multi-megawatt units and both horizontal and vertical axis types to take account of the wide range of products currently of interest to UK manufacturers.

European Community (EC)

In its efforts to stimulate a single European market of commercial wind turbines, the Commission of the European Communities (CES) is financing a project which aims at a draft European Safety Standard which is based on the best elements from existing standards.

International Electrotechnical Commission (IEC)

The IEC has established a technical committee (nr. 88) ''Safety of Windturbine generator systems''. Its aim is to establish a standard based on ongoing national activities. The scope of the standard will be limited to mechanical and electrical safety aspects with emphasis on environmental safety and safety during operation and maintenance. Members of the committee will be representatives of National Standard Committees. In order to stimulate harmonization of standards the IEA WECS, R&D programme has an observer status on the committee. The work will commence Mid 1988.

GENERAL SURVEY OF SAFETY STANDARDS

The format of the draft standards on safety obviously differs in various aspects, which complicates comparison. Nevertheless, it has been attempted to sum up to the most important characteristics of each standard in Table 1.

The table is divided into 7 items:

1. scope of the standards;
2. presentation of safety philosophy;
3. specification of load cases;
4. methods of calculation of the forces and moments in major components;
5. use of the concept of safety factors;
6. evaluation/test requirements;
7. status of standards.

The following should be borne mind when considering Table 1. Safety standards should be based upon a consistent overall philosophy. Such a philosophy can only be developed if sufficient practical design, operation and evaluation experience is available, usually only when the technology has already developed to a certain degree of maturity. However, standards are needed in the initial stages of the development process.

Most standard committees have attempted to overcome this dilema by compiling a draft based on available know-how from existing wind turbine experience or from other fields of engineering. This is especially true in those countries where experienced test stations participated in the work of the standard committees where knowledge based on practical experiments has been incorporated in the standard.

Scope

The application and the use of the standards being developed may vary in the different countries. This results in different scopes and varying degrees of specification. A few examples may serve as an illustration of what is meant here:

Unlike other standards, the Danish and Dutch standards only apply to horizontal axis machines because in these countries no vertical acis machines are being sold commercially.

Where standards give recommendations on the calculation methods to be used for determining the specified design loads, the scope is usually limited to wind turbines of a certain size. The reason being that smaller machines (say smaller than 20 m rotor diameter) normally are designed by rule of thumb, whereas for larger machines the design is carried out by analytical methods. The Canadian, Danish, Dutch and German standards are examples which are limited in scope with respect to machine size.

Table 1: General Review of Safety Standards

	USA	Can	NL	DK	D	S	UK
(See reference list)							
1. Scope							
1.1. Size of machine	<1MW	<100kW	2m<D<20m	>5m	<100kW	All 2)	13)
1.2. Type of machine							
• All types	+	+	-	-	+	+	
• Horizontal/vertical axis			Hor	Hor			
• Grid connected el. gen.			+	1)			
• Autonomous el. gen.			+	1)			
• Direct mechanical drive			-				
1.3. Aspects of safety							
• Structural	+	+	+	+	+	+	
• Electrical	+	+	+	-	-	-	
• O & M	+	+	+	-	-	-	
• Evaluation/Test requirements	+	+	0	+	-	+	
2. Presentation of Safety philosophy							
2.1. Overall presentation		+	+	+		+	
2.2. Partial presentation	+				+		
3. Specification of Load Cases							
3.1. In general terms	+	+	+	+	+	+	
3.2. Some are specified	+	+		+ 3)	+		
3.3. Most are specified			+	+		+	
4. Calculation methods for forces and moments in major components							
4.1. None at all	+	+				+	
4.2. To some extent				+	+		
4.3. Detailed calculations			+				
4.4. Reference to other codes	+	+	+	+	+	+	
5. Safety factors							
5.1. Implicit presentation 4)	+	+				+	
5.2. Explicit			+	+	+ 5)		
6. Evaluation/Test requirements							
6.1. In general terms		+				+	
6.2. Some are specified		+				+	
6.3. All are specified (more or less)				+ 8)			
6.4. None	+		+7)				
7. Status of Standards							
7.1. Operational	+		+		+		
7.2. Officially recognized by standard associations	+	+	+ 10)	+ 10)			
7.3. • Working Document					+	+ 6)	
• Draft in Final Stage	+	+	+ 12)	+ 9)			
• Draft available for comments	+	+			+11)		

Legend:

+: "Included" or "yes"
O: Not (yet) mentioned
-: "Explicitly excluded" qr "no"

Notes:

1) The standards have been developed for constant speed (stall controlled) electricity generating machines. This is not explicity mentioned in the document. The standard applies for Denmark, excluding Faerøe Islands and Greenland.
2) The document is most specific about large horizontal axis machines.
3) Only rotating wind turbines are considered.
4) By means of references to other standards or codes.
5) There is mention of safety factors but no specifications.
6) In Swedish.
7) Planned for future extension of the standard.
8) Not completed.
9) In Danish.
10) In last quarter of 1988. (NL: second revised version, DK: first version).
11) In German.
12) In Dutch.
13) Under Discussion.

SAFETY PHILOSOPHY

Introduction

The demands concerning safety factors, required safety-protection devices, design philosophies (safe life, fail safe) for different turbine components, should be derived from a generally accepted risk level, which is a product of the probability of failure and the consequences of failure. Such risk analyses have never been performed except for some specific large wind turbines. As a result the safety philosophies do not show much coherence or similarity.

However, from practical experience and from testing and evaluating wind turbines it has become clear which mechanisms initiate the most significant hazards. These hazardous incidents include blade or rotor throw, machine parts falling from the tower and tower collapse. Knowledge from such experiences has been incorporated in some standards and most of the newly developed standard requirements concern these wind turbine engineering problems.

In the following a brief description of the different safety philosophies are given.

The United States of America

Safety is covered by three documents [1], [2] and [3]. A fourth dealing with operations and maintenance safety issues is being prepared.

The basis of document [1] is the provision of design criteria for safe assembly and operation under specified environmental conditions to ensure system safety over a specific lifetime.

The major design elements to be addressed are:

1. normal and extreme environmental and operating conditions;
2. system loads, both static and dynamic;
3. component design criteria.

To conform to the standard a wind turbine rotor and the support sub-systems should be "safe life" designed to maintain structural integrity and safe operation. The controls should be designed for "fail-safe" operation, in such a way that in the event of failure of a control sub-system (component), the machine will remain in a non-hazardous condition.

Canada

The basic philosophy of the Canadian standard partly appears from the 'general requirements'.

These are reproduced here:

1. Rotor and support system conforming to the standard must be safe life designed.
2. SWECS* controls and protection systems must be designed for fail safe operation such that in the event of failure of a component the machine will remain in a non-hazardous condition.
3. SWECS must be designed such that maintenance can be safely carried out by following instructions given in the SWECS manual.
4. A SWECS manual, appropriate to the particular machine, shall be provided by the manufacturer. The SWECS manual must contain information on erection, inspection, maintenance and special tooling. A specific sequence of procedures to commission a new or repaired SWECS must be prescribed. Detailed procedures must be given to check proper function of safety, protection systems and trouble shooting routines.

SWECS: Small Wind Energy Conversion Systems.

5. In addition to this standard, SWECS located in severe environmental areas shall be evaluated using special criteria dictated by the site.
6. The procedure used to manufacture, transport and erect the SWECS shall consider loads, deformation and exposure to the environment of the components and assemblies.

Additionally, the following requirements are included, which complete the systematic basis of the Canadian document.

- A (quite detailed) set of environmental design requirements is to be applied as a minimum for safe turbine operation.
- A series of load cases/combinations of load cases are given (but not specified) which consist of both operational modes and external circumstances, such as extreme wind speeds. These load cases have to be applied over the design safe operating life of the wind turbine. Combined load case analysis shall include appropriate loading recurrence intervals.
- Each wind turbine model shall undergo a minimum of 12 months of testing to ensure a sound structural design, vibration free machine and safe operation of controls and emergency sub-systems.
- Each design of rotor blade shall be tested at loads equivalent to survival wind speeds.

Denmark

The Danish standard specifies the general requirements for safety systems and further describes the design loads which have to be applied under specified conditions.

General requirements:

In Scandinavia a system of three safety classes is used as a means of setting up safety regulations. In the standard a wind turbine is not allowed to be designed for the lowest safety class.

A wind turbine should be equipped with a control and safety system that avoids the wind turbine entering an extreme "unforeseen" load condition.

In this respect the maximum operating wind speed, the maximum power output and the maximum rotor speed have to be specified.

The general requirements with respect to control and safety systems are as follows:

- The control system shall limit the power to the specified maximum power output if the wind speed exceeds the specified maximum operating wind speed. Parking is only needed when load considerations prove that it is necessary.
- The machine shall be equipped with at least two (independently) working braking systems. A braking system consists of a monitoring device, an activating mechanism and braking unit. At least one system shall contain an aerodynamic brake. Yawing is not considered as a braking action.
- The primary system shall be able to monitor an error and be able to bring the rotor to a stand still under all load conditions while the rotor speed is lower than the specified maximum rotor speed. An error is defined as exceeding the maximum power output or the maximum operating wind speed or any other circumstance under which normal safety cannot be maintained.
- The secondary braking system shal limit the rotor speed to the specified maximum rotor speed, while the short term average wind speed is not higher than a maximum specified value. The monitoring and activating units must use an energy source other than the normal energy source.

Safety factor:

The Danish standard explicitly speficies safety factors, which depend on the type of load and on the combination of loads.

The design loads are determined by multiplying the calculated load with a factor which reflects the uncertainty of the quantity involved and the consequences of exceeding the limit state.

For the definition of limit state, see Annex 1.

The Federal Republic of Germany

A standard only exists in the state of Schleswig Holstein. Each wind turbine to be erected has to be approved by an authorized official as an element of the formal licensing process of the local authorities. To this aim Germanischer Lloyd has issued a report which is meant as a guide for the official approver, but generally, contains the same elements as the (draft) standards of the other countries described. The document does not describe the basis af the safety philosophy but specifies a number of requirements of safety and protection systems which have to be fitted to a wind turbine.

The most essential requirements are:

- A wind turbine shall be equipped with two independently working safety systems that limit the speed to the operating speed under all circumstances; one system must act as a brake in such a way that a complete stop of the rotor and safe maintenance and inspection is possible.
- Blade pitch control, spoilers, blade tip brakes and mechanical brakes are considered to be safety systems.
- The safety systems must be designed in such a way that a safe condition can be realised during loss of load whilst operating at maximum power.
- A vibration sensor is obligatory and must be connected to the safety system in such a way that the wind turbine is shut down when the vibration level becomes too high.

The wind turbine should be installed and commissioned according to a procedure submitted by the manufacturer.

The Netherlands

The aim of the standard is to guarantee the safety of the environment with regard to the structure of the wind turbine during its technical lifetime.

The aim is considered to be met if the following conditions are fulfilled:

- Operational limit states* shall never be exceeded in design situations which are defined as "instantaneous combinations"**.
- Failure limit states* shall never be exceeded in design situations which are defined as "fundamental, special and fatigue combinations"**.

The limitation of the rotor speed is required to avoid exceeding limit states. In order to realize this, safety systems and locking devices are applied.

The general requirements concerning these systems and devices are as follows:

- A wind turbine must be able to withstand failure of one component or system (single internal failure).
- The following phenomena are not considered to be internal failures. The components involved should be constructed in a "fail-safe" or "safe-life" manner:

* for definitions see Annex 1.

** for difinitions see page 23 and 24.

- fracture in the drive train;
- locking of generator or drive train component;
- tower collapse;
- blade fracture;
- disconnection of the nacelle from the tower;
- activation of locking system during operation;
- failure of locking system during stand-still.

The principles of operation of safety systems:

The wind turbine shall be equipped with at least two, independently activated and independently operating safety systems which are not of the same type.

Each system separately shall be able to limit the speed to acceptable values under normal and extreme operating modes.*

One of the safety systems must be able to bring the rotor to a complete stand still under normal operating conditions.

The rotor and other rotating components shall be able to be locked for safe maintenance and inspection.

Sweden

Like the Danish concept, the Swedish document distinguishes 3 safety classes. If the highest safety class is chosen, the probability of blade failure has to be extremely low and the possibility of blade throw must be eliminated. For lower safety classes the Building Code accepts a progressive failure of the whole structural system including the tower.

The Swedish draft also includes most load cases and combinations. A list of safety equipment required is given. In order not to impose too heavy an economic burden on smaller machines some of the more sophisticated equipment, such as vibration sensors, crack detection equipment, ice detectors, are not required but are only suggested for larger machines.

With the aim of making the operation of a wind turbine as risk free and as simple as possible the document suggests the following safety equipment to be necessary for at least the large wind turbines (> 25 m diameter):

- emergency braking system to prevent overspeeding of the rotor;
- vibration sensor;
- crack detection systems on the blades;
- ice detectors;
- lightning protection;
- warning lights;
- warning signs, fences around safety zone;
- lock on the rotor;
- lock on the yawing system.

* for definitions see page 22.

LOAD CASES

All standards mention or specify load cases which have to be considered in the design or evaluation process. The selection of the load cases in the different standards however seems arbitrary since the system of defining load cases varies from standard to standard or there is no system described at all.

It is therefore impossible to compare load cases without a defined framework.

In this section a system is proposed which is used to compare the load cases.

To understand the method it is essential to distinguish between the following:
- the OPERATIONAL MODE of a wind turbine;
- the EXTERNAL FACTORS under which the wind turbine operates;
- a LOAD CASE which is determined by the OPERATIONAL MODE of the wind turbine and the EXTERNAL FACTOR(S).

External factors comprise different loads (see table 2) and environmental and other phenomena, which are divided into *normal* and *extreme* factors.

Operational modes are subdivided in normal and failure modes.

Table 2: Different Load types

Aerodynamic Loads caused by:	Inertia Loads
mean wind speed peak wind speeds turbulence wind speed profile tower shadow skew wind	centrifugal force gyroscopic ,, coriolis ,, gravity ,, other accelera- tion forces

Table 3 gives a list of all *operational modes,* both normal and failures, that were found in the review documents. Some descriptions therefore may overlap.

Table 4 lists the *normal external factors,* whereas **Table 5** gives the *extreme external factors.*

Load cases can be systematically represented in the form of a matrix in which along one axis the external factors are specified and along the other axis the operational modes. See figure 1.

As the Danish and the Dutch standards contain the most detailed descriptions of load cases they will be compared qualitatively on the basis of the system described above.

The Danish standard describes load cases in terms of combinations of load types and load conditions which are understood to be operational modes. The combination load cases are described in detail in the text of the standard.

The matrix of load cases contains combinations which are not completely independent. For instance under load types the operational loads (braking loads, yawing loads, blade pitch loads) are not independent of aerodynamic and inertia forces.

The same applies for the load condition. One load condition deals with wind speeds only, while all others are describing the operating mode of the wind turbine.

In the Dutch standard, load cases are described as a combination of operational modes and loads, the latter to be interpreted as external factors. Four different load case matrices are given on the basis of the frequency of occurence of the phenomena involved.

Matrix 1 gives the combination of normal operational modes and normal external factors ("instantaneous combinations"). The forces are specified as instantaneous loads which occur regularly.

Matrix 2 combines normal operational modes and extreme external factors ("fundamental combinations").

Matrix 3 combines failing operational modes and normal external factors ("particular combinations").

Matrix 4 indicates the load cases for which a fatigue evaluation is required ("fatigue combinations"). Only normal external factors and normal operational modes are considered.

In order to compare the load cases of the two standards the combinations were translated into the system presented by Figure 1.

All coordinates of the matrix result in load cases which are seperately described in the texts. The result is presented in Figure 2.

The following remarks refer to the comparison.

Apparently both standards exclude the combination of extreme external factors and failing operational modes. The Danish standard takes into account extreme wind speeds but does not specify the operational modes with which it has to be combined. In both modes only single combinations of abnormal and normal conditions are considered.

Table 3

OPERATIONAL MODES
Normal
N1 Normal energy production $V_C<V<V_R$ N2 Normal energy production $V>V_R$ N3 Like N1 og N2 combined with skew flow and yawing N4 Starts & stops N5 Shut down N6 Locked
Failure
F1 Emergency stop by mechanical brake F2 Emergency stop by blade pitch control system F3 Airbrakes activated, max. acceptable r.p.m. F4 Failed yawing system (rotating rotor) F5 Failed pitch control a. one blade b. all blades F6 Failed safety system F7 Failed control system F8 Failed electrical conversion system F9 Failed electrical circuits a. disconnection from grid b. short circuit 2 phases c. short circuit all phases F10 Shutdown combined with failed blade pitch control system a. one blade b. all blades F11 Shutdown combined with failed yawing system F12 Shutdown combined with failed safety system F13 Shutdown combined with failed control system F14 Uncontrolled mechanical braking F15 Loss of (part of) blade during normal operation and controlled stop F16 Free running rotor with only one aerodynamic brake functioning
Transport
Erection

Table 4

EXTERNAL FACTORS	
Normal	
	Aerodynamic **loads** caused by:
n1	Mean wind speed
n2	Turbulence
n3	Wind speed profile (vertical)
n4	Tower shadow
n5	Skew flow a. stationary skew flow angle b. changing skew flow angle
n6	Gusts
n7	Turbulence caused by wakes of other wind turbines
n8	Unbalanced properties of rotor blades
	Inertia **loads** caused by:
n11	Centrifugal forces
n12	Gyroscopie ,,
n13	Coriolis ,,
n14	Gravity ,,
n15	Rotor unbalance
n16	Acceleration forces
	Effects caused by other external factors such as:
n21	Ice
n22	Snow
n23	Hail
n24	Birds Collision
n25	Temperature
n26	Lightning
n27	Corrosion
n28	Seismic phenomena
n29	Grid induced phenomena a. higher harmonics b. disconnection from grid/load

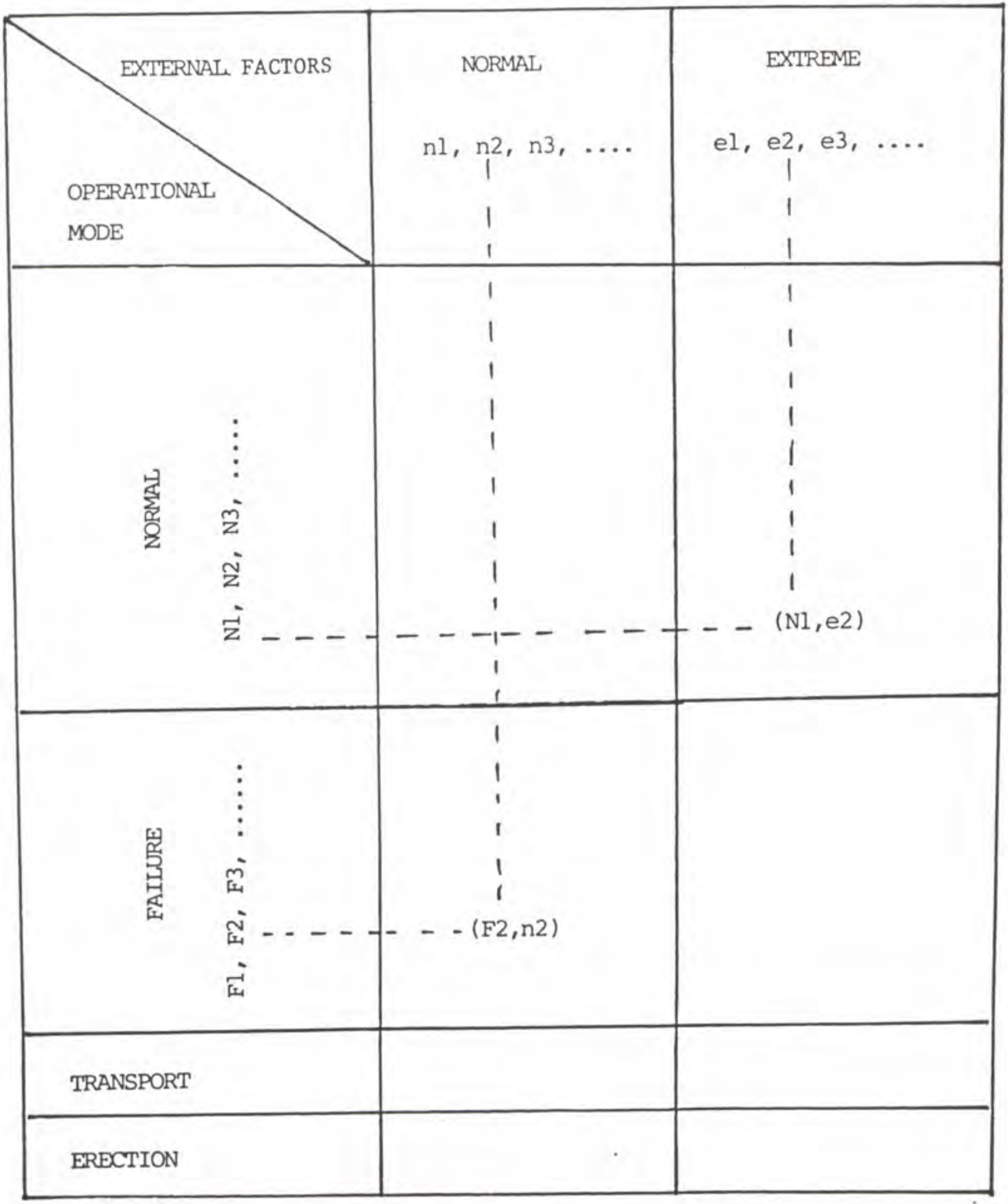
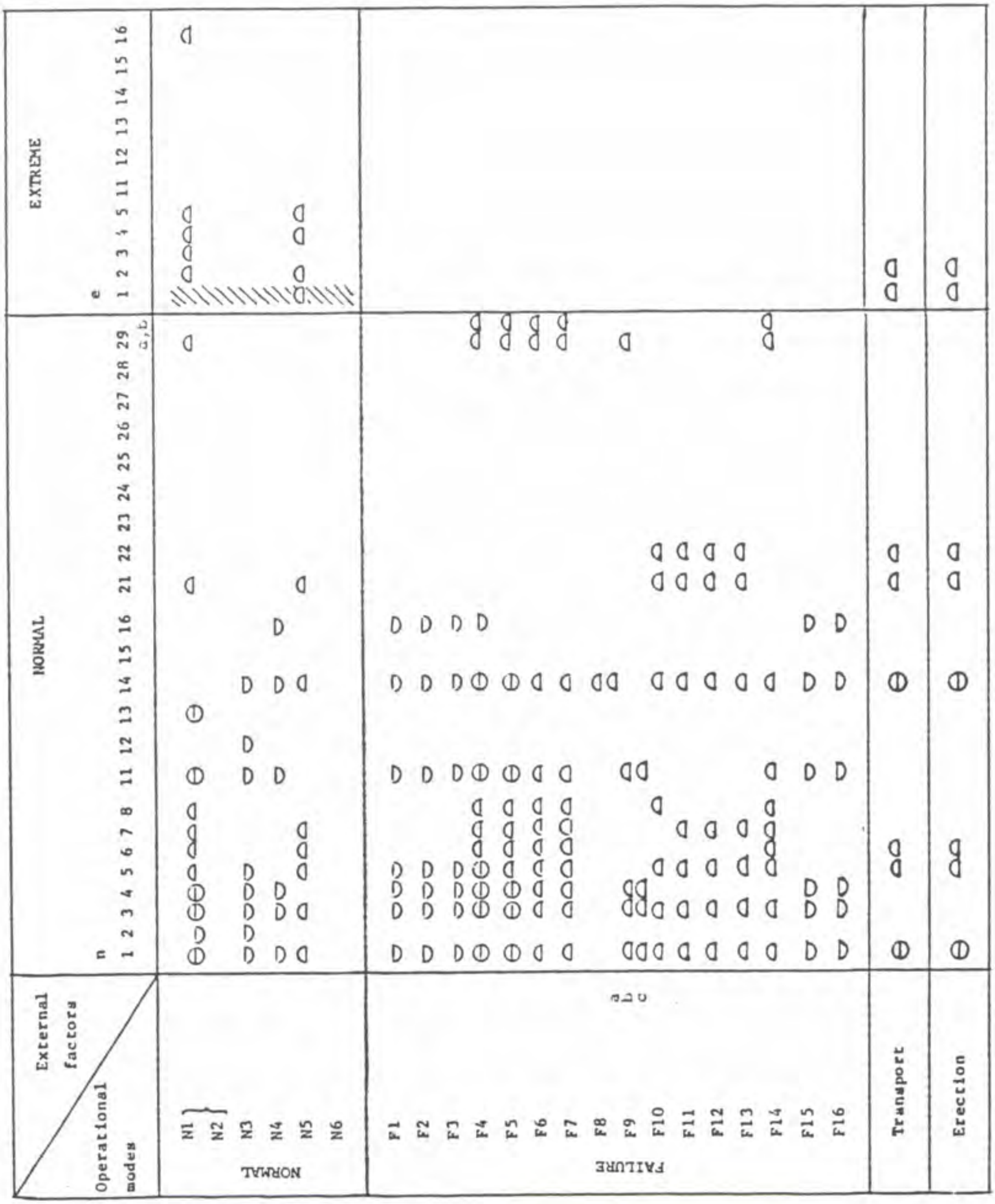


Figure 1. Load cases.

Table 5

EXTERNAL FACTORS	
	Extreme Aerodynamic Loads caused by:
e1	Wind speed (peak wind speed/survival wind speed)
e2	Gusts
e3	Wind speed profile (vertical)
e4	Skew flow a. stationary skew flow angle b. changing skew flow angle
	Effects caused by other external factors such as:
e11	Ice
e12	Snow
e13	Hail
e14	Temperature
e15	Seismic phenomena
e16	Grid induced phenomena: higher harmonics



Notes: Danish standard

Netherlands standard

Danish load combination, not specified in terms of operational modes.

Figure 2. Comparison of the Dutch and Danish load cases.

CONCLUSIONS AND RECOMMENDATIONS

- External factors, such as the climate or grid related factors, vary widely in the countries which are now developing safety standards for wind turbines. For this reason standards can never be the same.

  In order to promote the free exchange of products on the international markets it is however of utmost importance that design specifications and other requirements can be compared in a non overlapping way.

- In order to achieve compatibility it is necessary to agree on:
  - the formulation of the scopes;
  - the formulation of the safety philosophies;
  - the formulation of requirements concerning safety systems;
  - the system of defining load cases.
    (The quantification of load cases can be treated separately from country to country);
  - the system of defining safety factors.

- **Safety philosophy**

  It is recommended that a description based on the Dutch Standard be adopted (page 19 and 20).

- **Safety system requirements**

  It is recommended that the description should combine aspects of both the Danish and Dutch standard.

- **Load cases**

  It is recommended that a load case is defined as a combination of an operational mode and an external factor according to pages 15 and 16. A standardized (non interfering) list of external factors and operational modes should be arrived at in order to reduce the number of load cases which are specified in the different standards.

- **Safety factors**

  It is recommended that material and load factors contained in the Danish and Dutch documents be adopted.

- **Scope**

  There is a relation between the scope of a standard and the degree of detail by which load cases are described. The wider the scope the more load cases are described (non specified terms).

  It is recommended that the scope be limited to those machines which are used most commonly. Possibly making different standards for fundamentally different machines.

- **General**

  In further developing common standard formats it is recommended that special attention is given to:

  - description of wind models (gusts, extreme wind speeds, turbulence);
  - treatment of dynamic loads versus static (or extreme) loads.

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ANNEX 1

Definition of a limit state

$S (F_d, GE_d, M_d) = R (F_d, GE_d, M_d)$

S : Load function
R : Strength function
F_d : Calculated value for loads
GE_d : Calculated values for geometrical parameters
M_d : Calculated value for material properties

The operational limit state is the state within which normal operation is possible.

It the failure limit state is exceeded, components will fail or break, resulting in a non operational wind turbine.

Calculated value of loads

This value can be calculated by: $F_d = \gamma_f * F_{rep}$

Where F_d : calculated value of the load
F_{rep} : representative value of the load according to specifications in the standard
γ_f : load factor (partial factor) according to specifications in the standard

Calculated value of material properties

This value can be achieved by $M_d = \frac{M_{rep}}{\gamma_m}$

Where M_d : calculational value of the material properties
M_{rep} : representative value of the material properties
γ_m : materials factor

In the Danish and the Dutch Standard the load (or partial) factors are specified as follows:

NL: Load factors

Type of Load	Failure limit state per safety class		Operational limit state
	Class 1	Class 2	All classes
Constant by present load	1,2 (0,9)	1,2 (0,9)	1,0 (1,0)
Variable load	1,2	1,3	1,0
Fatigue load	1,2	1,2	1,0

DK: Load factors

Type of Load	Failure limit state		Accident*
	extreme loads	fatigue loads	
Gravaity forces	1,0	1,0	1,0
Aerodynamic forces	1,3	1,0	1,0
Intertia forces	1,3	1,0	1,0
Operational forces	1,3	1,0	1,0

* The accident loads are only to be applied for wind turbines in the highest safety class.

NL: Material factors

Material	Failure limit state	Operational limit state
Steel	1,0	1,0
Concrete steel	1,1	1,0
Concrete (compression)	1,1	1,4
Laminated wood	1,2	1,2
Aluminium	1,0	1,0
F.R.P.	1,2	1,2

The Danish standard gives all the load combinations in one matrix. One axis (vertical) specifies the load types, the other the operational conditions.

ANNEX 2

REFERENCE LIST

(Only documents for standard committees etc. are mentioned. Documents containing specifications for wind turbines for actual projects are omitted).

USA

[1] Design Criteria Recommended Practices Wind Energy Conversion Systems
AWEA Standards Program
Cooperative Agreement no. DE-FC04-80AL12926

[2] Recommended Practice for the Electrical Design and Operation of Wind Farm Generating Systems
IEEE Working Group on Standards for Windfarm Generating Stations
May 1988

[3] Recommended Practice for the Installation of Wind Energy Conversion Systems
AWEA Standards program
Preliminary draft, July 1987 (Published 1988)

Canada

[4] Small Wind Energy Conversion Systems Safety Design
CSA Preliminary Standard F416-M1985
Canadian Standards Association, May 1985

The Netherlands

[5] Veiligheidseisen voor Windturbines (Safety Requirements for Wind Turbines), Concept Standard, Netherlands National Committee of IEC and CENELEC, P.O. Box 5059, NL-2600 GB Delft, The Netherlands
Final version to be published in 3rd quarter of 1988

Denmark

[6] Udkast til norm for Last og Sikkerhed for Vindmøllekonstruktioner
(Draft standard on Load and Safety of Wind Turbine Structures)
Working Document, January 20, 1987

The Federal Republic of Germany

[7] Richtlinien für die Prüfung, Abnahme und Überwachung von Windkraftanlagen (Guidelines for the testing, Commissioning and Supervising of wind turbines), Germanischer Lloyd, Hamburg, September 1986

Sweden

[8] Vindkraftverks Konstruktionssäkerhet. Underlag för hållfasthetsdimensionering av bärande komponenter.
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(Structural Safety of Wind Turbine Systems)

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