ADVANCES IN WIND TURBINE TECHNOLOGY

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INTRODUCTION

The purpose of this paper is to give a small resume of the major technological development and to outline what is felt to the biggest technical challenges for wind industry in the years to come.

The wind industry is still an young industry compared to other types of heavy industry like the shipyard industry, car/truck, large machinery, oil equipment and so forth. This also explains partly why our industry has been able to achieve the impressive steps toward today's cheap electricity from the wind, which compare well with the achievement of the computer industry.

The paper has some minor historical aspects, which explain why this author feels the turbine industry has a technically good and healthy concept and the wind electricity has become competitive with any form for electricity generation. Many political and social reasons have been playing a major role in the wind industry development, but here is tried to concentrate on the technical aspects.

The second chapter explains the characteristics of a modern wind turbine in some detail since this is the background for this paper in general. The third chapter deals with historical aspects and the fourth chapter deals with the future challenges. The final chapter gives a short view of the future.

The future will bring most the technical challenges related to external condition for the turbines (Offshore-complex terrain) and how the turbines react to this.

It is postulated here that the wind industry has passed the point of no return, where a completely new concept can be more cost competitive compared to the well proven three bladed upwind turbine with stiff hub. The inertia is the wind industry simply does not allow the newcomers to enter the market, since the price graph of figure 6 has shown such great improvement.

CHARACTERISTICS OF A MODERN WIND TURBINE

The well proven 'Danish' turbine concept with three blades on a stiff hub sitting upwind (in front the machinery parts) has now become widely accepted as being optimal or at least cost competitive with other sources of electricity.

Three blades are advantageous primarily for noise and production reasons.

The development from stall regulated through pitch turbines with fixed speed to variable or semi variable speed has been is essential for turbines to cope with the challenge of today and of the future, namely the complex terrain and large scale wind development.

The power curve below a typical power curve of a modern turbine where blade feathering (Changing of angle of attack) below rated power optimise energy production and blade feathering and speed control the power

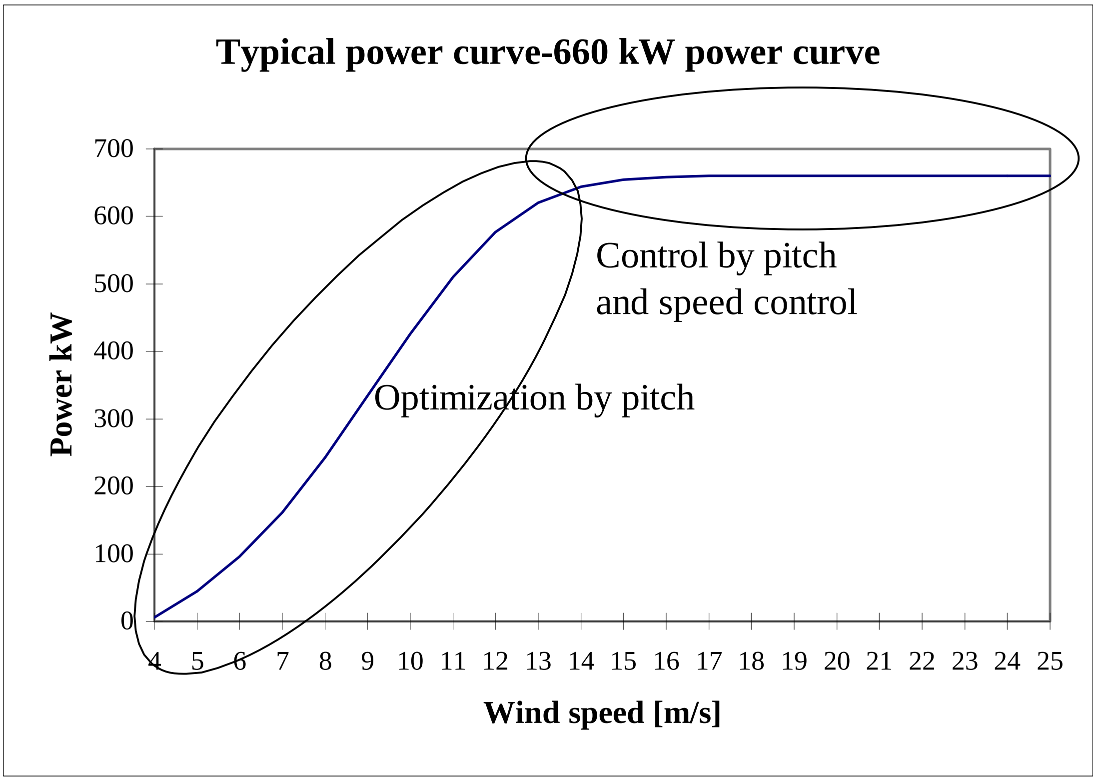

Figure 1. Regulation and optimisation

The typical turbine shown in Figure 2

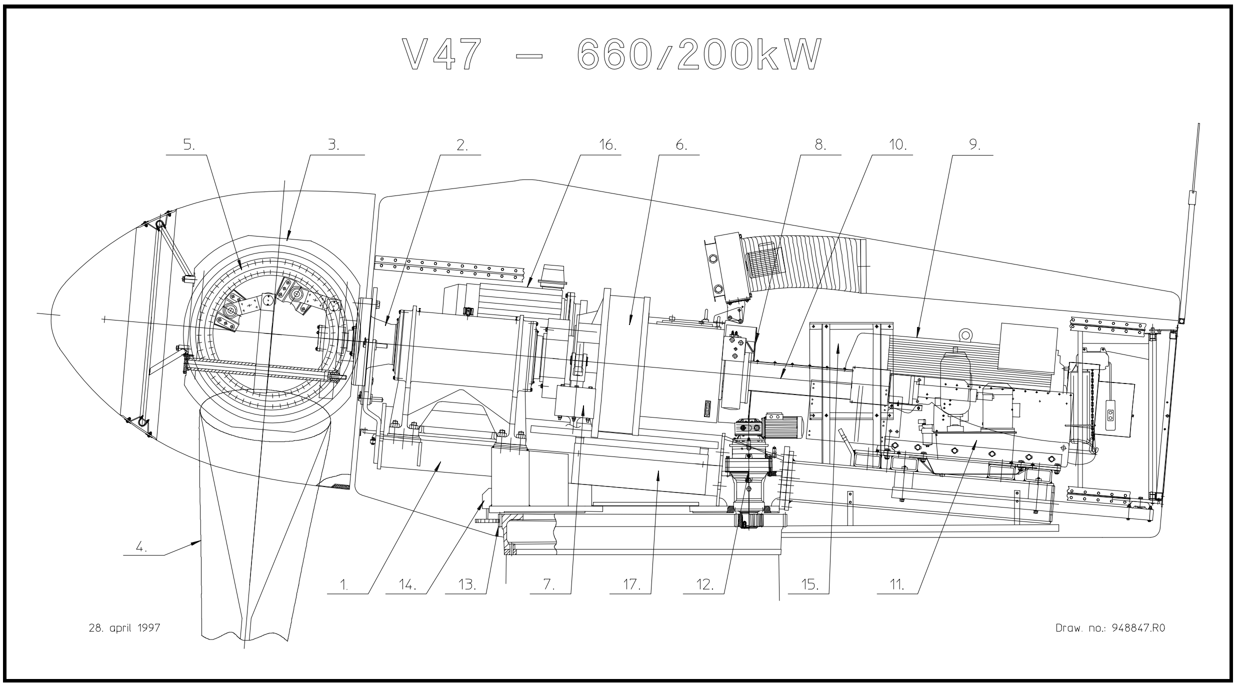

Figure 2. Structure of typical wind turbine.

1.	Base frame	9.	Generator
2.	Main shaft	10.	Cardan shaft
3.	Blade hub	11.	Hydraulic unit
4.	Blade	12.	Yaw gear motor
5.	Blade bearing	13.	Yaw ring
6.	Gearbox	14.	Yaw control
7.	Gear tie rod	15.	VMP top control unit
8.	Disc brake	16.	Small generator
		17.	Generator shift box

Turbine Power Control

Probably the most important issue for wind turbines is to regulate and control the power output, since this makes turbines able to reduce the loads and hereby fit better in complex areas and ensure reliability in these often remote areas. Reliability is a key word for remote areas and offshore.

In principle two different methods exist, namely pitch- and stall regulation. Pitch regulated turbines can turn or pitch the blades during operation to control and to optimize the output power, while stall regulated rely on the airfoil stall characteristics and the chaotic nature of stall.

The basic difference can be seen from figure 3, which show a typical pitch and stall power curve. It beyond the paper to elaborate much on the differences between pitch and stall, since this can be found in most basic literature and for example /1/

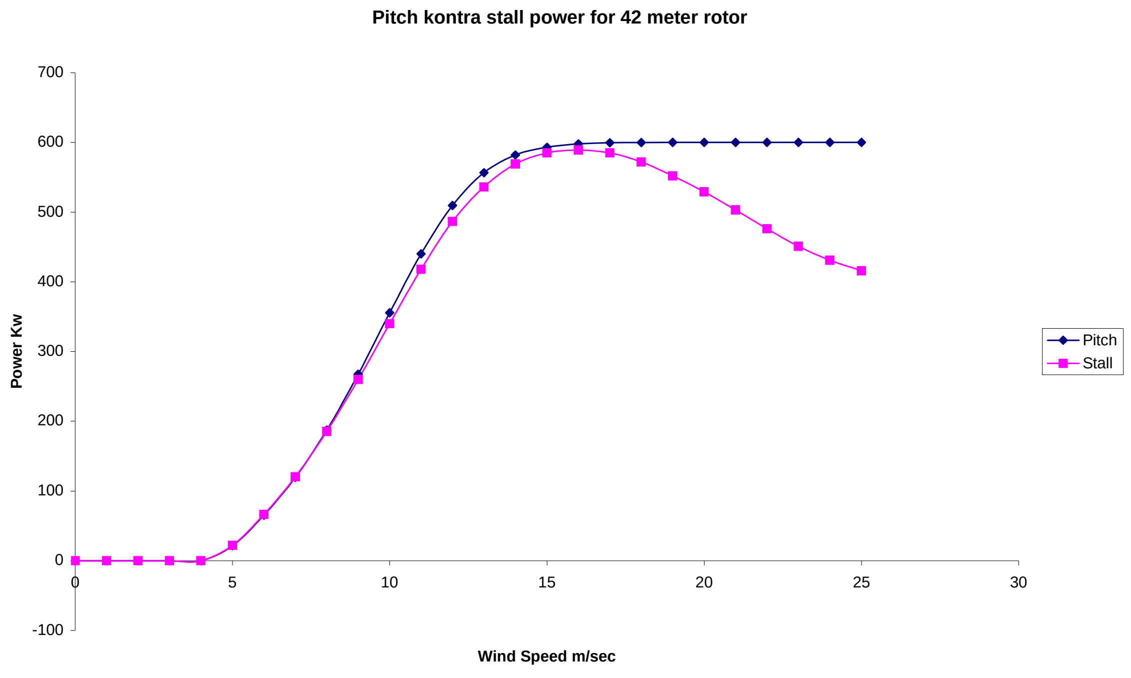

Figure 3. Pitch and stall power curve.

In the industry the tradition and experience in making pitch regulated turbines varies and it appears that the trend toward all turbines being pitch regulated is clear.

Likewise experience in forms of variable speed varies but the trend is also clear towards more and more manufacturer use this feature.

The advantages of the two features (Pitch regulation and variable speed) are to make stable power output at rated power and to optimize power below rated power, see figure 1 and 4.

To appreciate the advantages of pitch regulation and a form for variable speed, it is necessary to understand the basic climatic conditions in which a turbine operate, primarily the variations of wind speed.

Climatic conditions and power/load control

A wind turbine operate in a wide variety of temperatures, air densities, atmospheric pressures and mean wind speeds not mentioning environmental aspect affected the blades (dirt, insects). The variations can be classified as short and long term variation types like illustrated in the table 2 below.

In table 2 long means that it takes several minutes to change significantly, while short means, that this climatic parameter can change several times per second.

Table 2. Influence of climatic parameters on power and loads

No.	Climatic	Variation type	Effect
1	Air density	Long.	Lower density means lower power. Can be caused by altitude above sea level or temperature.
2	Temperature	Long	Higher temperature means lower air density.
3	Mean Wind speed	Long	This is the given by the power curves
4	Wind turbulence	Short	This cause power variations and fluctuations

The variation of types number 1 and 2 in table 2 will for stall regulated turbines cause variations in rated power while pitch regulated turbines will maintain same rated power.

The newer stall regulated turbines has introduced the concepts of active stall and combi stall to offset these long term variations to maintain the rated power. This is not to be confused as being a pitch regulation, since blade rotation do not act on the short term fluctuations (Type 4) in wind speed, which is the main reason for power variations seen as flicker, since the blade rotation is only meant to ensure that rated power can be achieved for mean variations in air density.

Type 3 variations are the predictions we hear about in the weather forecast as being the forecaster state that the wind tomorrow will be 8 m/sec and these variations are basically given as the power curve.

For these variations pitch regulated can optimize power output below rated power by the pitch regulation feature, which continuously move the blade angle to optimal position for the present instantaneous wind speed, since wind always vary around the mean speed. In other words a wind turbine uses the pitch regulation feature to maximise the mean power production for any mean wind speed below rated wind speed (The wind speed at which rated power is achieved)

Type 4 variation are the short wind variations (Turbulence) around the mean speed, which we all feel in our daily life. These wind speed changes happen often (1 to 2 times per second), which in more theoretical terms can be said as the frequency content of wind is between 0-2 Hz.

These type 4 variations cause fluctuations in power, which cannot be avoided below rated power, but are not present with pitch regulation and variable speed at rated power. This effect on the power output is illustrated by figure 4 below, which show time power series for a variable speed turbine.

The main problem with especially short term wind variations is the fact that these variations hit the rotor area unevenly around the rotor plane (Coherence in wind) and the turbine need to regulate on the wind that has all ready hit the rotor plane. This paradox has through times meant that turbine has moved the anometer of the turbine to many different positions to try to get the best placement. Therefore the availability of rotor speed variation like full or semi variable speed is very crucial to ensure stable power output, since this allows the rotor to speed up without power variations, see section 2.1.3.

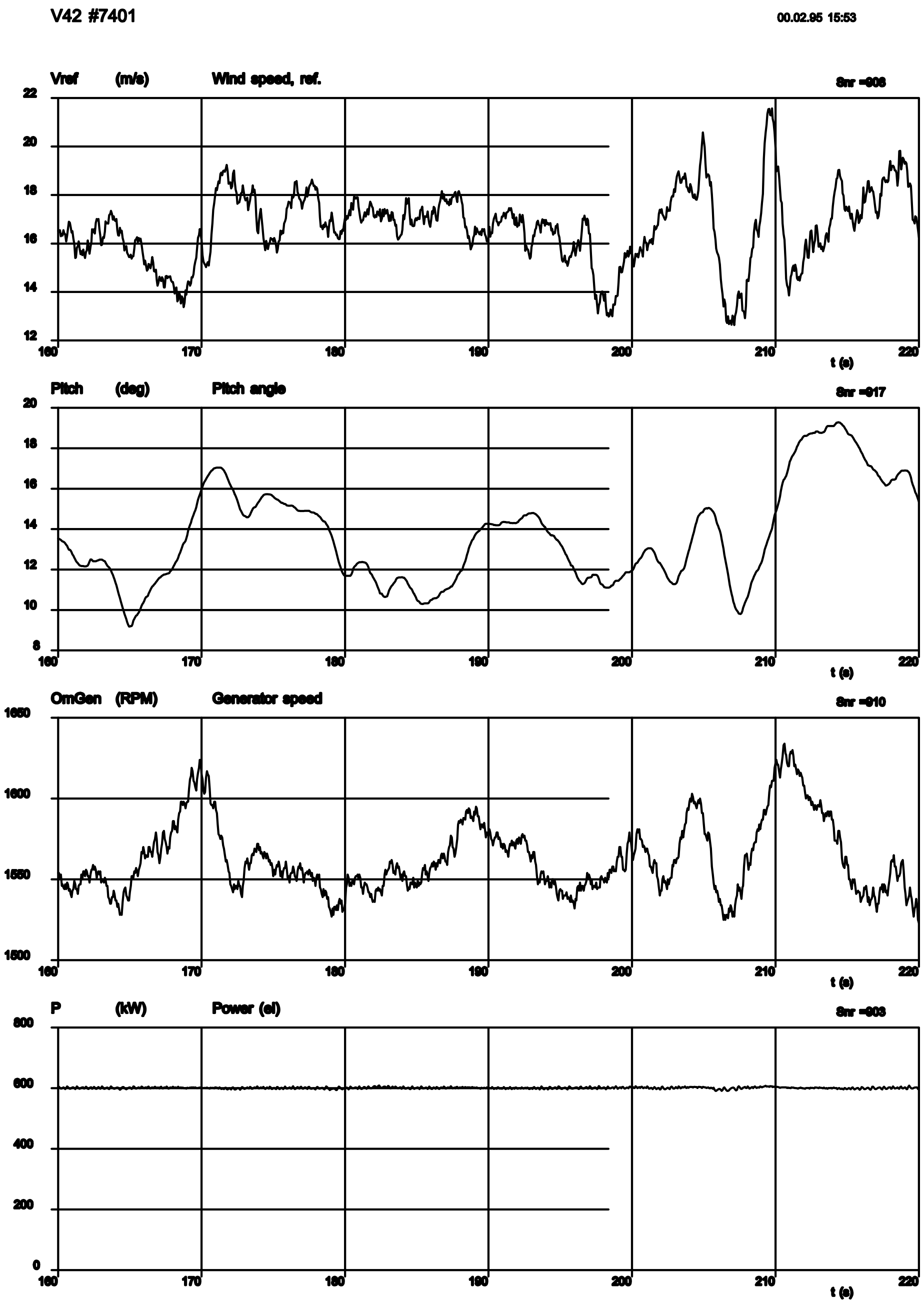

Figure 4. Power time series for a semi variable turbine.

The most remarkable difference between a stall regulated turbine and figure 4 are the power fluctuations for the stall regulated turbine above rated wind speed with significant instantaneous power peaks above rated power. This type of power peaks can vary significantly depending on air density, wind turbulence, wind gust acceleration and are not to be confused with variations in mean power as caused by variation types 1 and 2 in table 2.

Turbine 4 variation is today turbulence and it is clear today that work need to done to validate that turbulence in the IEC 61400 –1 definition does cover the wind behaviour in complex terrain.

Pitch regulation – blade feathering.

The pitch regulation feature in basically power optimization below rated power as illustrated by figure 1. The pitch system or the ability to turn the blade continuously is necessary because of the wide interval of wind speeds in which a turbine operate.

The variation of wind speed from appr. 4 to 14 m/sec cause different in flow angles on the blades airfoil, since the speed of rotation of most turbines today is constant below rated power. This means that blade should be turned to different blade angles at operation between 4 and 15 m/sec to perform optimally as can be seen at figure 5 below. This is what pitch regulation concept does.

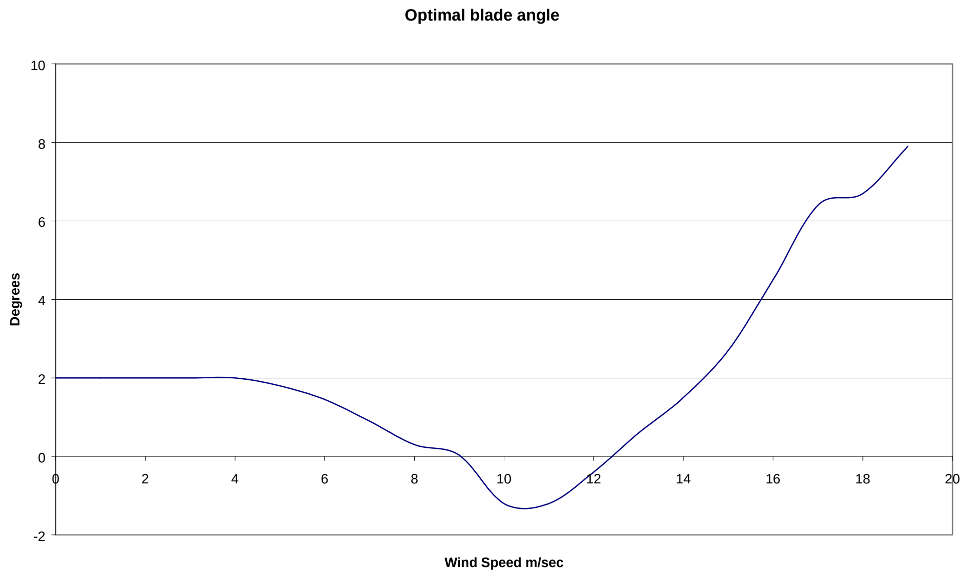

Figure 5. Optimal inflow angle as function of wind speed.

Speed control – variable speed.

The speed control feature is a system to vary the generator speed between synchronous speed and at least 10 % higher speed for semi variable or more for full variable speed. This means for a 4 polet generator at 50 Hz grid a generator speed variation between 1500 and 1650 rpm.

The most important advantage by variable speed is best illustrated by the basic equation for power in a rotating system

$P = T * \omega$ (1)

P = Power in kW
T = Torque in the drivetrain in kNm.
ω = Rotor speed in rad/sec.

Above equation together with basic formula for the power in the wind below are the background, why optimal turbines in the future are being pitch regulated with a form for variable speed.

$P = (1/2)*C_p (\rho v^3 A)$ (2)

When a wind gust hits the rotor, the wind increase and the power with the wind in third power, see equation (2). This create not necessary a big increase in torque since the variable speed will in equation (1) allow ω to increase and this is much faster type of regulation than trying to turn the blade.

Variable speed does for some turbines mean, that biggest momentary power peak is less than 4 % higher than nominal, which is very important for the transformator design.

Power quality.

In connection with turbine design and power quality we need to distinguish between:

1. Conventional wind turbines with fixed rotational speed – Stall.
2. Conventional wind turbines with fixed rotational speed – Pitch.
3. Inverter connected turbines with variable speed.
4. Semi variable speed wind turbines.

The basic difference between 3 and 4 is the interval of variable speed and the frequency converter, while the difference between 1 and 2 was touched in the above and in /1/. In the wind industry it has long been debated if it is possible to combine 1 with either 2 or 3 to achieve the good power quality of 3 and 4. This is probably not possible and that is why many manufacturers start to make active stall or semi pitch systems.

Moreover it very important to define grid quality at common network point. A weak grid is one where the changes in the real and reactive power, which flows into or out of the grid, will cause changes in the voltage at that point and neighbouring points. Therefore on a stronger grid turbines are less likely to cause power quality problems.

Previously we discussed the pitch regulation and variable speed features and the effect on power and this is not elaborated deeply here.

Power quality can be defined as:

1. Stationary voltage conditions.
2. Flicker.
3. Harmonics.

Stationary voltage conditions are changes in maximum power (peaks), where variable speed minimise these significantly.

Flicker is defined as the effect of rapid voltage variations on incandescent light and is present at continuous operation, during cut-in (start) and cutout (stop).

Normal cut-out or stop is also performed softly with the pitch system and form for variable speed in modern turbines to avoid large torque in the drive train and to minimize loads on the turbine.

Harmonics is deviation from the perfect 50 or 60 Hz sinus shape of the voltage and caused by some variable speed turbines. Harmonics are present on the grid before turbines arrive and it hard to find out sometimes if the turbines cause extra harmonic or amplify existing harmonics.

HISTORICAL ASPECTS

The history of wind industry has shown dramatic decrease in the cost of wind generated electricity, which are illustrated with graph in figure 6.

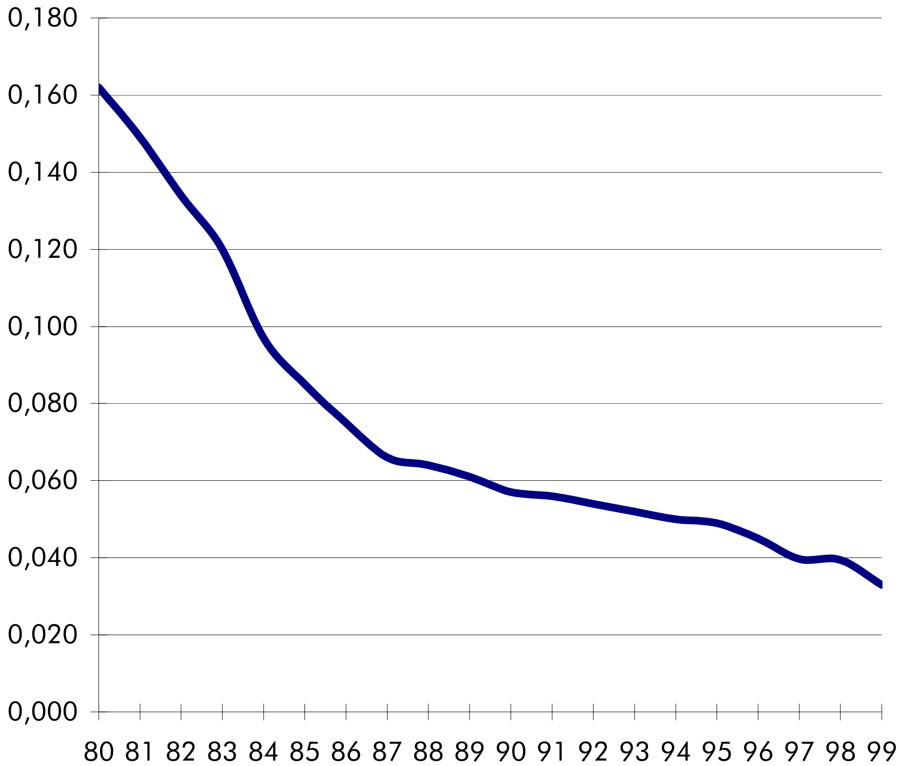

Figure 6. Price in US cents for wind generated electricity with time.

The decrease has mainly been driven by bigger and more efficient turbines together with a decrease of cost in manufacturing of the turbines.

Today the turbines are getting so big that other factors like infrastructure, transport and erection becomes a key factor to keep the development of figure 6 going down. This is especially true for the future market in complex terrain and offshore.

The technical development has been much driven by research in the correct tools for predicting the wind conditions and how these wind conditions affect the turbine load wise. Today we all have tools to predict loads in most situations and the IEC 61400-1 with some shortcomings give a good background for design and comparison of turbines.

All turbines are designed by a factor method meaning the equation below must be satisfied for both extreme and fatigue loads.

$F_{aeroynamic} * \gamma_{load} < (\text{Allowable load})/\gamma_{material}$ (3)

In simple words the safety is the product of the load factor γ_{load} and the material factor $\gamma_{material}$. Hereby the confidence in 20 years lifetime or correct extreme safety becomes a discussion of how high this product shall be chosen.

In the Danish steel code when we started making turbines this product of material and load factor was high and this drive the Danish turbines to be heavy and safe, when the load calculation programs was not as developed as today.

Today when good and proven load programs for most turbine location, the challenge of the wind industry and certification is to the make the sure the above equation (3) becomes optimised such that the wind turbines of the future will be optimal.

We shall remember that turbines of today are machines, which are produced in a mass production environment with ISO quality control. This is important to remember when trying to make cheaper electricity from the wind at the same time as some part of industry are demanding higher safety in calculations.

Past problems has often not been caused by bad engineering design but simply because of:

- Too little experience
- Lack of engineering analysis
- Bad quality.
- Ignorance.

This is important to remember when moving forward in the wind future, since we must not base code and certification practice on past problems, but on good engineering judgement plus the developed and proven methods, which we have got throughout the first 20 years.

FUTURE CHALLENGES

Based on the previous chapters the future challenges of the wind industry in a technical content are simply.

1. Get better understanding of wind in complex terrain through better site measurement.
2. Avoid too conservative approaches in design due to requirements not based on the right reasons. One example of this is a tendency to demand higher safety on towers despite no problem with tower designs presently.
3. Work much with infrastructure, transport and erection since both offshore and complex terrain demand this.
4. Develop offshore and erection methods.
5. Develop techniques to reduce loads.

VIEW OF FUTURE

Cheaper electricity from wind by making turbines more efficient and by getting better economics of scale in manufacture since the market is still growing.

The turbine will become bigger since this will minimise the effect on environment and tend to lower the cost by long term considerations.

Since the industry is a ’green industry’ we strive to make turbines better the environment by ensuring

- Higher Production.
- Lower Noise. Pitch option and variable speed options.
- Less visibility in terrain. Reflection, speed, colours, types of towers.
- Lower loads by flexible design (Blade etc) and different form of load control

Recently some manufacturers are making lighter and flexible blade, since this reduces the loads on the turbine significantly. By making the new blade for a 47 rotor the loads was reduced with 10 – 20 % compared to the older blade concepts. Flexible blade design requires pitch turbines since these do not have the tip brake in the blade tip.

The future will mean load optimisation meaning lower loads and much of the future will happen offshore in Europe at least.

Better site assessments since sites are getting tougher. Sites are flat land as in the old days.

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During the time in the R&D Henrik Kanstrup Jørgensen was involved the development of the various Vestas turbines from V39-500 kW to the V66-1650 kW.

Before joining Vestas in 1991 Henrik Kanstrup Jørgensen was working at Bang & Olufsen A/S as CAD/CAE consultant.

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