Review of Contemporary Wind Turbine Concepts and their Market Penetration

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ABSTRACT
The main aim of this paper is to investigate the market penetration and share of different wind turbine concepts during the years 1998-2002, a period when the increase in the wind power capacity is starting to mark an abrupt evolution (more than two GW per year). A detailed overview is performed based on suppliers market data and concept evaluation for each individual wind turbine type sold by the Top Ten suppliers over the selected five years. The investigation is processing information on a total number of approximately 90 wind turbine types from 13 different manufacturers, which have been on the Top Ten list of wind turbine suppliers during 1998 to 2002. The analysis is based on very comprehensive data, which cover approximately 76% of the accumulated world wind power installed at the end of 2002. The paper also provides an overall perspective on the contemporary wind turbine concepts, classified with respect to both their speed control ability and to their power control type. Trends for wind turbine concepts are discussed.

Keywords: wind turbine concepts, fixed speed wind turbine, variable speed wind turbine, market penetration

1. INTRODUCTION
The increasing environmental concern during the 20th century has moved the research focus from conventional electricity sources to renewable sources. A number of renewable power generation sources exist, such as wind energy, solar energy, wave energy, hydro-power and more sophisticated systems based on hydrogen (Stanley, R.B., 2001), (Heier, S., 1998). In renewable power generation, wind energy has been noted as the most rapidly growing technology; it attracts interest as one of the most cost-effective ways to generate electricity from renewable sources.

Wind turbine technology has matured during the last decade. Wind turbine design objectives have changed over these years from being convention-driven to being optimised-driven within the operating regime and market environment. As well as becoming larger, wind turbine designs were progressing from fixed-speed, stall-controlled and with drive trains with gearboxes, to become pitch controlled, variable speed and with or without gearboxes. The present general availability of low-cost power electronics increasingly supports the trend toward variable speed turbines.

Today, the wind turbines on the market have a variety of innovative concepts, with proven technology for both generators and power electronics (Hansen, L.H., et al., 2001a). The continuously increased and concentrated electrical penetration of large wind turbines into electrical power systems inspires the designers to develop both custom generators and power electronics (Blaabjerg, F. and Chen, Z., 2003), and to implement modern control system strategies.

The main aim of this paper is to investigate and to provide an overall perspective on the contemporary wind turbines topologies, focusing on their market penetration and share during the years 1998-2002. It is beyond the scope of the paper to survey the generator and power electronics concepts in wind turbines, as detailed in several references (Hansen, L.H., et al., 2001a), (Heier, S., 1998), (Blaabjerg, F., et.al., 2003), (Hansen A.D., 2004).

The paper is organised as follows. First a brief description of the wind turbine impact on the market is done and then, the most commonly applied wind turbine concepts in industry are summarised and classified by both their ability of speed control and power control. A list with the Top Ten wind turbine suppliers in the world for 2002 is also provided. An investigation of the market penetration for different wind turbine concepts during the selected period, based on available suppliers market data is then performed. Also some future trends in wind turbine concepts are presented.

2. WIND TURBINE MARKET IMPACT

During the last decade, the installed wind power capacity has grown rapidly. As illustrated in Figure 1, the world cumulative installed capacity by the end of 2002 reached 32 GW, consisting of wind turbines installed in more than 40 countries. Europe is the major player in the installation of wind power, with an installed wind power capacity of 75% of the global capacity. Germany is the mainly responsible for this, installing 53% of the Europe capacity in total. Spain and Denmark are the next dominant contributing countries in Europe. At the end of 2002, the wind energy projects across Europe produced enough electricity to meet the domestic needs of 10 million people.

The yearly installed power is presented in Figure 2, showing an annual growth of 35.7% during the years 1998 to 2002 (BTM Consults Aps., 2003). Notice that, in Europe in 2002 was installed 87% of the global power capacity.

The penetration of wind power in the total world's electricity supply had reached 0.4% by the end of 2002. Yet, in Denmark, by the end of 2002, wind power capacity covered about 16.4% of the electricity demand.

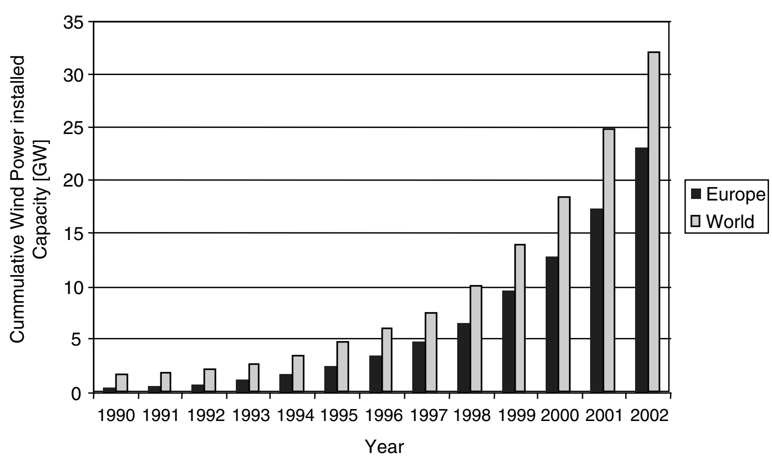

Figure 1: World and Europe – cumulative wind power installed capacity (GW). Source: EWEA, *Wind Power Monthly*.

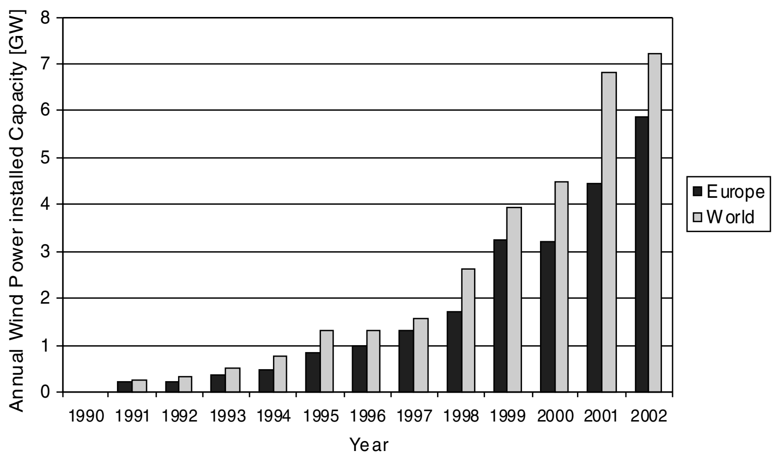

Figure 2: World and Europe - annual wind power installed capacity (GW). Source: EWEA, *Wind Power Monthly*.

The cost of wind-generated electricity has declined drastically over the years, as shown in Figure 3. The technological development and the increased production levels, together with the use of larger machines, have driven this cost reduction. There has been a consistent relationship between machine size and balance of plant costs, with larger machines reducing the cost of the remaining infrastructure on a per unit installed capacity basis.

According to (BTM Consults Aps., 2003), the growth in wind energy capacity will continue. Wind energy will become more competitive to conventional generated power in the years to come and the decrease in the cost per kWh will continue too. The main key is the power scaling.

3. WIND TURBINE CONCEPTS

In the following, the most commonly applied wind turbine concepts are classified by both their ability of speed control and their type of power control. In this paper, the attention is mainly drawn to the standard wind turbine configurations existing in the industry, with their particular advantages and disadvantages. The other alternative wind turbine designs, with slightly differences are not discussed.

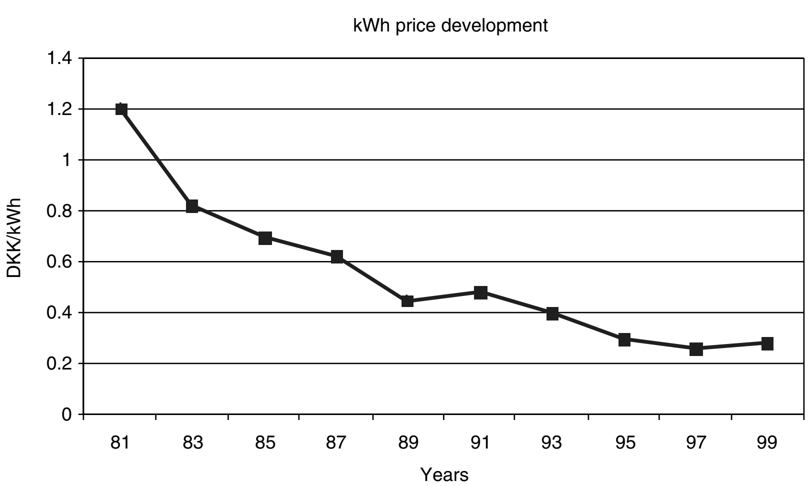

Figure 3: Estimated costs of wind generated electricity in Denmark. Source: IEA Wind 2002 Annual Report.

3.1 Speed control ability

The speed control ability criterion divides the wind turbine into two significant classes:

- *Fixed speed wind turbines*: In the early 1990s, most installed wind turbines had standard induction generators that operated at almost fixed speed. Neglecting the generator slip as having a very small aerodynamic effect, this implies that regardless of the wind speed, the wind turbine's rotor speed is fixed and determined by the frequency of the supply grid, the gear ratio and the generator layout.

Characteristic for the fixed speed wind turbines is that they are equipped with an induction generator (squirrel cage induction generator SCIG or wound rotor induction generator WRIG) connected directly to the grid, a soft-starter and a capacitor bank for reduction of the reactive power consumption. They are designed to obtain maximum efficiency at one wind speed. In order to increase the power production, some of the fixed speed wind turbines are equipped with two sets of windings in the generator: one is used for low wind speeds (typically 8 pole-pairs) and one is used for medium and high wind speeds (typically 4-6 pole-pairs).

A fixed speed wind turbine has the advantages of being simple, robust and reliable, well proven and with low cost of the electrical parts. Its direct drawbacks are the uncontrollable reactive power consumption, mechanical stress and limited power quality control. Due to its fixed speed operation, wind speed fluctuations are converted to mechanical torque fluctuations, beneficially reduced slightly by small changes in generator slip, and transmitted as fluctuations into electrical power to the grid. The power fluctuations can also yield large voltage fluctuations in the case of a weak grid and thus, significant line losses (Larsson, Å., 2000).

- *Variable speed wind turbines*: The variable speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. By introducing the variable speed operation, it is possible to continuously adapt (accelerate or decelerate) the rotational speed ω of the wind turbine to the wind speed v, in such a way that tip speed ratio λ is kept constant to a predefined value corresponding to the maximum power coefficient. Contrary to a fixed speed system, a variable speed system keeps the generator torque nearly constant, the variations in wind being absorbed by the generator speed changes.

The introduction of variable speed wind turbine concept increases the number of applicable generator types and further introduces several degrees of freedom in the combination of generator type and power converter type (Hansen, L.H, et al., 2001a). The electrical system of a variable speed wind turbine is thus more complicated than for a fixed speed wind turbine. It is typically equipped with an induction or synchronous generator and connected to the grid through a power converter. The power converter controls the generator speed in such a way that the power fluctuations caused by wind variations are more or less absorbed by changing the generator speed and implicitly the wind turbine rotor speed.

The presence of the power converter makes the variable speed operation itself possible. The variable speed wind turbines can therefore be designed to achieve maximum power coefficient over a wide range of wind speeds. The power converter controls the generator speed in such a way that the fast power fluctuations caused by wind variations are more or less absorbed by changing the generator speed and implicitly the wind turbine rotor speed. Seen from the wind turbine point of view, the most important advantages of the variable speed operation compared to the conventional fixed speed operation are:

1. *reduced mechanical stress on the mechanical components such as shaft and gearbox* – the high inertia of the wind turbine is used as a flywheel during gusts, i.e. the power fluctuations are absorbed in the mechanical inertia of the wind turbine.

2. *increased power capture* – due to the variable speed feature, it is possible to continuously adapt (accelerate or decelerate) the rotational speed of the wind turbine to the wind speed, in such a way that the power coefficient is kept at its maximum value.
3. *reduced acoustical noise* – low speed operation is possible at low power conditions (low wind speeds).

Additionally, the presence of power converters in wind turbines also provides high potential control capabilities for both large modern wind turbines and wind farms to fulfil the high technical demands imposed by the grid operators (Eltra, 2000), (Sørensen, P., et al., 2000), such as:

1. *controllable active and reactive power (frequency and voltage control)*
2. *quick response under transient and dynamic power system situations*
3. *influence on network stability*
4. *improved power quality (reduced flicker level, low order harmonics filtered out and limited in-rush and short circuit currents)*

The disadvantages of variable speed turbines are: additional losses due to power electronics, more components, thereby reliability issues, and an increased capital cost due to the power electronics.

The most commonly applied wind turbine designs can be categorised into four wind turbine concepts, as illustrated in Figure 4. The main differences between these concepts concern the generating system and the way in which the aerodynamic efficiency of the rotor is limited during above the rated value in order to prevent overloading. These concepts are distinguished as following:

- **Type A - constant speed wind turbine concept.**

This configuration denotes the fixed speed controlled wind turbine, with asynchronous squirrel cage induction generator (SCIG) directly connected to the grid via a transformer – see Figure 4. Since the squirrel cage induction generator always draws reactive power from the grid, a capacitor bank is applied in this configuration for reactive power compensation. Smoother grid connection occurs by incorporating a soft-starter.

Regardless the power control principle in a fixed speed wind turbine, the wind fluctuations are converted into mechanical fluctuations and further into electrical power fluctuations. These can yield to voltage fluctuations at the point of connection in the case of a weak grid. Because of these voltage fluctuations, the fixed speed wind turbine draws varying amounts of reactive power from the utility grid (in the case of no capacitor bank), which increases both the voltage fluctuations and the line losses. Thus the main drawbacks of this concept are: (1) it does not support any speed control, (2) it requires a stiff grid and, (3) its mechanical construction must be able to support high mechanical stress caused by wind gusts.

- **Type B - variable speed wind turbine concept with variable rotor resistance.**

This configuration corresponds to the limited variable speed controlled wind turbine with variable generator rotor resistance, known as OptiSlip. It uses a wound rotor induction generator (WRIG) and it has been used by the Danish manufacturer Vestas Wind Systems since the mid 1990's. The generator is directly connected to the grid. The rotor winding of the generator is connected in series with a controlled resistance, whose size defines the range of the variable speed (typically 0-10% above synchronous speed).

A capacitor bank performs the reactive power compensation and smooth grid connection occurs by means of a soft-starter. The unique feature of this concept is that it has a variable additional rotor resistance, which is changed by an optically controlled converter mounted on the rotor shaft. Thus, the total rotor resistance is controllable. This optical coupling eliminates the need for costly slip rings, which needs brushes and maintenance. By varying the rotor resistance, the slip and thus the power output in the system are controlled. The dynamic speed control range depends on the size of the variable rotor resistance. Typically the speed range is 0-10% above synchronous speed. The energy coming from the external power conversion unit is dumped as heat loss.

(Wallace, A.K., et al, 1998) describes an alternative concept using passive component instead of a power electronic converter. This concept achieves 10% slip, but it does not support controllable slip.

- **Type C - variable speed wind turbine concept with partial-scale frequency converter.**

This configuration, known as the doubly-fed induction generator (DFIG) concept, corresponds to the variable speed controlled wind turbine with a wound rotor induction generator (WRIG) and partial-scale frequency converter (rated to approx. 30% of nominal generator power) on the rotor circuit. The stator is directly connected to the grid, while a partial-scale power converter controls the rotor frequency and thus the rotor speed. The power rating of this partial-scale frequency converter defines the speed range (typically +/– 30% around synchronous speed). Moreover, this converter performs the reactive power compensation and a smooth grid connection. The control range of the rotor speed is wide compared to that of OptiSlip. Moreover, it captures the energy, which in the OptiSlip concept is burned off in the controllable rotor resistance.

The smaller frequency converter makes this concept attractive from an economical point of view. Its main drawbacks are the use of slip-rings and the protection schemes in case of fault grids.

- **Type D - variable speed concept with full-scale frequency converter.**

This configuration corresponds to the full variable speed controlled wind turbine, with the generator connected to the grid through a full-scale frequency converter. The frequency converter performs the reactive power compensation and a smooth grid connection for the entire speed range. The generator can be electrically excited (wound rotor synchronous generator WRSG) or permanent magnet excited type (permanent magnet synchronous generator PMSG). The generator stator is interconnected to the grid through a full-scale power converter.

Some full variable speed wind turbines systems have no gearbox – see dotted gearbox in Figure 4. In these cases, a bulky direct driven multipole generator is used. The wind turbine companies Enercon, Made and Lagerwey are examples of manufacturers using this configuration.

3.2 Power control ability

All wind turbines are designed with some sort of power control. There are different ways to control aerodynamic forces on the turbine rotor and thus to limit the power in the case of very strong winds. This is in order to avoid damages on the wind turbine. The power (blade) control ability classifies the wind turbine concepts in the following classes:

- *stall control* (passive control) - the simplest, most robust and cheapest control method. The blades are bolted onto the hub at a fixed angle. The design of rotor

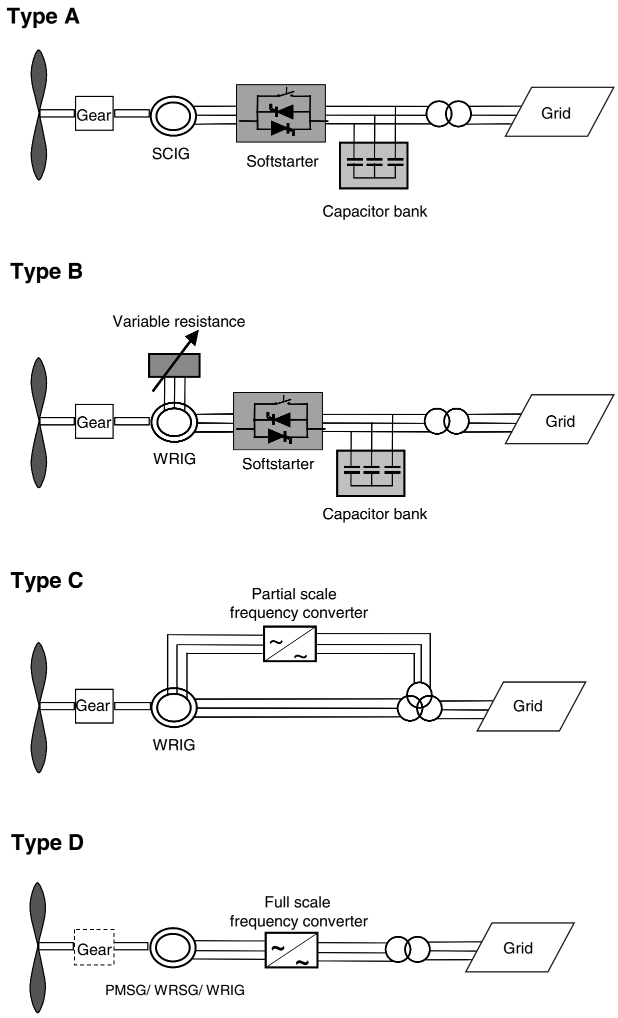

Figure 4: Typical wind turbine concepts:
Type A: constant speed wind turbine concept;
Type B: variable speed wind turbine concept with variable rotor resistance;
Type C: variable speed wind turbine concept with partial scale frequency converter;
Type D: variable speed concept with full scale frequency converter.

aerodynamic causes the rotor to stall (so losing efficiency) when the wind speed exceeds a certain level. Thus the aerodynamic power produced by the blades is 'automatically' limited in the rated power region. As wind speed increases, stall conditions occur gradually, starting at the blade root. Such slow aerodynamic power regulation causes less power fluctuations than a fast pitch power regulation. Some drawbacks of this design are: (1) lower efficiency at low wind speeds, (2) no assisted start-up and, (3) potential variations in the maximum steady state power due to variation in the air density and grid frequencies.

- *pitch control* (active control) - the blades can be turned away from or into the wind as the power output becomes too high or too low, respectively. Below rated wind speed the blades are pitched for optimum power extraction, while above rated wind speeds the blades are pitched to small angle of attack for limiting the power. Generally, the advantages of this type of control are good power control performance, assisted start-up and emergency-stop power reduction (the blades are forced rapidly out of the wind). From an electrical point of view, good power control means that, at large wind speeds, the mean value of the power output is kept close to the rated power of the generator. The instantaneous power fluctuates around the rated mean value of the power, due to gusts and the limited response time of the pitch mechanism. Some disadvantages are: (1) the extra complexity due to the pitch mechanism, and (2) the inherent large power fluctuations that appear from the turbulence at large wind speeds.

- *active stall control* - as the name indicates, the stall of the blade is actively controlled by pitching the blades to larger angle of attack. At wind speeds less than for rated power, the blades are pitched for optimum power extraction, as with a pitch controlled wind turbine, so achieving the maximum efficiency. However, at wind speeds greater than for rated power, the blades go into a deeper stall by being pitched to larger angle of attack (i.e. in the opposite direction to a pitch-controlled turbine in the same conditions). Active stall wind turbine achieves a smooth limitation of power, without the large inherent power fluctuations of pitch control wind turbines. This control concept has the advantage of being able to compensate for variations in air density. The combination with the pitch mechanism facilitates both emergency stop and assisted start-up of the wind turbine.

Table 1 indicates possible different combinations of wind turbine configurations, when both criteria (speed control and power control) are taken into account. For each combination of these two criteria, a label is associated. Type A0 denotes e.g. the fixed speed stall controlled wind turbine. A grey zone in Table 1, e.g. Type B0, indicates a type of combination, which is not used in the wind turbine industry today.

Notice that in Table 1 the fixed speed wind turbine Type A is used in the wind turbine industry with all three-power control versions (Type A0, Type A1, Type A2). They are characterised by:

Type A0 (stall control) is the conventional concept applied by many Danish wind turbine manufacturers during the 1980´s and 1990´s, i.e. an upwind stall regulated three bladed wind turbine concept. It has been very popular due to its relatively low price, simplicity and robustness. Stall regulated wind turbine does not have assisted start, which implies that the power of the turbine cannot be controlled during grid connection.

Type A1 (pitch control) has also been used. The main advantages of it are that it facilitates power controllability, controlled start-up and emergency stopping. The major drawback is that at high wind speeds, even a small variation in wind speed introduces a large variation in output power, the pitch mechanism being not fast enough to avoid these power fluctuations. By pitching the blades, slow variations in the wind can be accommodated. This is not possible in the case of gusts in the wind.

Type A2 (active stall control) has recently become popular. This configuration, basically maintains all the power quality characteristics of the stall-regulated system. The improvements

Table 1: Combination criteria of wind turbine concepts.

Speed control	Blade control	Stall	Pitch	Active-Stall
Fixed-speed:	Type A	Type A0	Type A1	Type A2
	Type B	Type B0	Type B1	Type B2
Variable speed:	Type C	Type C0	Type C1	Type C2
	Type D	Type D0	Type D1	Type D2

result from better utilisation of the overall system, due to the use of active stall control. The flexible coupling of the blades to the hub also facilitates emergency stop and assisted start-up. Compared with a stall wind turbine, a drawback is the higher price due to the pitching mechanism and to its controller.

Referring to Table 1, the variable speed wind turbines (Type B, Type C and Type D) are only used in practice together with a fast pitch mechanism, due to power limitation considerations. The reason why variable speed stall or variable speed active stall control wind turbines are not considered is the lack of ability for rapid reduction of power. If the wind turbine is running at maximum speed and encounters a large wind gust, the aerodynamic torque can become critically large and may result in a run-away situation. Therefore, as illustrated in Table 1, Type B0, Type B2, Type C0, Type C2, Type D0 and Type D2 are not used in the wind turbine industry.

4. MARKET PENETRATION

According to (BTM Consults Aps., 2003), the Top Ten largest markets in the world in 2002 were headed by Germany, Spain, Denmark and USA. On the supply side, in 2002, the Danish company VESTAS Wind Systems A/S was on the top position among the largest manufacturers of wind turbines in the world, followed by the German manufacturer ENERCON, as the second largest in the world. Danish NEG MICON and Spanish GAMESA are in third and fourth positions, respectively.

Table 2 and Table 3, respectively, contain a list with the Top Ten wind turbine suppliers in the world for 2002 (BTM Consults Aps., 2003), ranked by the installed power. The tables include: (a) the main markets of each supplier (market where the supplier has one of the three top leading positions), (b) the wind turbine type and rated power, (c) the concept according to this paper, (d) control features, and (e) some generator characteristics.

As illustrated in Table 2 and Table 3, all Top Ten manufacturers, at the end of 2002, had commercial turbines available in the 2-MW to 3-MW size range and there are prototypes running of up to 4.5 MW capacity (i.e. Enercon E112, erected in August 2002).

Notice that as expected, the first three largest suppliers (Vestas, Enercon, NEG Micon) had much larger markets with the first leading positions, compared to the others.

Until 2002, the most attractive concept seemed to be the variable speed wind turbine with pitch control. Out of the Top Ten-suppliers, only Danish Bonus used the 'traditional' active stall fixed speed concept, while the other manufacturers had at least one of their two largest wind turbines with the variable speed concept. The most used generator type was the induction generator (WRIG and SCIG). Only two manufacturers, ENERCON and MADE, of the Top Ten suppliers, used the synchronous generator (WRSG). Only one of the Top Ten manufacturers, ENERCON, offered a gearless variable speed wind turbine. Notice that, MADE, specialised before in a range of fixed-speed stall control wind turbines, has started to change to variable speed concept with synchronous generator.

Notice too that all Top Ten wind turbines manufacturers used a step-up transformer for connection of the generator to the grid.

Comparing Table 2 and Table 3 with the analysis made by (Hansen, L.H, et al., 2001a), a trend towards the configuration using a doubly-fed induction generator concept (Type C1) with variable speed and variable pitch control, can be identified. In order to illustrate this trend, a dedicated investigation of the market penetration for the different wind turbine concepts over five years (1998 to 2002) was performed. The analysis was based on the suppliers market data provided by BTM Consults Aps. and on concept evaluation (Internet data) for each individual wind turbine type sold by the top-10 suppliers over the considered five years. The investigation processed information on a total of approximately 90 wind

Table 2: Applied concept of each Top Ten manufacturers (position 1 to 5) based on 2003 public available data concerning the largest (alias newest) wind turbines from each manufacturers.

Manufactures (top 10 supp.)	Main markets	Wind turbine	Concept	Control features	Generator characteristics
1. VESTAS (Denmark)	Germany Denmark USA The Netherlands Australia Italy	V80 - 2.0 MW	Type C1	Pitch DFIG variable speed concept	WRIG Gen. voltage: 690 V Gen. speed range: 905 - 1915 rpm Rotor speed range: 9 - 19 rpm
		V80 - 1.8 MW	Type B1	Pitch OptiSlip variable speed concept	WRIG Gen. voltage: 690 V Gen. speed range: 1800 - 1980 rpm Rotor speed range: 15.3 - 16.8 rpm
2. ENERCON (Germany)	Germany The Netherlands India Italy Greece	E112 - 4.5 MW	Type D1	Pitch Full variable speed Concept	Multipole WRSG (gearless) Gen. Voltage: 440 V Gen./rotor speed range: 8 - 13 rpm
		E66 - 2 MW	Type D1	Pitch Full variable speed Concept	Multipole WRSG (gearless) Gen. voltage: 440 V Gen./rotor speed range: 10 - 22 rpm
3. NEG MICON (Denmark)	Spain Denmark The Netherlands India Australia Greece	NM80 / 2.75 MW	Type C1	Pitch DFIG variable speed concept	WRIG Gen. stator/rotor voltage: 960 V / 690 V Gen. speed range: 756 - 1103 rpm Rotor speed range: 12 - 17.5 rpm
		NM72 / 2 MW	Type A2	Active stall Fixed speed concept	SCIG Gen. voltage: 960 V Two gen. speeds: 1002.4 / 1503.6 rpm Two rotor speeds: 12 / 18 rpm
4. GAMESA (Spain)	Spain	G83 - 2.0 MW	Type C1	Pitch DFIG variable speed concept	WRIG Gen.voltage: 690 V Gen. speed range: 900 - 1900 rpm Rotor speed range: 9 - 19 rpm
		G80 - 1.8 MW	Type B1	Pitch Optislip variable speed concept	WRIG Gen. voltage: 690 V Gen. speed range: 1818 - 1944 rpm Rotor speed range: 15.1 - 16.1 rpm
5. GE WIND (United States)	Germany USA	GE 104 / 3.2 MW	Type C1	Pitch DFIG variable speed concept	WRIG Gen. stator/rotor voltage: 3.3 kV/ 690 V Rotor speed range: 7.5 - 13.5 rpm Gen. speed range: 1000 - 1800 rpm
		GE 77 / 1.5sl MW	Type C1	Pitch DFIG variable speed concept	WRIG Gen. voltage: 690 V Rotor speed range: 10.1 - 20.4 rpm Gen. speed range: 1000 - 2000 rpm

turbine types from 13 different manufacturers, which had been in the top-10 list of wind turbine suppliers during 1998 to 2002: VESTAS (DK), GAMESA (SP), ENERCON (GE), NEG MICON (DK), BONUS (DK), NORDEX (GE/DK), GE-WIND/ENRON (US), ECOTECHNIA (SP), SUZLON (IND), DEWIND (GE), REPOWER (GE), MITSUBISHI (JP) and MADE (SP). The results of the processing of these data are presented in Table 4. Notice that the common share of the world market supply (installed power by the 13 suppliers), based on data provided by BTM Consults Aps., for each year is more than 90%, which gives a high reliability to the present investigation. These data cover approximately 76% of the accumulated world power installed at the end of 2002. They are therefore very comprehensive and illustrative.

Table 3: Applied concept of each Top Ten manufacturers (position 6 to 10) based on 2003 public available data concerning the largest (alias newest) wind turbines from each manufacturers.

Manufactures (top 10 supp.)	Main markets	Wind turbine	Concept	Control features	Generator characteristics
6. BONUS (Denmark)	Denmark Greece	Bonus 82 / 2.3 MW	Type A2	Active stall Fixed speed concept	SCIG Gen. voltage: 690 V Two gen. speeds: 1000 / 1500 rpm Two rotor speeds: 11 / 17 rpm
		Bonus 76 / 2 MW	Type A2	Active stall Fixed speed concept	SCIG Gen. voltage: 690 V Two gen. speeds: 1000 / 1500 rpm Two rotor speeds: 11 / 17 rpm
7. NORDEX (Germany)	Japan	N80 / 2.5 MW	Type C1	Pitch DFIG variable speed Concept	WRIG Gen. voltage: 690 V Gen. speed range: 700 - 1300 rpm Rotor speed range: 10.9 - 19.1 rpm
		S77 / 1.5 MW	Type C1	Pitch DFIG variable speed Concept	WRIG Gen. voltage: 690 V Gen. speed range: 1000 - 1800 rpm Rotor speed range: 9.9 - 17.3 rpm
8. MADE (Spain)	Spain	MADE AE-90 2 MW	Type D1	Pitch Full variable speed Concept	WRSG Gen. voltage: 1000 V Gen. speed range: 747 - 1495 rpm Rotor speed range: 7.4 - 14.8 rpm
		MADE AE-61 1.32 MW	Type A0	Stall Fixed speed concept	SCIG Gen. voltage: 690 V Two gen. speeds : 1010 - 1519 rpm Two rotor speeds: 12.5 - 18.8 rpm
9. REPOWER (Germany)	—	MM 82 - 2 MW	Type C1	Pitch DFIG variable speed Concept	WRIG Gen. voltage: 690 V Gen. speed range: 900 - 1800 rpm Rotor speed range: 10 - 20 rpm
		MD 77 - 1.5 MW	Type C1	Pitch DFIG variable speed Concept	WRIG Gen. voltage: 690 V Gen. speed range: 1000 - 1800 rpm Rotor speed range: 9.6 - 17.3 rpm
10. ECOTECNIA (Spain)	—	Ecotecnia 74 1.67 MW	Type C1	Pitch DFIG variable speed Concept	WRIG Gen. voltage: 690 V Gen. speed range: 1000 - 1950 rpm Rotor speed range: 10 - 19 rpm
		Ecotecnia 62 1.25 MW	Type A0	Stall Fixed speed concept	SCIG Gen. voltage: 690 V Two gen. speeds: 1012 / 1518 rpm Two rotor speeds: 12.4 / 18.6 rpm

Table 4 presents a detailed overview of the market share for each wind turbine concept over five years 1998-2002. Figure 5 illustrates graphically the results of Table 4. It is obvious, that the market interest on the fixed speed wind turbine concept (Type A) has decreased during this period, while the doubly-fed induction generator wind turbine concept (Type C) has become the most dominating concept. Regarding the full variable speed wind turbine

Table 4: World share of the wind turbine concepts during five years (1998-2002).

Concept	1998	1999	2000	2001	2002
Type A	39.6%	40.8%	39.0%	31.1%	27.8%
Type B	17.8%	17.1%	17.2%	15.4%	5.1%
Type C	26.5%	28.1%	28.2%	36.3%	46.8%
Type D	16.1%	14.0%	15.6%	17.2%	20.3%
Installed power of 13 manufacturers (MW)	2349	3788	4381	7058	7248
Common share of the world market-supply	92.4%	90.1%	94.7%	97.6%	97.5%

concept (Type D), the interest over the years has increased slightly, being the third dominating concept during 2001 and 2002.

The market evolution of the Optislip concept (Type B) was almost unchanged the first three years of the analysed period, while during the last two years, it decreased in the favour of Type C concept. The trend of Type B, depicted in Table 4 and Figure 5, indicates that Type B would be soon out of the market. This fact is mainly due to the variable speed range of Type B, which is much more limited than the variable speed range of Type C. Table 4 also provides information on the total installed power (13 suppliers) per year. Notice that the total installed power in 2002 was three times bigger than that in 1998, primarily due to the increased rated power of the wind turbines.

Figure 6 illustrates the number of installed units per year for each wind turbine concept over 1998 to 2002. The graph shows clearly that in 1998, the number of installed wind turbines concept Type A was almost twice as big compared to the others. Notice that in 2001, Type A and Type B reached a maximum number of installed units, while the Type C and Type D present a continuously increase. After 2001, the number of units with Type A and Type B decreases drastically and the market is clearly dominated by Type C.

Figure 7 shows the average size of the installed wind turbines during the selected five years. It shows that during 1998-2000 the average size of all wind turbine concepts is almost

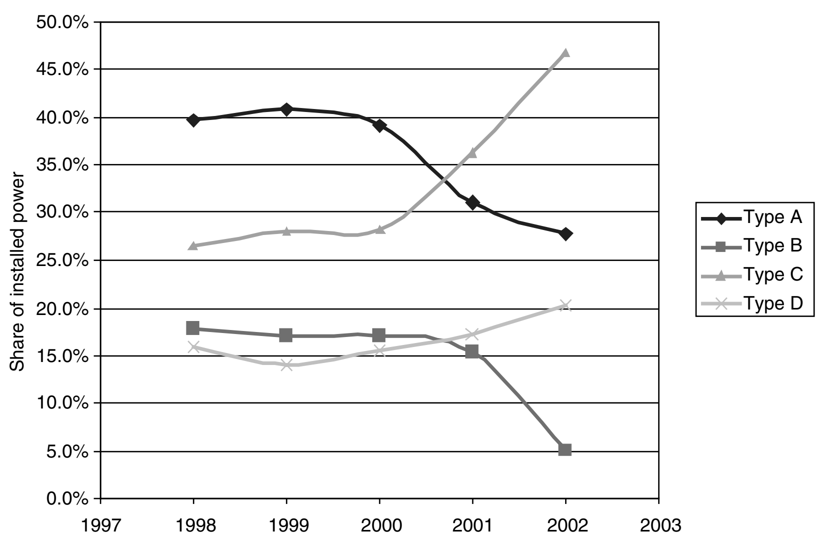

Figure 5: World share of the installed power during years 1998-2002 for different wind turbine concepts.

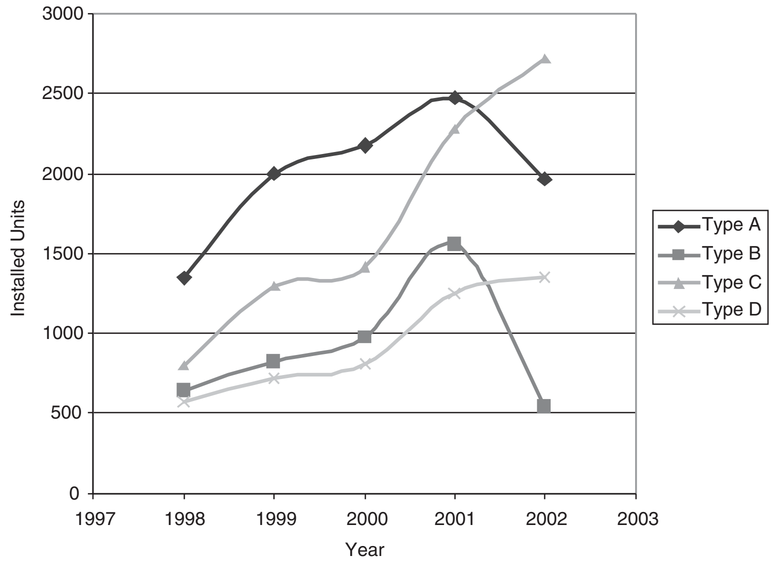

Figure 6: Installed units per year during 1998-2002.

constant around 800 kW. After 2000 a more outstanding differentiation in the average size of the four wind turbine concepts appears. It can be noticed that the wind turbine size of Type B has always remained in the power range of 600-800 kW, while the other concepts have gradually been applied on larger wind turbines over the years. Notice that the size of Type D wind turbines has almost linearly increased (with ca. 12% per year) during the selected years, while the sizes of Type C and A have a more dramatic increase around 22% and 12%, respectively, in 2001 compared to the other years.

As a general remark, the size of the wind turbines using Type C has always been bigger than the size used by the other concepts. Both the bigger wind turbine size and the number of installed wind turbines of the concept Type C (see Figure 6) explain its increased position on the market.

For all manufacturers there it is a clear tendency that the size of wind turbines is increasing more and more, MW-size turbines becoming the dominant size in the commercial market,

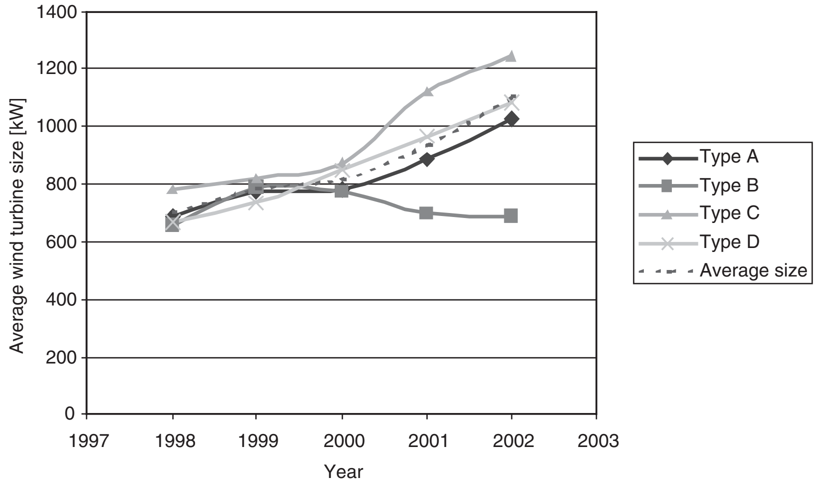

Figure 7: Average wind turbine size of the installed wind turbine concepts during 1998-2002.

during the last years. For example, Figure 7 illustrates that in 2002 all wind turbine concepts, with Type B as exception, are using wind turbines in a size scale bigger than 1 MW. During 2002 the average size of the wind turbines installed reached 1.1 MW, an increase from 930 kW in 2001. MW-size wind turbines accounted at the end of 2002 for more than 60% of the installed turbines (BTM Consults Aps., 2003).

There are still no signs of a pause in the up-scaling in the size of wind turbines. On contrary, the offshore market is calling for even larger machines. Industrial development in 2002 focused on upsizing and refining the 2MW plus class of turbines and adapting them to offshore use (IEA, 2002). For example, in 2001, the first megawatt-turbine offshore wind farm (Middelgrunden, out of the harbour of Copenhagen) was put in operation, consisting of "only" twenty 2 MW Bonus wind turbines (Type A). Just one year later (2002), the offshore wind farms were already of order of 100 MW capacity, and looking further ahead they are likely to become even larger. For example, the first major offshore wind farm in Denmark, installed in 2002, is the 160 MW Horns Rev, consisting of eighty 2-MW turbines (Type C) placed in the North Sea 14 km from the coast at Blaavands Huk. A second large wind farm, installed in 2003, is the 165 MW Nysted, consisting of seventy-two 2.3-MW turbines (Type A) placed in the Baltic Sea south of the island of Lolland.

The move to larger machines is driven by both economics and wind farm size. The increased size of wind turbines yields to a decrease of the kWh price. In countries with a densely population and limited onshore wind resource, where the space also is limited, larger machines have the benefit of increasing the total capacity that can be installed in a given area.

5. CURRENT/FUTURE TRENDS AND DEVELOPMENT

It is obvious that there is an increasing trend both to remove dispersed single wind turbines in the favour of concentrated wind turbines in large wind farms and to move to the MW-size wind turbines, in order to reduce the cost. The percentage of wind power within the total grid capacity continues therefore to increase drastically, from year to year in the wind power contributor countries. The connection of such large wind turbines and wind farms to the grid has a large impact on grid stability and therefore, one major research challenge, in the present and in the next years, is directed towards connecting and optimised integration of large wind farms within the electrical power grid. It is therefore clear that the survival of different wind turbine concepts is strongly conditioned by their ability to support the grid, to handle faults on the grid and to comply with the stringent requirements of the utility companies. Consequently, there is much worldwide research investigating the suitability of different wind turbine concepts to comply with the grid utilities requirements (Slootweg, J.G., et al., 2001), (Gjengedal, T., 2003).

Back in 1998, typically installations were dispersed single small fixed-speed wind turbines, as seen in Figure 5. These were popular due to their robustness, simplicity and low cost. One reason why the fixed speed wind turbine concept was so popular at that time was that the alternatives required power electronic frequency converters that were very expensive at that time. Since then, the price of these components has decreased every year, so now they are attractive to use. The penetration of wind turbines in the power system was also, at that time, not as significant as today, so the turbines could be switched off without detrimental effect, e.g. in the case of a major grid problem. Such a solution is not applicable today, when the electrical power system depends on the increased and concentrated penetration of wind energy. Therefore the power system is more vulnerable and dependent on the wind energy production.

Today, there are very onerous grid connection requirements (Eltra, 2000), which require MW-size wind turbines concentrated in large wind farms to support the grid actively and to remain grid-connected during grid problems (i.e. voltage dip), otherwise it could cause a grid blackout. The main role for such technical demands of the grid operators is played today by the power electronics within the wind turbines and wind farms. The presence of power electronics gives increased interest in variable speed concepts. Moreover, power electronic can also support common variable speed operation for wind farms consisting of fixed speed wind turbines (Type A), as it is the case of HVDC (High Voltage Direct Current) wind turbine configuration (Hansen, L.H, et al., 2001b). Consequently, variable speed operation is attractive for wind turbines within wind farms for a number of reasons, including reduced mechanical stress, increased power capture, reduced acoustical noise and, not least, its controllability, which is a prime concern for the grid integration of large wind farms. It is therefore clear that variable speed operation will continue to be the norm and not the exception.

It has been shown that the market interest for the fixed speed wind turbine concept (Type A) has decreased slightly in favour of variable speed wind turbine concepts. However, the market interest for fixed speed turbines may increase if it is demonstrated that HVDC-based wind farms of such Type A turbines are robust to grid faults, as technically they should be.

Today, variable speed wind turbine concepts (Type C and Type D) have already a substantial increasing share of the wind power market. In future, it seems that they still may dominate and be very promising wind technologies for large wind farms. What is remarkable, from a wind turbine industry perspective, is that the doubly-fed induction generator wind turbine concept has developed into a semi-industry standard for gear-driven wind turbines, being increasingly adopted by a wide range of international suppliers. At the same time, there is presently an intensive research activity in gearless drives and other types of synchronous generators, which makes the Type D concept potentially attractive in the future too.

The Type C and Type D wind turbine concepts will continue to compete in the market, each with weaker and stronger features. Presently, the main advantage of the doubly-fed induction concept, Type C, is that the percentage of power generated in the generator passing through a frequency converter is only 30%, as compared with 100% for a synchronous generator concept, Type D. Even with low priced power electronics, doubly-fed technology has a substantial cost advantage as compared to the conversion of full power. On the other hand, compared with full power converters, the doubly-fed induction concept shows, at the moment, a more technically difficult grid behaviour, because, during failure situations, large peak currents are introduced into the system. This requires advanced protection systems. In contrast, full power converters are attractive because they do not suffer from these “built-in” grid-related problems. The Type D wind turbine concept is slightly more efficient, less complicated from an electrical engineering point, easier to construct but more expensive.

Looking to the future, further developments of Type C and Type D are expected, focusing on more optimised turbines and, thus, towards more cost-effective machines. Different and improved versions of these concepts may be developed. For example, the brushless doubly-fed induction generator concept and other types of generators may be exploited.

As with all technologies, the future is difficult to predict. Concepts borrowed from other fields or other applications could have profound effects on future designs. However, one thing is sure - power electronics will continue to play a vital role in the integration of large future wind farms. The very fast development of power electronics offers both enlarged capabilities and lower price per kW capacity. In this context, more new wind turbine generator concepts may be developed. Such new concepts will be specifically designed for the application and will require demonstrated performance to survive market expectations. Yet they will be tested for different criteria, as the market expectations are not universal. Market needs will continue to drive wind turbine design innovation for many years to come.

6. CONCLUSIONS

This paper provides an overall perspective on contemporary wind turbine concepts, focusing on their market penetration and share during the years 1998-2002. A detailed analysis is performed based on suppliers' comprehensive market data, so giving concept evaluation for each individual wind turbine type sold by the Top Ten suppliers over the selected five years. The largest markets in the world in 2002 were headed by Denmark, Germany, Spain and USA. On the supplier side, the Danish company VESTAS Wind Systems A/S was in top position among the largest manufacturers of wind turbines in the world, followed by the German manufacturer ENERCON, as the second largest in the world.

Technical developments during the last years imply that the size of wind turbines is continuously increasing, MW-size turbines have become the dominant size in the commercial market. For example, the most popular wind turbines delivered to the market in 2002 were in the MW range, accounting for more than 60% of the installed turbines. Even more growth is expected, both in terms of turbine size and wind farm development. This aspect places the unit cost of wind-generated electricity in a range that is increasingly competitive with electricity from conventional power plants.

The main trend of modern wind turbines design is clearly using variable speed operation. Two variable speed wind turbine concepts, with a substantially fast growing market demand, dominated the market at the end of 2002: the variable speed doubly-fed induction generator wind turbine and the variable speed full-scale frequency converter wind turbine. The increased interest in variable speed wind turbines is due to their very attractive features, including the power converter, which supports the wind turbine itself and the increasingly onerous grid requirements. It is obvious that power electronics will continue to play a vital role in the development of wind turbines and in the integration of future large wind power within the electrical supply system.

As a large amount of concentrated wind power grid integration is presently planned, the future success of different wind turbine concepts will be strongly conditioned by their ability to comply with both market expectations and the stringent requirements of the utility companies.

ACKNOWLEDGMENTS

The authors would like to thank to BTM Consults, in particularly Birger T. Madsen, for providing relevant market data for the present analysis. Without the help from this company it would have been very difficult to collect the necessary information to illustrate the trend.

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