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Wind Energy Power Plants

Rising pollution levels and worrying changes in climate, arising in great part from energy-producing processes, demand the reduction of ever-increasing environmentally damaging emissions. The generation of electricity – particularly by the use of renewable resources – offers considerable scope for the reduction of such emissions. In this context, the immense potentials of solar and wind energy, in addition to the worldwide use of hydropower, are of great importance. Their potential is, however, subject to transient processes of nature. Following intensive development work and introductory steps, the conversion systems needed to exploit these power sources are still in the primary phase of large-scale technical application. For example, in Germany around 8% of electricity is already being provided by wind turbines. However in the German provinces Mecklenburg-Western-Pomerania, Schleswig-Holstein, Brandenburg and Saxony-Anhalt there are about 50% wind power feed in. In Germany more power is supplied by wind energy than by hydroelectric plants.

These environmentally friendly technologies in particular require a suitable development period to establish themselves in a marketplace of high technical standards.

The worldwide potential of wind power means that its contribution to electricity production can be of significant proportions. In many countries, the technical potential and – once established – the economically usable potential of wind power far exceeds electricity consumption. Good prospects and economically attractive expectations for the use of wind power are, however, inextricably linked to the incorporation of this weather-dependent power source into existing power supply structures, or the modification of such structures to take account of changed supply conditions.

1.1 Wind Turbine Structures

In the case of hydro, gas or steam, and diesel power stations (among others) the delivery of energy can be regulated and adjusted to match demand by end users (Figure 1.1(a)). In contrast, the conversion system of a wind turbine is subject to external forces (Figure 1.1(b)). The delivery of energy can be affected by changes in wind speed, by machine-dependent factors such as disruption of the airstream around the tower or by load variations on the consumer side in weak grids.

Grid Integration of Wind Energy: Onshore and Offshore Conversion Systems, Third Edition. Siegfried Heier.

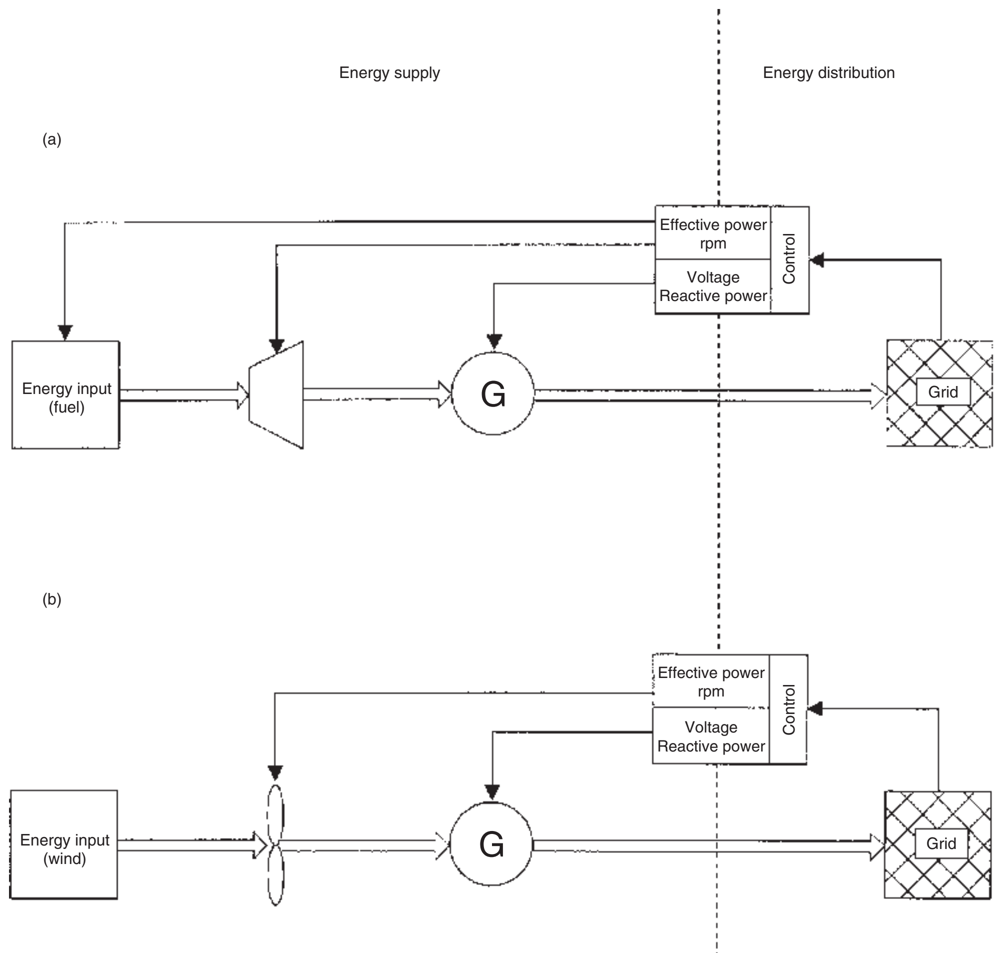


Figure 1.1 Energy delivery and control in electrical supply systems: (a) diesel generators, etc., and (b) wind turbines

The principal components of a modern wind turbine are the tower, the rotor, the nacelle (which accommodates the transmission mechanisms and the generator) and – for horizontal-axis devices – the yaw systems for steering in response to changes in wind direction. Switchgear and protection systems, lines, and maybe also transformers and grids, are required for supplying end users or power storage systems. In response to external influences, a unit for operational control and regulation must adapt the flow of energy in the system to the demands placed upon it. The next two figures show the arrangement of the components in the nacelle and the differences between mechanical–electrical converters in the modern form of wind turbines. Figure 1.2 shows the conventional drive train design in the form of a geared transmission with a high-speed generator. Figure 1.3, by contrast, shows the gearless variant with the generator being driven directly from the turbine. These pictures represent the basis for the functional relationships and considerations of the system.

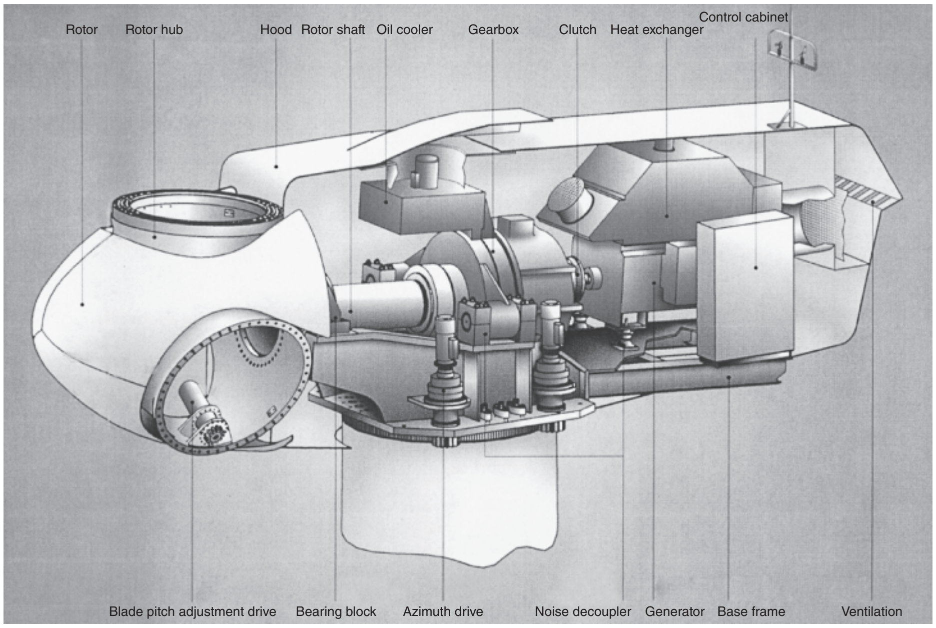


Figure 1.2 Nacelle of a wind turbine with a gearbox and high-speed 1.5 MW generator (TW 1.5 GE/Tacke). Reproduced by permission of Tacke Windenergie

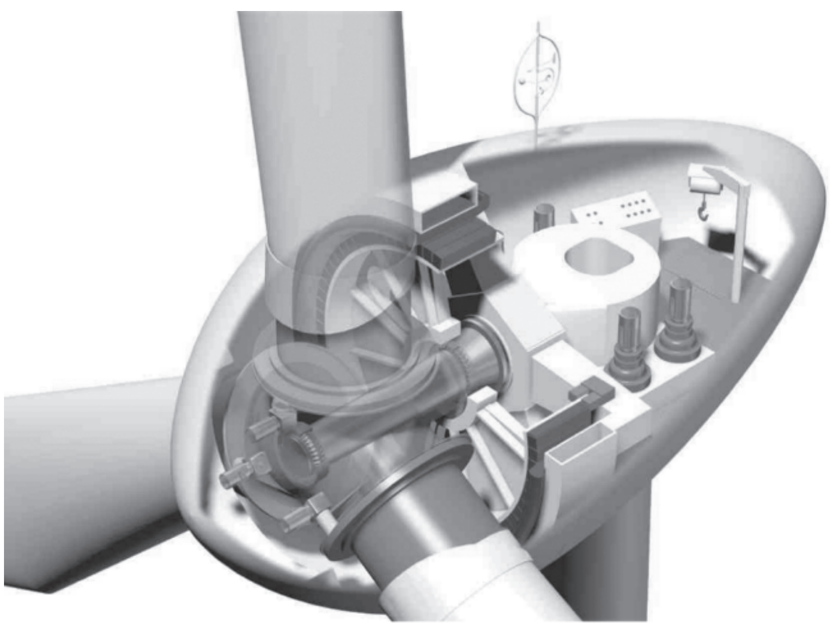


Figure 1.3 Schematic structure of a gearless wind turbine (Enercon E66, 70 m rotor diameter, 1.8/2 MW nominal output). Reproduced by permission of Enercon

Following a brief glance back into history, developmental stages and different wind turbine designs and systems will be briefly highlighted and the processes of mechanical–electrical power conversion explained. Moreover, particular importance is assigned to the interconnection of wind turbines to form wind farms and their combined effect in grid connection.

1.2 A Brief History

For thousands of years, mankind has been fascinated by the challenge of mastering the wind. The dream of defying Aeolos[1] and taming the might of the storm held generations of inventors under its spell. To attain limitless mobility by using the forces of Nature, thereby expanding the horizons of the then known world, was a challenge even in antiquity. Thus, sailing and shipbuilding were constantly pursued and developed despite doldrum, hurricane, tornado and shipwreck. Progress could only be achieved by employing innovative technologies. These, together with an unbridled lust for voyages of discovery, built up in the minds of sovereigns and scholars a mosaic of the world, the contours of which became ever more enclosed as time went by.

With wind-harnessing technology on land and on the sea, potentials could be realized and works undertaken that far outpaced any previously imagined bounds. For example, using only the power of animals and of the human arm, it would never have been possible for the Netherlands to achieve the drainage that it has through wind-powered pumping and land reclamation.

Archaeological discoveries relating to the use of wind energy predate the beginning of the modern era. Their origins lay in the Near and Middle East. Definite indications of windmills and their use, however, date only from the tenth century, in Persia [1.1]. The constructional techniques of the time made use of vertical axes to apply the drag principle of wind energy capture (Figure 1.4). Such mills were mostly found in the Arab countries. Presumably, news

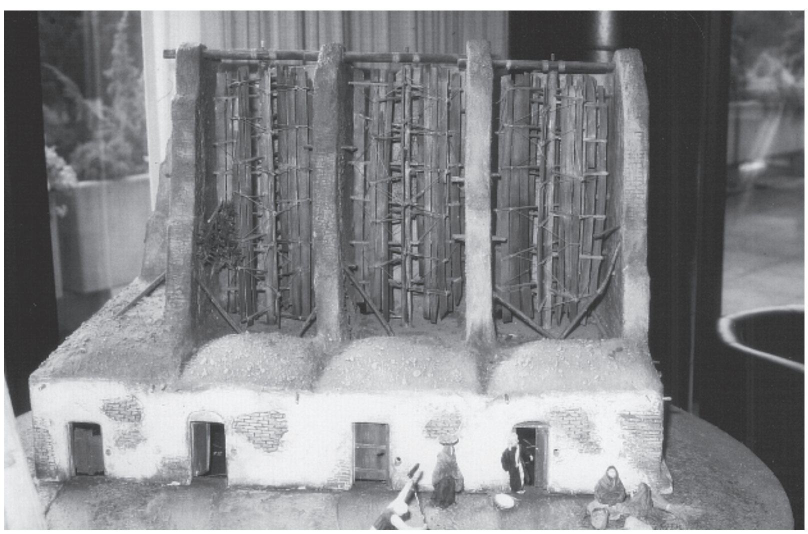


Figure 1.4 Persian windmill (model)

[1] Aeolos: Greek god of the winds.

Figure 1.5 Sail windmill

of these machines reached Europe as a result of the Crusades. Here, however, horizontal-axis mills with tilted wings or sails (Figure 1.5) made their appearance in the early Middle Ages.

The use of wind energy in Western Europe on a large scale began predominantly in England and Holland in the Middle Ages. Technically mature post mills (Figure 1.6) and Dutch windmills (Figure 1.7) were used mostly for pumping water and for grinding. More than 200 000 (two hundred thousand) of these wooden machines were built throughout North-West Europe, representing by far the greatest proportion of energy capture by technical means in this region. At the beginning of the twentieth century, some 20 000 (twenty thousand) windmills were still in use in Germany.

From the nineteenth century onwards, mostly in the USA, the so-called ‘western wheel’ type of turbine became widespread (Figure 1.8). These multibladed fans were built of sheet steel, with around 20 blades, and were used mostly for irrigation. By the end of the 1930s, some 8 million units had been built and installed, representing an enormous economic potential.

1.3 Milestones of Development

The first attempt to use a wind turbine with aerodynamically formed rotor blades to generate electricity was made over half a century ago. Since then, besides the design and construction of large projects in the 1940s by the German engineers Kleinhenz [1.2] and Honnef [1.3], the pilot

Figure 1.6 Post mill

projects of the American Smith-Putnam (1250 kW nominal output, 53 m rotor diameter, 1941), the Gedser wind turbine in Denmark (200 kW nominal output, 24 m rotor diameter, 1957) and the technically trail-blazing Hütter W34 turbine (100 kW nominal output, 34 m rotor diameter, 1958) are worthy of mention (Figure 1.9).

The German constructor Allgaier started the first mass production of wind power plants in the early 1950s. They were designed to supply electricity to farmsteads lying far from the public grid. In coastal areas these turbines drove 10 kW generators; inland they were fitted with 6 kW units. Their aerodynamically formed blades of 10 m diameter could be pitched about the longitudinal axis so as to regulate the power taken from the wind. Even today, some of these

Figure 1.7 Dutch windmill

turbines (see Figure 1.10) are in operation with full functionality, after more than 50 years of service.

After the 1960s, cheaper fossil fuels made wind energy technology economically uninteresting, and it was only in the 1970s that it returned to the spotlight due to rising fuel prices. Some states then developed experimental plants in various output classes.

In particular in the USA, Sweden and the Federal Republic of Germany, turbines with outputs in the megawatt class have attracted most attention. Here, with the exception of the American MOD-2 (Figure 1.11) with five units and the Swedish–American WTS-4 (Figure 1.12) with five or two units, large converters such as the German GROWIAN (Figure 1.13), the Swedish WTS-75 AEOLUS model, the Danish Tvind turbine and the US MOD-5B variants in Hawaii were all one-offs. Despite many and varied teething troubles with the pilot installations, it was

Figure 1.8 American wind turbine

clear even then that technical solutions could be expected in the foreseeable future that would permit the reliable operation of large-scale wind turbines. Second-generation megawatt-class systems such as the WKA 60 (Figure 1.14) and the Aeolus II (Figure 1.15) have confirmed this expectation.

Mainly in the US state of California, but also in Denmark, Holland and the Federal Republic of Germany, considerable efforts were being made, independently of the development of large turbines, to use wind power to supply energy to the grid on a large scale. In the 1980s, wind turbines with total capacity of around 1500 MW were installed in California alone. In the initial phases, turbines of the 50 kW categories were used (Figure 1.16). Scaling-up the systems that were successful through the 100, 150 and 250 kW classes (Figures 1.17 and 1.19) and the 500/600 kW order of magnitude (Figures 1.18 and 1.20) has led to wind farms with turbines in the megawatt range (Figure 1.21).

Figure 1.9 Hütter W 34 turbine

This development has made the mass production of wind turbines possible. A considerable improvement of performance can thus be achieved. Progressively increasing turbine size (see Figures 1.22 to 1.25) using designs of widely differing types and costs has led to the development of machines in the 500 kW and megawatt classes that are remarkable for their high availability and good return-on-investment potential.

The individual manufacturers have chosen very different routes to market success in relation to this trend. NEG Micon has retained the classic Danish stall-regulated turbines with an asynchronous generator rigidly coupled to the grid in the power classes up to 1.5 MW (Figure 1.22). Bonus (Figure 1.23), Nordex (Figure 1.24) and Vestas (Figure 1.25) as well as GE/Tacke (Figure 1.26) have altered their turbine configuration in the different size classes, particularly with regard to the turbine regulation (stall or pitch) and generator systems (fixed-speed or variable-speed with a thyristor/ IGBT frequency converter). Currently 3 to 5 MW systems from all well-known manufacturers are being operated as prototypes or are available on the market.

One new development has been the trend towards gearless wind turbines. Several attempts have been made to introduce and establish in the market small, high-speed, horizontal-axis

Figure 1.10 Allgaier turbine

turbines with direct-drive generators. Up until now these attempts have met with limited success. Microturbines (Figure 1.27) with a permanent-magnet synchronous generator driven directly from the turbine are usually used as battery chargers. The success of such systems is rooted in their attractive design and low price as well as in the modern worldwide sales concept and the simple installation of the plants.

To some degree, companies that have entered into the production of wind generators at a later stage have been able to draw upon existing developments and techniques, thus allowing their first efforts to overtake the systems of established manufacturers. DeWind started its development (Figure 1.28) with a pitch-regulated 600 kW turbine and a variable-speed generator system (double-fed asynchronous machine), which could not have been produced at an economical cost a few years previously and which is currently favoured by most manufacturers. Then 1 and 2 MW systems of the same design followed.

Figure 1.11 MOD 2 in the Goodnoe Hills (USA): 2.5 MW nominal output, 91 m rotor diameter, 61 m hub height

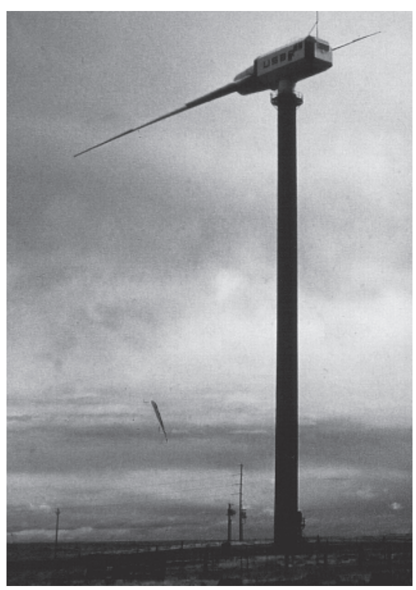


Figure 1.12 WTS-4 turbine in Medicine Bow, USA.: 4 MW nominal output, 78 m rotor diameter, 80 m tower height

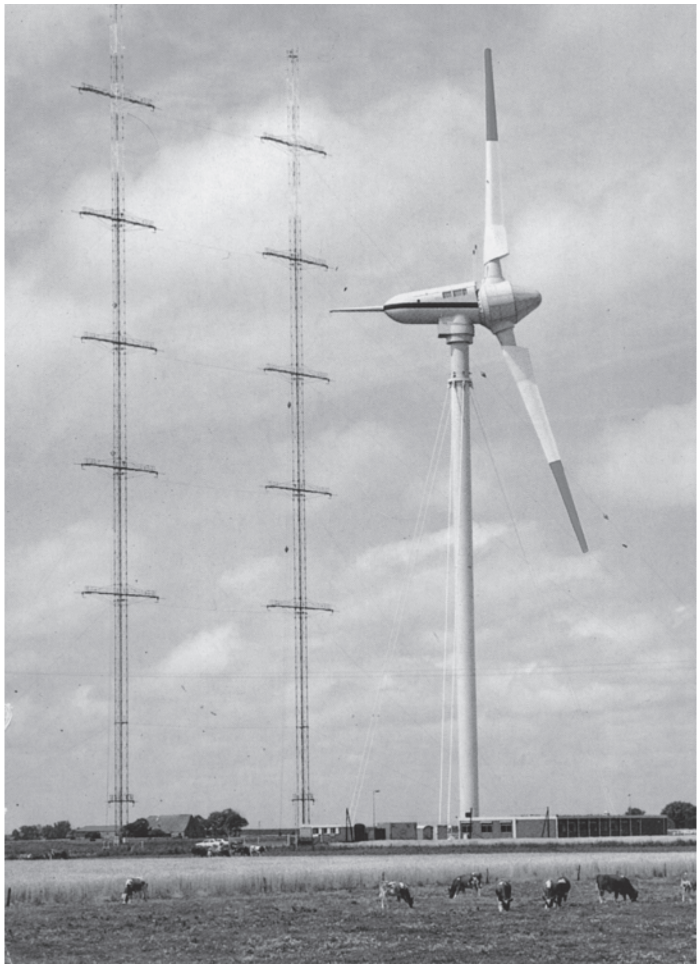


Figure 1.13 GROWIAN by Brunsbüttel/Dithmarschen, 3 MW capacity, 100 m rotor diameter, 100 m hub height

The development of wind power systems has largely been carried out by medium-sized companies. Smaller manufacturers, however, face financial limits in the development of MW systems. The 1.5 MW turbine MD 70/MD 77 (Figure 1.29), again with the double-fed asynchronous generator design, which was developed by pro + pro for the manufacturers BWU, Fuhrländer, Jacobs Energie (now REpower Systems) and Südwind / Nordex is opening up new developmental and market opportunities for smaller companies in the field of large-scale plants.

Vertical-axis rotors, so-called Darrieus turbines, are enchantingly simple in structure. In their basic form they have up until now mostly been built with gearing and generators at base level

Figure 1.14 WKA 60 in Kaiser-Wilhelm-Koog: 1.2 MW nominal output, 60 m rotor diameter, 50 m tower height

(Figure 1.30). Variants in the form of so-called H-Darrieus gearless turbines in the 300 kW class were first designed with rotating towers and large multiple generators at ground level (Figure 1.31(a)). Further development led to machines with fixed tripods and annular generators in the head (Figure 1.31(b)). These variants have not, however, been successful in establishing themselves widely in the wind power market.

The Enercon E 40 horizontal-axis turbine was the first system in the 500 kW class with a direct-drive generator to establish itself in the market with great success in a very short time. Figure 1.32 shows the schematic construction of the nacelle. The generator, specially developed for this model, connects directly to the turbine and needs no independent bearings. In this way, wear on mechanical components running at high speed is reduced to a minimum. Operational run times of 180 000 hours have been quoted for many years.

Figure 1.15 AEOLUS II near Wilhelmshaven: 3 MW nominal output, 80 m rotor diameter, 88 m tower height

The gearless E 30, E 40, E 58, E 66 and E 112/E 126 models from Enercon were produced as a development of the stall-regulated geared models E15/E16 and E17/E18, by way of the E 32/E 33 variable-pitch turbines (Figure 1.33). In parallel, but with a slight delay, the conversion from thyristors to pulse inverters was accomplished. This configuration thus unites the advantages of variable speeds (and the associated reduction in drive-train loading) with those of a grid supply having substantially lower harmonic feedback.

In comparison to the gearless designs with electrically excited synchronous generators, as shown in Figure 1.33(d) to (h), permanent-magnet machines permit the arrangement of higher numbers of poles around the rotor or stator. By using high-quality permanently magnetic

Figure 1.16 Wind farm in California with turbines in the 50/100 kW class

Figure 1.17 Wind farm in California with turbines in the 250 kW class

Figure 1.18 Wind farm in Wyoming with turbines in the 600 kW class

Figure 1.19 Wind farm in North Friesland with turbines of the 250 kW class

Figure 1.20 Wind farm on Fehmarn Island with turbines of the 500 kW class

(a) On land

(b) At sea. Reproduced by permission of GE Wind Energy

Figure 1.21 Wind farm with 1.5 MW turbines

(a) NTK 150/25 (b) NTK 300/31 (c) NTK 600–180/43 (d) NEG 1500/60

Figure 1.22 Size progression of stall-regulated turbines of the same design (fixed-speed, fixed-pitch machines) from NEG Micon / Nordtank. Reproduced by kind permission of NEG Micon

(a) 300 kW / 33-2 (b) 600 kW / 44-3 (c) 1 MW / 54 (d) 2 MW

Figure 1.23 Size progression of Bonus turbines: (a,b) fixed-speed, stall-controlled turbines; (c,d) active (combi-)stall turbines with a slight blade pitch adjustment

(a) N 27/29 (150/250 kW)

(b) N 43 (600 kW)

(c) N 62 (1300 kW)

(d) N 80/90 (2500 kW). Reproduced by permission of Nordex

Figure 1.24 Size progression of Nordex turbines: (a,b,c) fixed-speed, fixed-pitch machines; (d) a large-scale, variable-speed, variable-pitch unit

materials, relatively favourable construction sizes can thus be achieved (Figure 1.34) and very high efficiencies attained, particularly in the partial load range. Such a plant configuration of the 600 kW class (Figure 1.34(a)) has been able to achieve excellent returns over several years of fault-free operation. A 2 MW unit with such a generator design (Figure 1.34(b)) was designed with a medium-voltage generator of 4 kV system voltage.

A further possibility, which has been considered for large, slow-running turbines in particular, is the combination of a low-speed generator and a turbine-side gearbox, as shown in Figure 1.35. The single-stage gearbox turns the generator shaft at around eight times the turbine speed of approximately 100 revolutions per minute. Thus, even for units in the 5 MW range, generators in compact and technically favourable construction sizes of approximately 3 m diameter can be used.

Further large-scale turbines in the 5MW class with a rotor diameter of over 125m are REpower 5 M and 6 M and Siemens SWT 6-154 (Fig. 1.36). A double-fed asynchronous generator with medium-voltage isolation in the low-voltage range (950 V stator-side or 690 V rotor-side) is used in the Repower system. The Siemens turbine has a direct drive permanent excited synchronous generator.

In the following we consider various real operational situations, the essential differences between the systems involved and the resulting effects on supply to the grid, taking as a basis the functional structure of wind power machines and their influences.

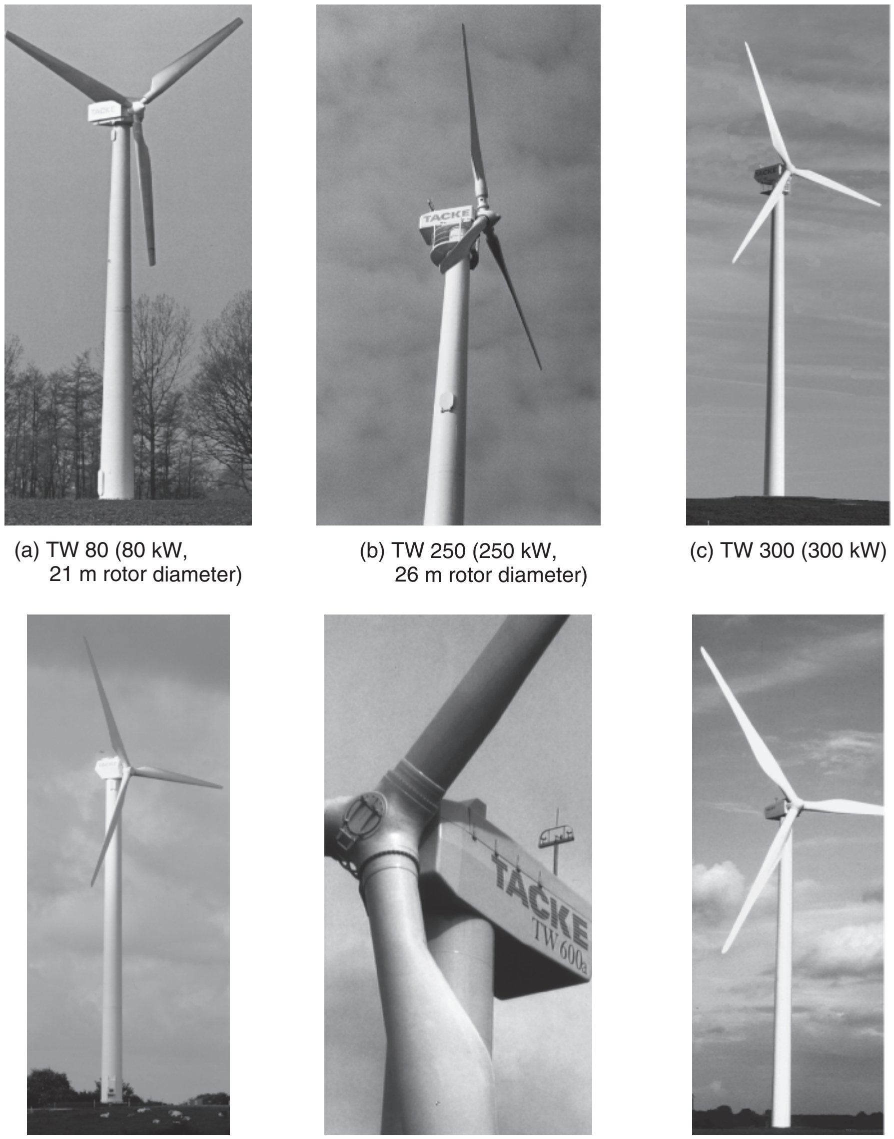
(a) V 17 (55 kW) (b) V 25 (225 kW) (c) V 39 (500 kW)

(d) V 44 (600 kW) (e) V 66 (1650 kW) (f) V 112 (3 MW)

Figure 1.25 Size progression of Vestas turbines: (a) small, fixed-speed, fixed-pitch machine; (b,c,d) larger variable-pitch units; (d,e) machines with speed elasticity; or double-fed asynchronous generators; (f) machines with permanent excited synchronous generators.

1.4 Functional Structures of Wind Turbines

For the following consideration, which is mainly concerned with the mechanical interaction of electrical components and with interventions to modify output, we will draw upon the nacelle layout shown in Figure 1.2. With the correct design, the influences of the tower and of steering in response to changes in wind direction can be handled separately (Section 2.2.1) or treated as changes in wind velocity. The block diagram shown in Figure 1.37 (see page 28),



(a) TW 80 (80 kW, 21 m rotor diameter)

(b) TW 250 (250 kW, 26 m rotor diameter)

(c) TW 300 (300 kW)

(d) TW 600 (600 kW, 43 m rotor diameter)

(e) TW 1.5/1.5S (1500 kW, 65/70 m rotor diameter)

(f) GE 3.6 (3.6 MW, 100 m rotor diameter). Reproduced by permission of GE Wind Energy

Figure 1.26 Size progression of turbines from GE / Tacke: first (a,b) and second (c,d,e,f) generation machines, from fixed-speed, fixed-pitch turbines (a to d) to large-scale, pitch-controlled, variable-speed turbines (e,f)

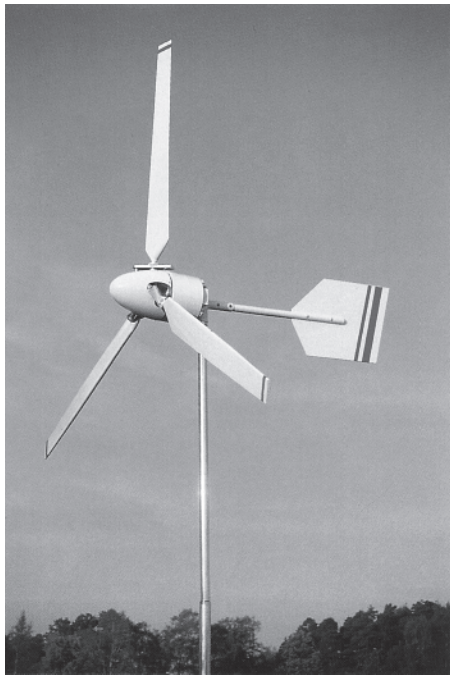
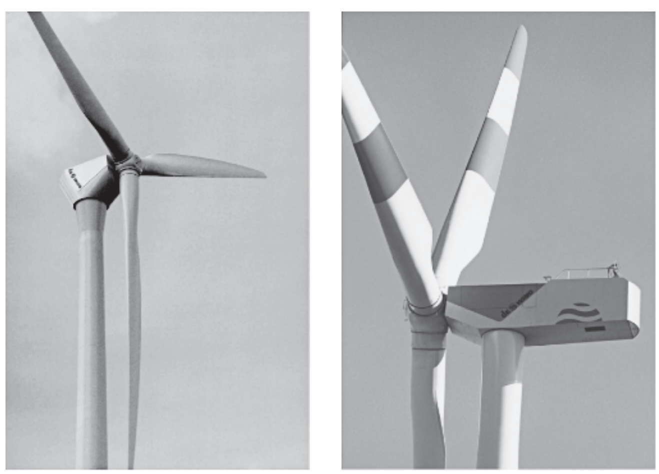


Figure 1.27 Small system-compatible turbine from aerosmart. Reproduced by permission of Aerodyn Energiesystems GmbH



(a) DeWind 4 (600 kW, 46/48 m rotor diameter)

(b) DeWind 6 (1000/ 1250kW, 60/62/64 m rotor diameter)

Figure 1.28 DeWind 4 (600 kW, 46/48 m rotor diameter). Reproduced by permission of DeWind

Figure 1.29 Joint development of the 1.5 MW MD 70/MD 77 turbine (70/77 m rotor diameter)

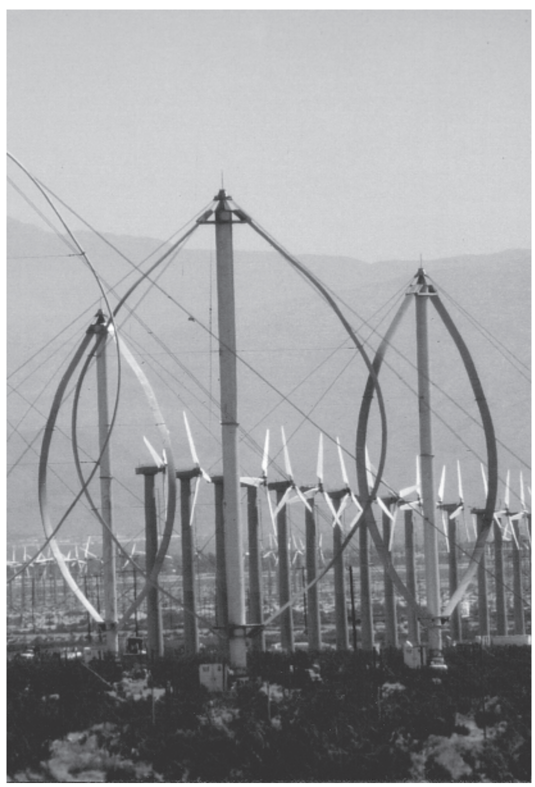


Figure 1.30 Fixed-speed 300 kW Darrieus unit with gearing and a conventional generator

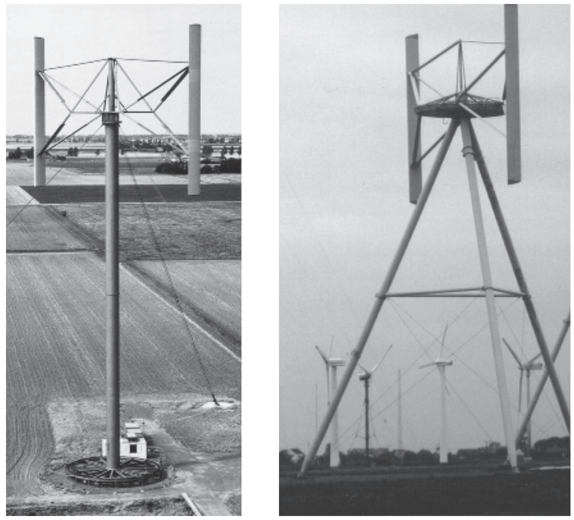


Figure 1.31 Variable-speed 300 kW gearless H-Darrieus unit

which illustrates the links between the most important components and the associated energy conversion stages, may serve as the basis for later detailed observations. This diagram also gives an idea of how operation can be influenced by control and supervisory processes. Furthermore, the central position occupied by the generator is made particularly clear.

The following pages therefore explain the physical behavior of a wind energy extraction system and the conversion of this mechanical energy to electrical energy by means of generators. We examine how mechanical moments are handled in the drive unit when the generator is connected to the grid, the design of generators suitable for wind turbines and the combined effects of turbines and power supply grids, as well as the regulation of turbines in isolation and in grid operation, bearing in mind the conditions imposed by the grid and the consumer.

From Figure 1.37 (see page 28), the functional structures for entire wind energy conversion systems, or for particular types of wind energy converter as shown in Figure 1.38(a) and (b) (see page 29), can be further developed. Such simplified block diagrams can help us to understand how the principal components of pitch- or stall-regulated horizontal-axis wind energy converters work and interact.

Wind energy converters with variable-blade pitch (Figure 1.38(a)) allow direct control of the turbine. Figure 2.61 shows that by varying the blade pitch it is possible, firstly, to influence the power input or torque of the rotor, with a smaller blade pitch angle β (or greater ϑ) leading to a lower turbine output and a greater β leading to a higher turbine output (pitch regulation). Secondly, by a few degrees adjustment of the rotor blades, the profile can be brought more fully into stall when β is greater (active stall regulation) and the turbine power falls. A slight

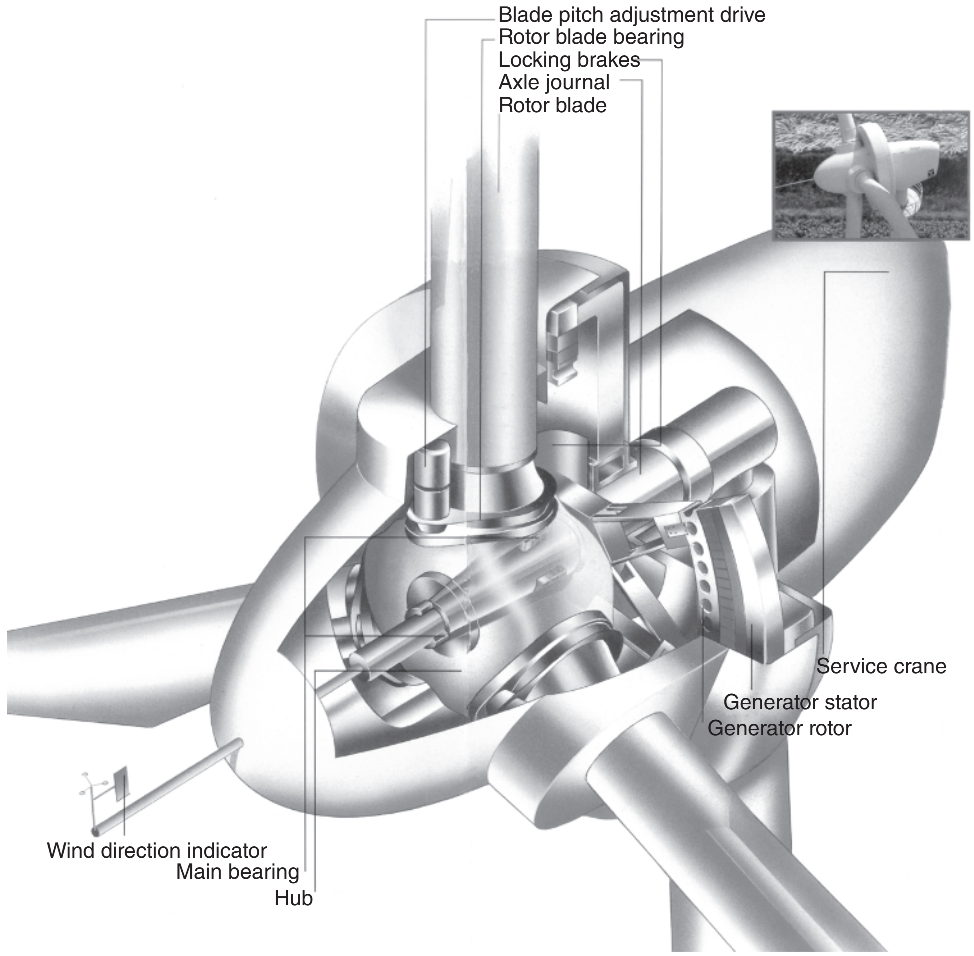
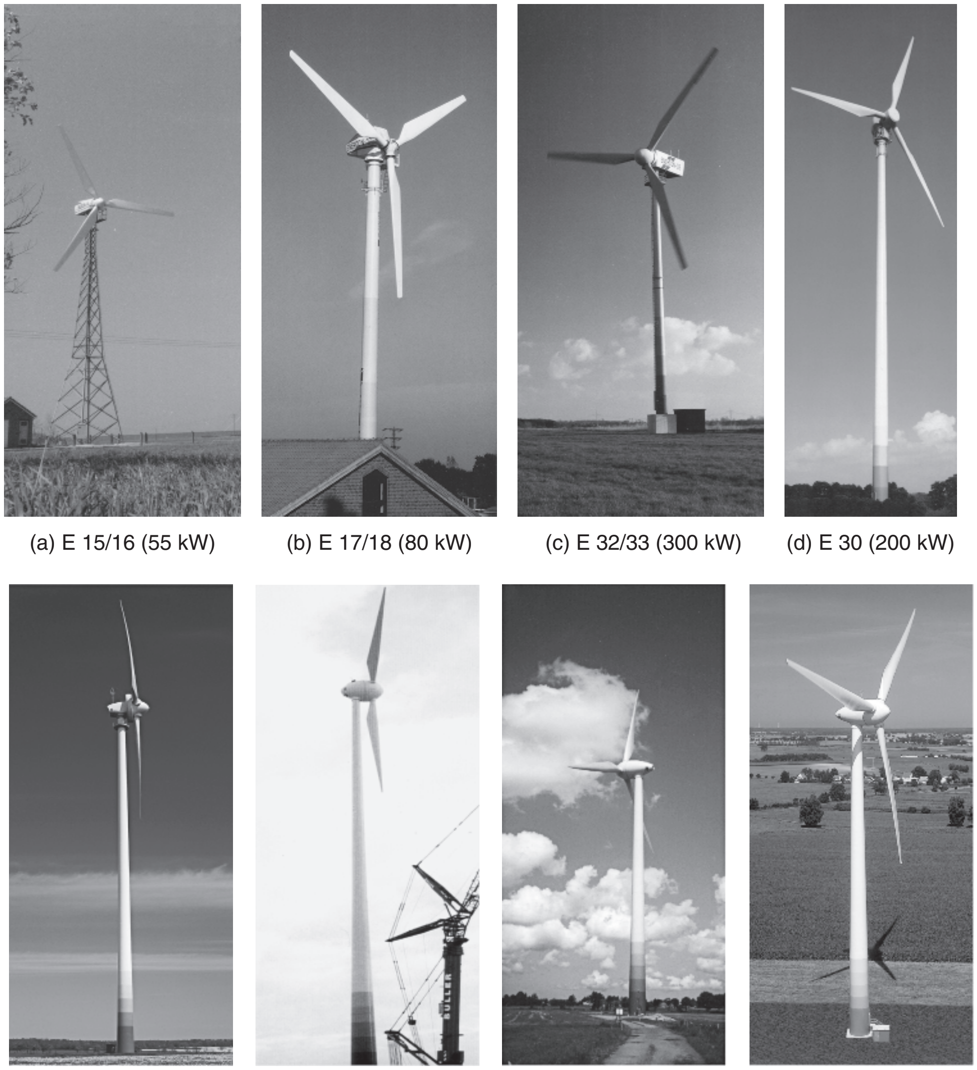


Figure 1.32 Schematic layout of the Enercon E 40 gearless turbine. Reproduced by kind permission of Enercon

reduction to the blade pitch angle, on the other hand, guides the rotor out of stall and power increases until laminar flow is achieved on the blade profiles. In this way, the speed of rotation, determined by integration of the difference between turbine torque and the generator's load torque, taking rotating masses (or mechanical time constants) into account, can be influenced at all performance levels – insofar as sufficient energy is available. The pitch control of a wind turbine therefore makes it possible to regulate energy extraction. In this way, adaptation to user needs (e.g. in standalone operation) can be achieved, as well as a measure of protection in storm conditions.



(a) E 15/16 (55 kW) (b) E 17/18 (80 kW) (c) E 32/33 (300 kW) (d) E 30 (200 kW)

(e) E 40 (500 kW) (f) E 58 (850 kW / 1000 kW) (g) E 66 (1500 kW / 1800 kW) (h) E 112 /E 126 (4,5 MW/6 MW/7,5 MW)

Figure 1.33 Enercon turbines from variable-speed geared models with thyristor inverters (a,b,c) to gearless configurations with pulse inverters (d,e,f,g,h); (a,b) with fixed and (c,d,e,f,g,h) with variable pitch. Reproduced by kind permission of Enercon

In (passive) stall-controlled converters (Figure 1.38(b)), the rotor speed is kept at an almost constant speed by the load torque of a rigidly coupled asynchronous (mains) generator, usually of large dimensions. When wind strength rises above nominal levels, the flow over the rotor blades achieves partial or even total stall – whence the so-called ‘stall regulation’. The power take-up of the turbine is thereby passively (i.e. design-dependently) limited under full loading

(a) Genesys 600

(b) Zephyros Z72 (70.65 m rotor diameter and 2 MW nominal output) with medium-voltage generator. Reproduced by permission of Harakosan

Figure 1.34 Gearless wind turbines with permanent-magnet synchronous generator (46 m rotor diameter, 600 kW nominal output)

Figure 1.35 Nacelle of the large-scale Multibrid N 5000 (5 MW, 116 m rotor diameter) with single-stage gearing, integral hub and low-speed synchronous generator. Reproduced by permission of Multibrid Entwicklungsgesellschaft GmbH

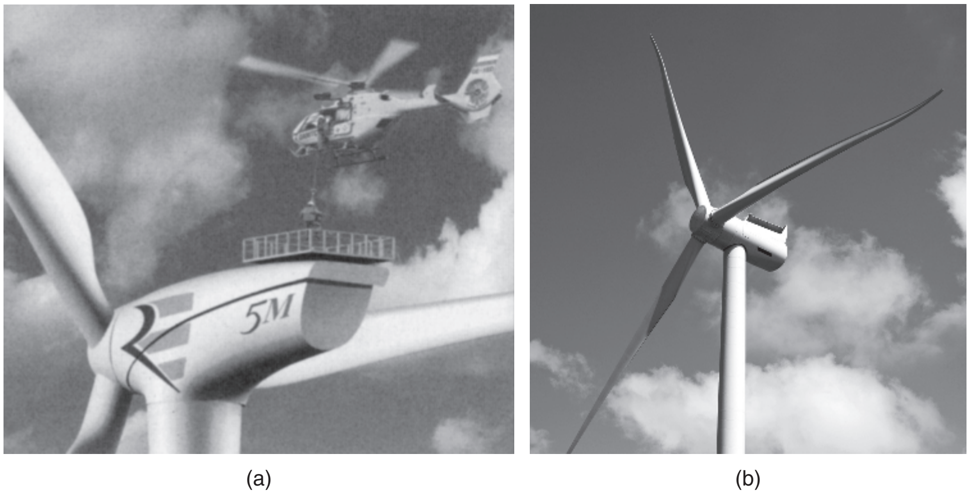


Figure 1.36 Offshore turbines: (a) Repower offshore and onshore turbine 5M/6M, 5 MW/6 MW nominal output power, 126,5 m rotor diameter. *Source:* Repower; (b) Siemens offshore turbine SWT 6-154, 6 MW nominal output power, 154 m rotor diameter. *Source:* Siemens

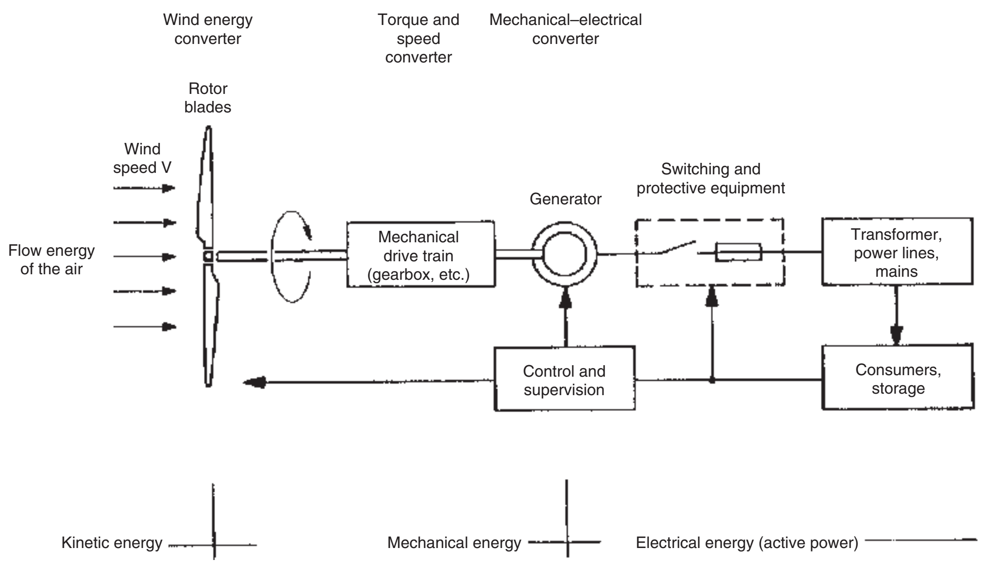


Figure 1.37 Functional chain and conversion stages of a wind energy converter

to values such that under operational wind speed conditions the nominal output of the generator is not significantly exceeded.

The use of variable-speed generators in both regulation systems allows the reduction of sudden load surges, and considerably extends the range of operation. The optimal power can be produced by adjusting the speed of the rotor to the desired speed. For example, it is also

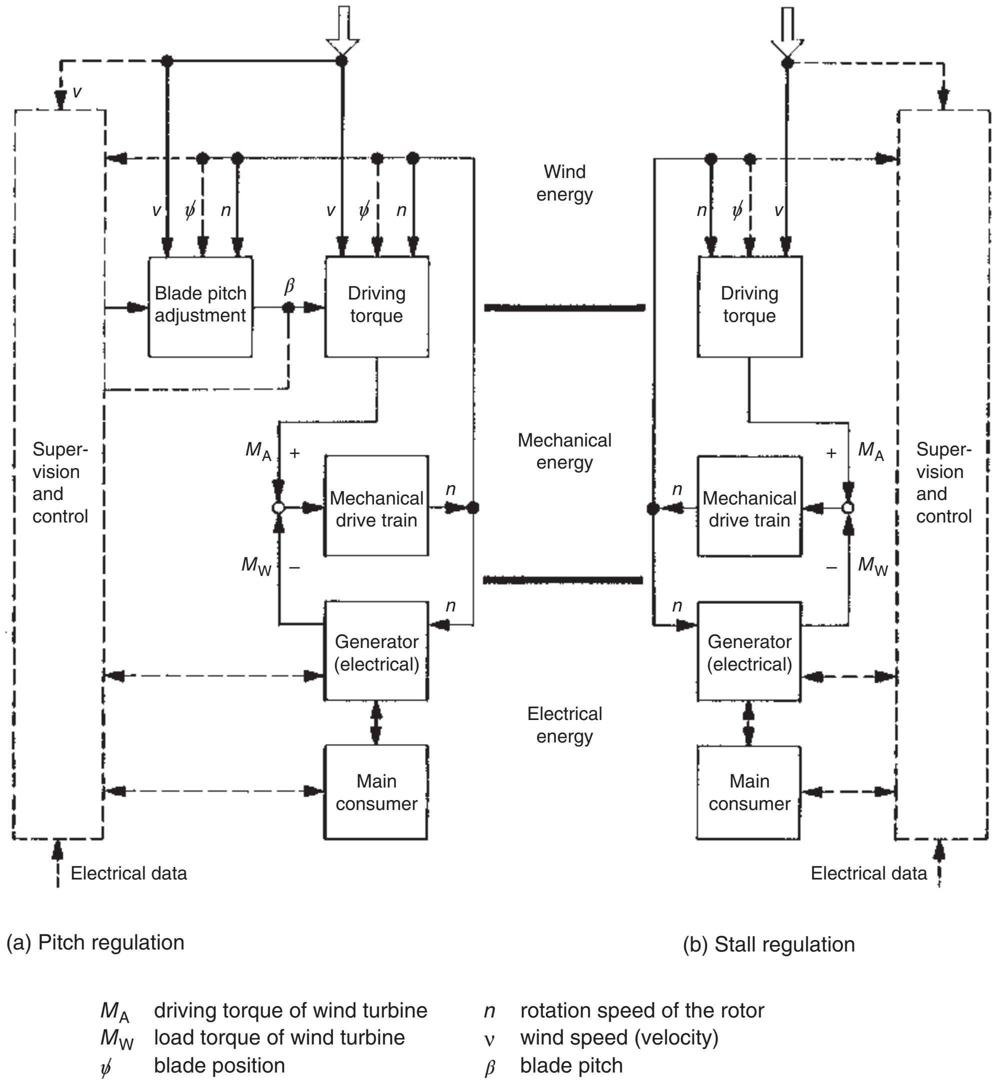


Figure 1.38 Functional structure of a wind energy converter

possible, in cases where partially increased transitional loads must be handled, to influence the drive torque of stall-regulated turbines by varying the rotational speed of the generator.

A detailed treatment of the generator and associated discussions on the theme of turbine regulation require knowledge of the physical processes and a review of the mathematical laws governing the entire converter system. The following text should encompass this, insofar as is necessary. More detailed studies are also necessary regarding the combined effects of wind turbines working together with existing grid systems and the measures that must be applied to control these effects throughout the entire system.

The following chapters summarize the results of years of research and development. Through practical references achieved from completed projects, particular weight has been given to the usefulness of the results for plant conception and design.

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