Chapter 10
Electrical System

The electrical system of a wind turbine includes all components for converting mechanical energy into electric power as well as the electrical auxiliaries and the entire control and supervisory system. Next to the mechanical drive train, the electrical system thus constitutes the second essential subsystem in a wind turbine.

In a wind turbine, the actual mechanical-electrical energy converter, the generator, as in a conventional power plant, is the focal point for all the preceding components in the functional chain (Fig. 10.1). Its characteristic properties are all the more important for a wind turbine as the rotor as prime mover with its unsteady torque causes the most varied problems.

In principle, a wind turbine for electric power generation can be equipped with any type of generator. The demand for grid-compatible electric current can be met today by connecting downstream inverters, even if the generator supplies alternating current of variable quality, or direct current.

Generators producing direct current have the advantage of being operable at variable speed. High power direct current generators are, however, no longer in common use today. Several other reasons such as a high-maintenance commutator and their comparatively high cost also speak against them. Very small wind turbines which are merely used for recharging batteries and are, therefore, only intended for generating direct current, are still in use today, of course. They are, however, unsuitable for larger wind turbines.

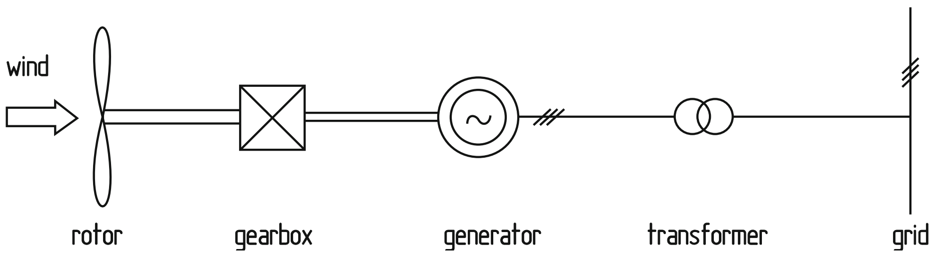

Fig. 10.1. Mechanical-electrical functional chain in a wind turbine

Current wind turbines, therefore, have three-phase AC generators, or alternators, similar to those used in conventional power plants. As mentioned before, the electrical system of a wind turbine is by no means restricted to the electric generator. The generator merely represents the core of an extensive overall electric and electronic system. The electrical equipment used for current distribution, the connection to the grid, monitoring and control are all parts of this system. Wind turbines are current-generating power plants which must meet the requirements concerning automatic operation, monitoring and safety just like other conventional power plants of comparable output. This fact is sometimes overlooked, thus causing the complexity, and costs, of the electrical equipment to be underestimated.

The selection and design of the electric generator system is primarily subject to the aspects of production costs and of the electrical efficiency. But its maintenance and operational reliability is also an aspect not to be neglected, especially in off-shore applications. The control characteristics of the electric generator and the remaining control-related properties of wind turbines, particularly blade pitch control or stall behaviour, must always be considered collectively. They constitute an almost inseparable functional total system (s. Chapt. 11).

Not lastly, the quality of the electric current fed into the public utility grids is determined to a considerable degree by the technical concept of the electrical system. Particularly in weak grids, grid reactions in the form of power and voltage fluctuations or harmonics, are important criteria in the selection and design of the electrical system [1].

10.1 Synchronous and Asynchronous Generator

It is not the task of this book to provide a general introduction into electric generator technology. The standard literature of this field is better suited to this purpose [2]. Nevertheless, some of the essential properties of the two most important types of alternators will be summarised in the following sections. Knowledge of these is a prerequisite for understanding the functional behaviour of a wind turbine. Continuing from the general characteristics of the synchronous and induction generator, the most important electrical concepts of wind turbines will then be discussed.

From the point of view of their physical-electrical principle of operation, three-phase machines can be built as synchronous generators or as asynchronous (or induction) generators. Both machines have the same basic design with respect to the three-phase winding of the stator. The difference lies in the way the electric field is generated in the generator rotor.

10.1.1 Synchronous Generator

Synchronous electric machines have a rotor (pole wheel) which is excited with direct current via *slip rings* (Fig. 10.2). An alternating voltage is either generated in (generator operation) or applied to (motor operation) the stator windings. The currents flowing in the stator winding and having the frequency f generate the so-called “armature field”. The rotor winding, through which direct current flows, generates the exciter field, which is rotating at synchronous speed. The speed of the synchronous machine is determined by the frequency of the rotary field and the number of pole pairs of the rotor. The rotor speed n of a synchronous machine is:

$$n_{syn} = \frac{f}{p}$$

where:

f = frequency of the rotary field (grid frequency) in Hz
p = number of pole pairs,
n_{syn} = rotational speed in 1/s.

For the European grid frequency of 50 Hz, a speed of 1500 r.p.m. is obtained with two pole pairs. In the US with a 60-Hz grid, the rotational speed is 1800 r.p.m..

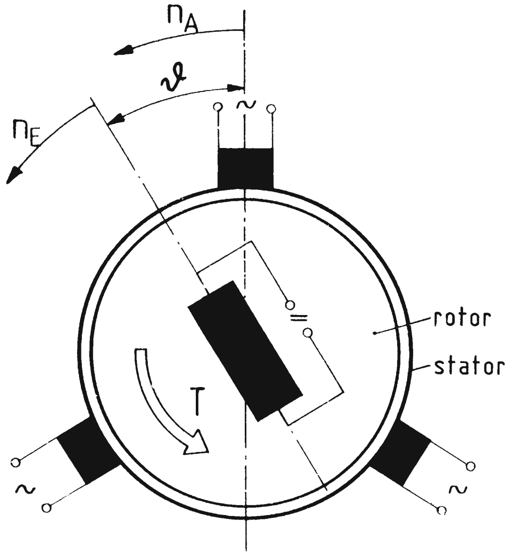

Fig. 10.2. Synchronous generator

Synchronous generators are built as so-called "cylindrical-rotor" machines or as "salient-pole" machines. Cylindrical-rotor machines with only a few pole pairs and a rotor with a small diameter are suited to high rotational speeds. In large power plants they are used as turbine generators driven by steam turbines at a speed of 1000 to 3000 r.p.m. Salient-pole machines, with a larger number of pole pairs and correspondingly larger diameter, are used in combination with hydro turbines at 60 to 750 rpm. At a speed of for example 75 r.p.m., 40 pole pairs are required. In horizontal-axis wind turbines, salient-pole machines are used as a rule (Fig. 10.3).

The direction of rotation and the rotor speed of a synchronous machine are always synchronous with the rotation of the rotating stator field. Thus, there is no relative field movement *(slip)* between rotor speed and the synchronous speed of the rotating stator.

Instead, the rotor is turned forward or back, compared to its idling position, by the so-called *load angle* (rotor displacement angle), when mechanical power is added or, respectively, taken out. The size of the load angle is a measure of the level of loading. During idling it is zero, when energy is released (generator operation) it has a positive value, and when energy is consumed it has a negative value (motor operation) (Fig. 10.4). The load angle is equivalent to the time lead or lag of the grid voltage compared to the pole-wheel (rotor) voltage.

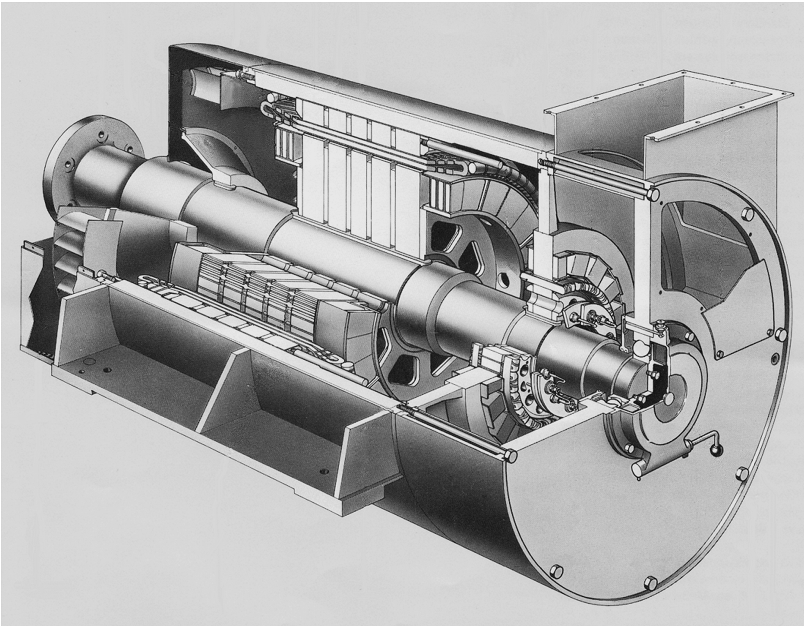

Fig. 10.3. Synchronous generator (salient-pole machine) (AEG)

The torque characteristic of a synchronous machine is represented as a function of the load angle. A stable operating point is only possible in the range of π = -180° to +180°. The highest torque *(pull-out torque)* is reached at π = 90°. According to the VDE (Association of German Electrical Engineers) standard, the nominal operating point should be at π = 30°. Normally, the pull-out torque has twice the value of the nominal torque. The torque characteristic can be influenced to a limited extent by varying the excitation voltage of the pole wheel.

The efficiency of synchronous machines is generally higher than in comparable induction machines. In practice, this difference is relatively small (1 to 2 %), at least in large machines. Efficiency increases with increased size (rated power), as is the case in other machines. The efficiency as a function of the load is of particular interest with respect to their use in wind turbines (Fig. 10.5). Smaller generators do not only have a lower nominal efficiency at full load, but also exhibit a greater drop in efficiency at partial load.

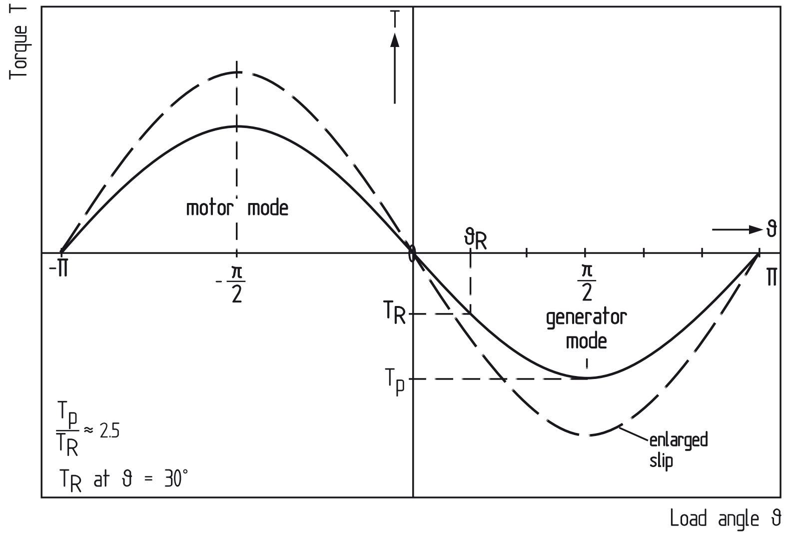

Fig. 10.4. Torque vs. load angle of a synchronous machine [3]

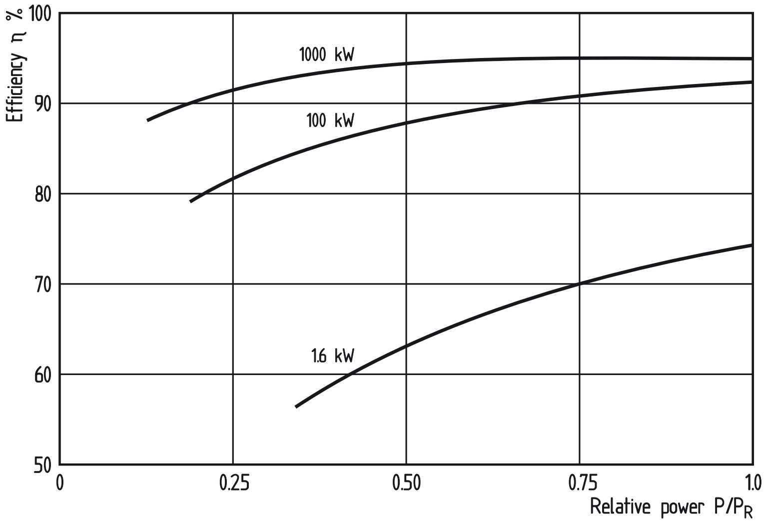

Fig. 10.5. Efficiency of synchronous generators of different rated power as a function of load [3]

Next to efficiency, generator mass is of importance to the wind turbine designer, particularly in horizontal-axis wind turbines, where the generator is located at the tower head. The generator mass is influenced considerably by the speed level at a given rated power (Fig. 10.6). The faster the generator rotates, the lighter and, as a rule, more cost-efficient it becomes. With respect to their application in a wind turbine, this does not, however, imply that a generator rotating as fast as possible is the most economical solution. As the generator speed increases, so does the complexity and cost of the gearbox. The task is to find the optimal combination of generator speed and gear ratio.

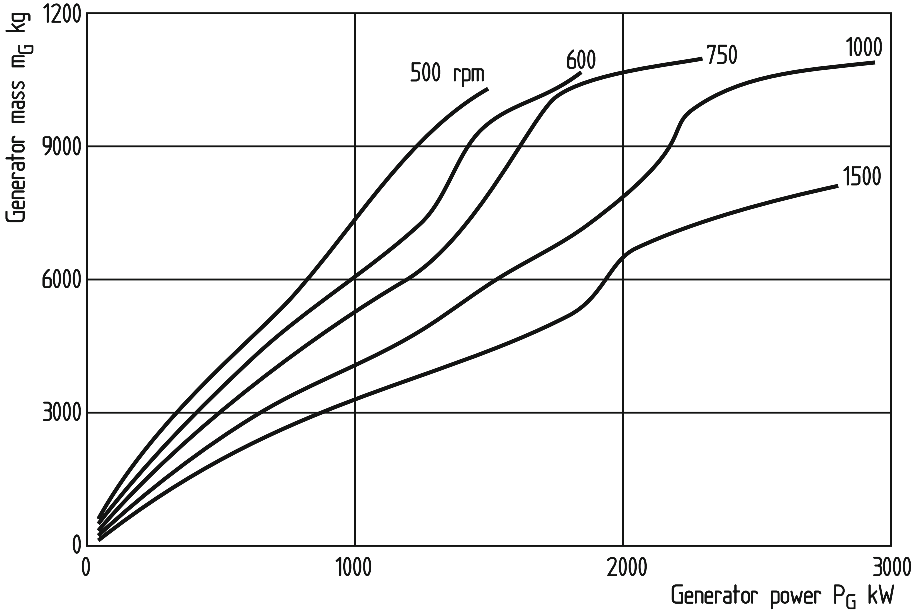

Fig. 10.6. Generator mass of synchronous generators [3]

10.1.2 Induction Generator

In the induction machine (or asynchronous machine), an electric field is induced by a relative movement (slip) between the rotor and the rotating stator field which produces a voltage across the rotor winding. The interaction of the associated magnetic field of the rotor with the stator field results in the torque acting on the rotor (Fig. 10.7).

The rotor of an induction generator can be designed as a *squirrel-cage rotor* or, with additional slip rings, as a *slip-ring rotor* (Fig. 10.8). The slip-ring rotor allows the electrical characteristics of the rotor to be influenced from the outside. By changing the electric resistance in the rotor circuit, greater slip can be attained and with it a degree of speed compliance for direct coupling to a fixed-frequency grid. If an inverter is used in the rotor circuit, it is possible to achieve variable-speed operation in parallel grid operation.

Like synchronous generators, induction generators can be operated both as motors and as generators. The induction version is wide-spread among electric motors. Almost all modern electric motors are induction machines. The squirrel-cage versions, in particular, stand out because of their unrivalled robustness and low maintenance requirements. Apart from the rotor bearings, they have practically no rotating, wearing parts and, moreover, their price/performance ratio is advantageous.

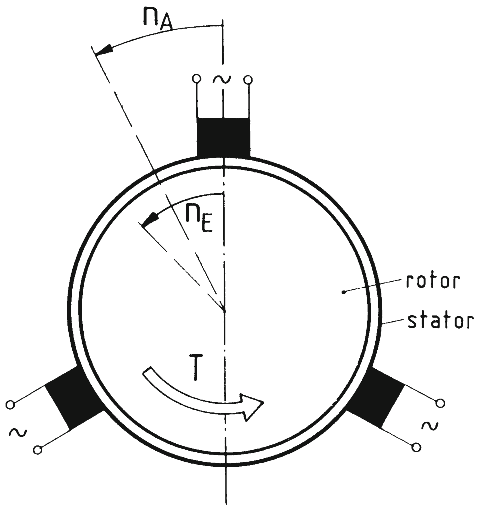

Fig. 10.7. Induction generator

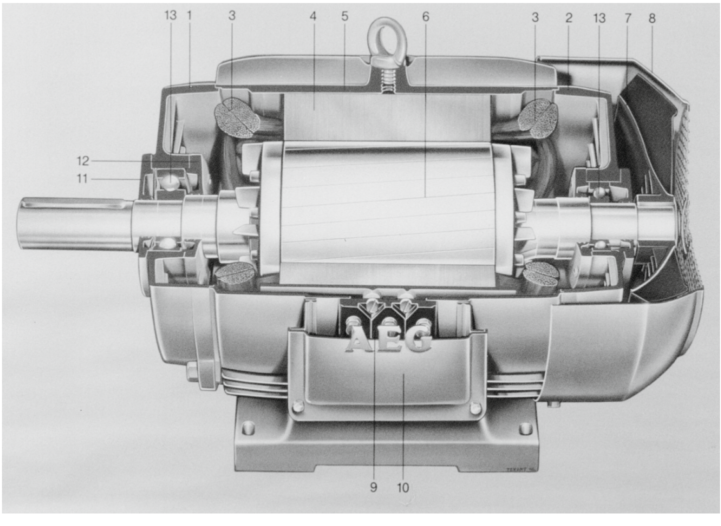

Fig. 10.8. Induction generator with squirrel-cage rotor (AEG)

1. End shield (front side)
2. End shield (rear side)
4. Stator laminations
5. Housing
6. Rotor
7. Internal fan
9. Terminal board
10. Terminal box
11. Outer bearing cover
12. Inner bearing cover
13. Roller bearing

In generator technology, the asynchronous design no longer plays a significant role. Large power plant generators are synchronous generators. It is only in connection with smaller hydroelectric turbines that induction generators are occasionally used. For wind turbines, on the other hand, the induction generator is a suitable type of generator, the reasons for which will be discussed later. A look at its basic characteristics is, therefore, indispensable.

For a start, an important fact for operating an induction machine in generator mode is that the rotor must be supplied with a magnetizing current for generating and maintaining its magnetic field. This so-called *reactive-power* demand depends on active power. In parallel grid operation, the reactive power can be taken from the grid. In isolated operation, *power factor compensation* must be provided in the form of capacitors.

The synchronous speed of the rotor of an induction generator depends on the grid frequency and the number of pole pairs:

$$n_{syn} = \frac{f}{p}$$

where

f = grid frequency in Hz,
p = number of pole pairs,
n_{syn} = rotational speed in 1/s.

For two pole pairs, frequently used, a synchronous speed of 1500 r.p.m. is obtained at $f = 50$ Hz, whereas a 60 Hz grid as in the US requires a generator speed of 1800 r.p.m. In motor operation, the mechanical rotor speed is a few percent below this value and in generator operation a few percent above it, due to the slip.
The slip s is:

$$s = \frac{n_{syn} - n_{mech}}{n_{syn}}$$

The mechanical rotor speed then becomes:

$$n_{mech} = n_{syn}\,(1 - s)$$

The torque of the asynchronous machine is a function of the slip. Accordingly, its torque characteristic is specified in dependence on the slip (Fig. 10.9). When the slip is $s = 0$ and $s = \infty$, the machine does not produce torque, or cannot absorb torque, respectively. In between, the torque exhibits a maximum, the so-called *pullout torque.* According to VDE 0530, the ratio between pull-out torque T_P and rated torque T_R must be at least 1.6 in grid operation.

The electrical efficiency of induction generators is a function of the nominal slip. In larger turbines in the megawatt range, the nominal slip is below 1 % (Fig. 10.10). The associated efficiency of approximately 96 to 97 % is not much lower than in a comparable synchronous generator. Due to the absorption of reactive current from the grid, the power factor cos φ is comparatively low and amounts to approximately 0.87 to 0.90.

Smaller induction generators in the kilowatt power range have a much poorer efficiency, with correspondingly higher values for the nominal slip.

In contrast to a DC machine, it is very difficult to make an induction machine change its speed. It is possible to influence the speed within a very narrow range by increasing the terminal voltage. By connecting external resistors in the rotor circuit, the speed can be varied at least in one direction by increasing slip. This, however, requires a slip-ring rotor. The rotational speed of a squirrel-cage rotor can be changed in steps by means of pole reconnection. This requires the stator winding to have two separate windings with different numbers of pole pairs, a version which is occasionally used in induction generators for wind turbines (Chapt. 10.3.4).

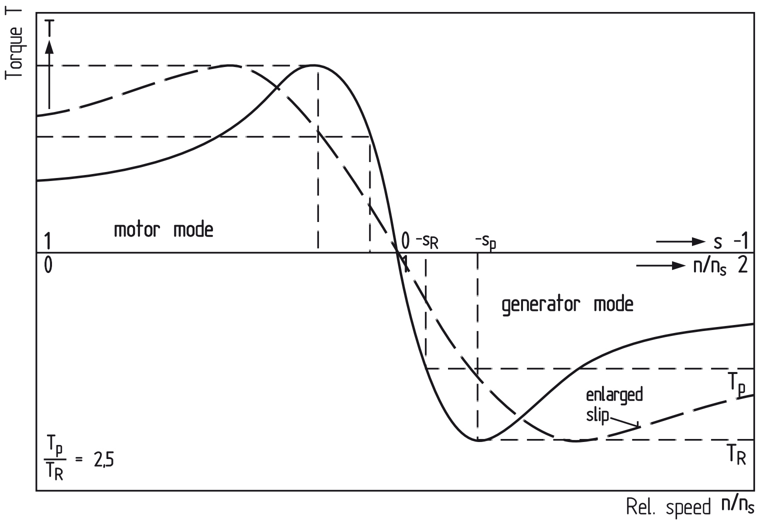

Fig. 10.9. Torque characteristic of an induction generator [4]

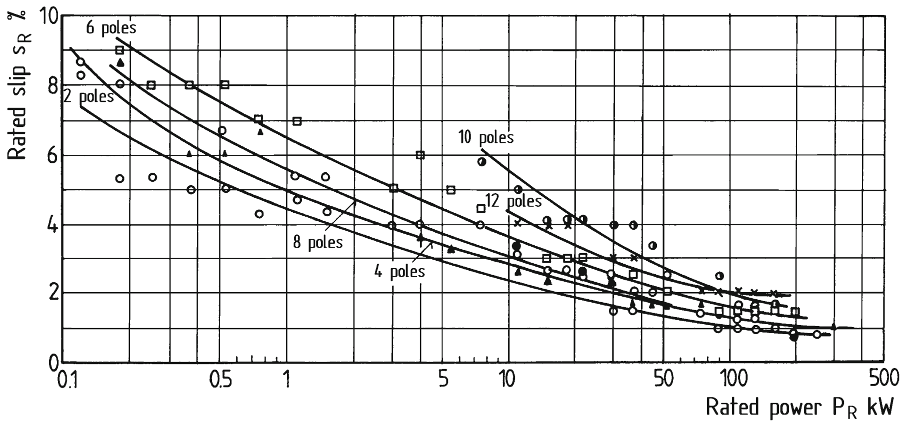

Fig. 10.10. Nominal slip of induction generators with increased rated power and varying numbers of poles [3]

10.1.3 Generator with Permanent Excitation

Low-power electric motors having permanent magnets are widely used in drive engineering. When the dimensions become larger, the high costs of materials for the magnets, so-called “neodymium iron” (NdFeB), and occasionally also exotic materials such as samarium-cobalt alloys, become much more significant so that there is no longer any saving compared with conventional designs. On the other hand, the permanent magnet technology has also been penetrating the Megawatt power range in drive engineering, for example in compact marine propulsion units, in recent years so that it has been possible to lower the costs of magnetic materials with the consequence that generators for wind turbines can also be manufactured economically (Fig. 10.11).

In principle, the permanent magnet technology can be used for all types of construction of electric machines [5]. The essential advantages are that there is no longer any exciter current and the efficiency is thus higher. With the great power density, the mass is reduced for a given power or, in other words, the construction becomes more compact. On the other hand the controllability is less because the voltage can not be controlled via the exitation frequency. The no-load voltage can, therefore, be 30 to 40% below the nominal voltage. The disadvantage which is the most severe one up to the present day lies in the high costs for the material of the permanent magnets and their complicated assembly.

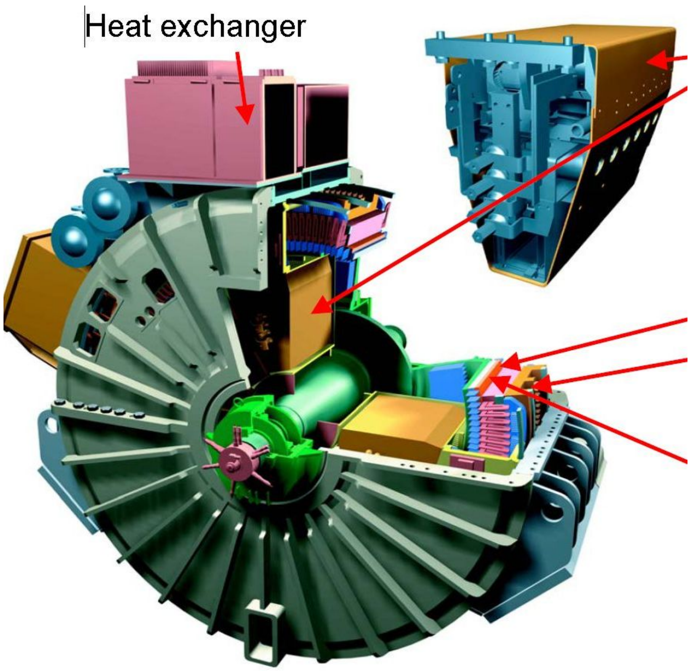

Fig. 10.11. Electric marine drive motor with permanent-magnet excitation (Siemens)

High–speed generators

The decreasing costs of the permanent magnets have encouraged the industry to use this technology for electric generators in the megawatt-power range. Standard high-speed generators with permanent excitation have been on offer for some time (Fig. 10.12). The efficiency of these generators achieves values exceeding 98% (Fig. 10.13). In the recent years they are used for wind turbines by an increasing number of manufactures.

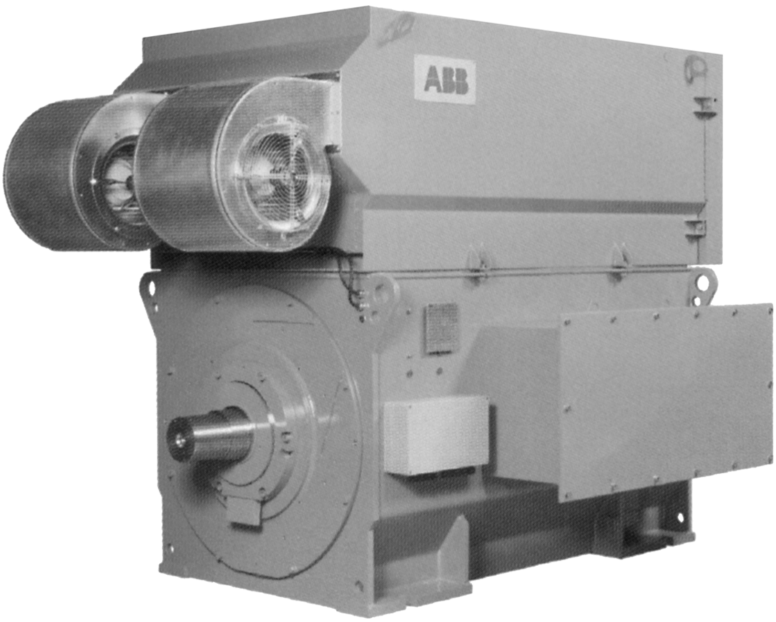

Fig. 10.12. High-speed permanent magnet generator, 2.5 MW rated power (ABB)

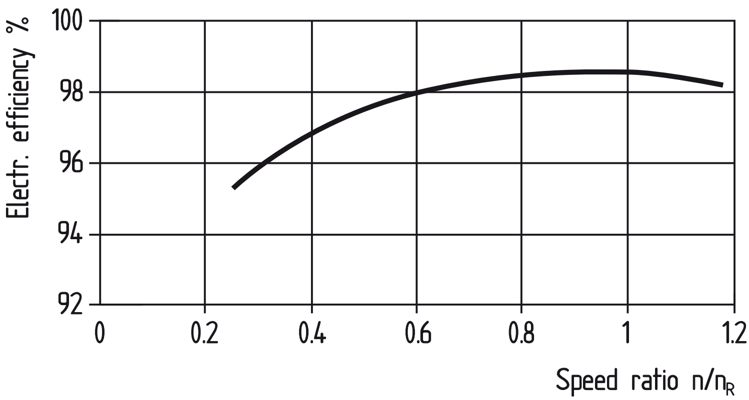

Fig. 10.13. Electrical efficiency vs. rel. speed of a high-speed permanent-magnet generator, 2.5 MW rated power [6]

Low-speed generators

The success of the gearless drive train concept developed by Enercon has encouraged the developers of the technology of permanent magnets for electric generators for some years to use this type of generators in gearless designs. Its advocates rightly point out that the disadvantage of electrically excited multi-pole generators, their bulky construction, can be largely avoided by applying permanent-magnet technology. The advantages of permanent-magnet technology undoubtedly lie in the fact that it is possible to achieve high power densities in a very narrow space and the generators thus become much more compact.

At the beginning of the nineties, the German manufacturer “Heidelberg Magnetmotor” built some vertical-axis turbines with direct-drive generator and permanent excitation [7] but the concept of the wind turbines proved to be unsuccessful, regardless of the generator design, and this development was discontinued.

Some years later, permanent magnet technology was developed for generators of commercial wind turbines, by several manufacturers of conventional electric motors and generators.

Low-speed generators with permanent magnet excitation are designed either with inner rotor design, as usual, but also with outer rotor (i.e. Vensys) (Fig. 10.14). In the last case, the outer rotating ring contains the magnets. The advocates claim, that this type will lead to a more compact construction.

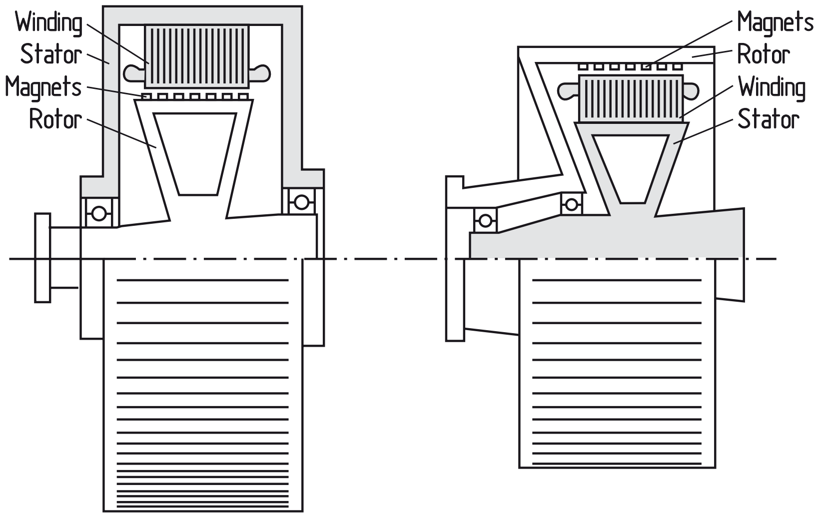

Fig. 10.14. Low-speed permanent magnet generators with “inner” and “outer” rotor design

The electric efficiency of the low-speed generators is somewhat less compared to the high-speed design. The bandwidth is higher depending on the specific design features. In any case the efficiency at partial load is superior to generators with electric excitation

(Fig. 10.15). In the last years wind turbines with permanent magnet generators are developed and manufactured by an increasing number of wind turbine companies as an alternative to the conventional generators (Fig. 10.16).

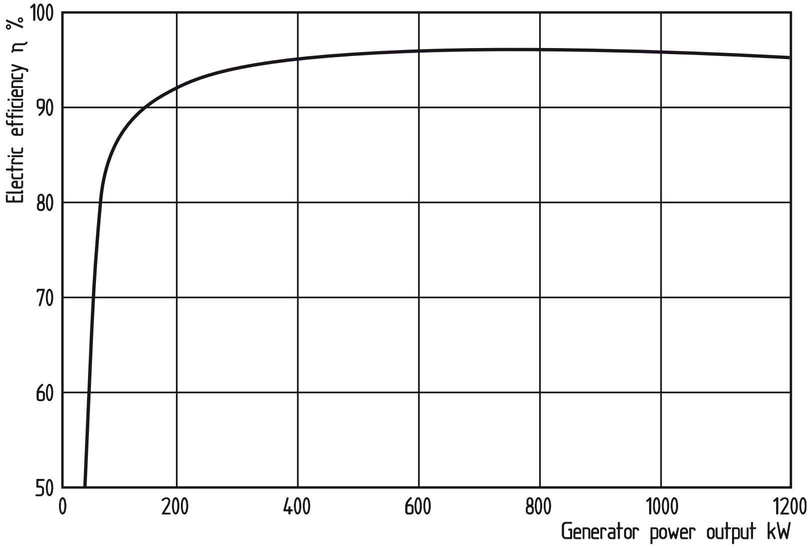

Fig. 10.15. Measured electric efficiency of a 1.5 MW low-speed generator with permanent magnets [8]

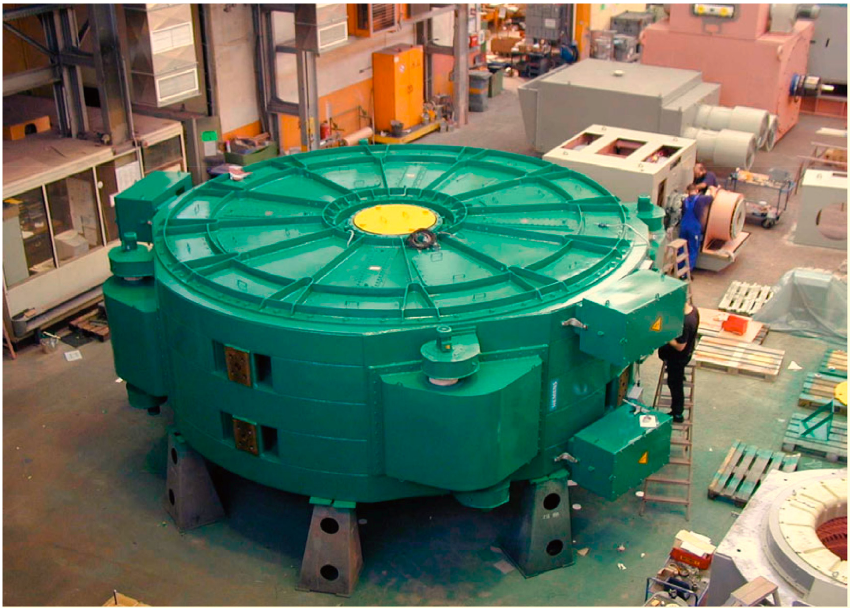

Fig. 10.16. 3 MW low-speed permanent magnet generator (Siemens)

10.2 Assessment Criteria for Using Generators in Wind Turbines

The brief discussion of the fundamental properties of synchronous and induction generators shows that both versions can really only be used without problems when they are combined with a drive unit which provides a steady driving torque at a fixed speed. But in a wind turbine rotor this, of all things, is not the case. Apart from simple synchronous or induction generators, variable-speed generator systems with inverters are increasingly used in wind turbines for precisely this reason. These systems can be implemented on the basis of either generator type.

Before discussing the different electrical systems in greater depth, however, it is useful to compile a "catalogue" of assessment criteria which can be used for assessing the different generator systems against the background of the different operating conditions, for example in parallel with the grid or in isolation. As usual, it becomes obvious here that there is not *one* solution, but that different generator systems appear to be advantageous depending on what relative importance is given to the individual properties. The most important assessment criteria to be applied to electric generators or generator systems with respect to their suitability for use in wind turbines can be summarised by means of the following characteristics.

Dynamic response in operation on the fixed-frequency grid

Coupling the generator directly to the fixed-frequency grid forces the generator to run at a constant speed. On the other hand, the wind turbine rotor wants to follow the variations in wind speed. In between there is the mechanical drive train of the wind turbine. High dynamic loads on the mechanical components and severe fluctuations in the electrical power output are the consequences.

Reduction of the dynamic loads can only be achieved by allowing the wind rotor speed a degree of freedom from the grid frequency, regardless of how this is realised, mechanically or electrically. One decisive question is what amount of speed variability is required to decisively reduce the dynamic load level. Answering this question requires the consideration of a whole series of system properties of the wind turbine, such as the aerodynamic rotor design, the pitching rate of the blade pitch control and, if available, generator torque control, to name only the most important. Computer simulations, but also empirical values from practical operation suggest that with a speed "elasticity" of only 2 % to 3 % a lasting improvement can be achieved [4]. A speed elasticity of this magnitude can be achieved via the slip of the induction generator.

Apart from speed coupling, the dynamic behaviour on the grid is also influenced by the damping of any generator speed fluctuation about the grid frequency. Induction generators have much better damping characteristics than synchronous generators. They are, therefore, also dynamically less problematic with respect to their oscillatory response, apart from the speed slip.

In the case where a synchronous generator is used, an additional mechanical device is needed in the drive train, for example a fluid coupling which provides damping and speed compliance (mechanical slip).

Speed range

Although it is true that a speed elasticity of 2 to 3 % is sufficient to distinctly reduce the dynamic loads, this is insufficient to obtain speed variability in the sense of a wind-oriented operation. Based on the background discussed in Chapter 14, completely wind-oriented operation requires a speed range of approximately 40 to 100 % of the maximum speed. A speed range of this extent can only be achieved with a variable-speed generator and an inverter. However, the inverter costs and decreasing efficiency are factors to be considered.

Controllability

Apart from controlling power output by blade pitching, it is also desirable to have a second control capability on the electrical side. If it is possible to influence the generator torque, a variable-speed mode of operation of the rotor can be implemented in parallel grid operation. This will relieve the comparatively inert aerodynamic blade pitch control and thus improve the overall control characteristics of the turbine. The controlled variable-speed generator inverter systems almost completely smooth out the electrical power output within the given speed limits (Chapt. 6.6.4).

Reactive power

The reactive-power requirement of the generator system is a central issue primarily in isolated operation, preventing the use of an induction generator. But also in parallel-grid operation the reactive power characteristics cannot be left out of consideration, at least in the case of large turbines or of a large number of turbines. The public utilities charge high fees for supplying reactive power from the grid. With induction generators the reactive-power consumption must be compensated for by connecting capacitors. In synchronous generators the *power factor* cos φ, i.e. the reactive power, can be controlled by regulating the voltage at the terminals. Apart from the higher efficiency, this is an important advantage. In the case of generator systems with inverter, the reactive-power requirement of the inverter must be taken into consideration, but the cos φ can be influenced by the inverter.

Grid perturbations

Even drawing reactive power from the grid represents an undesirable perturbation. Furthermore, other interferences with the grid must be noted. Among them are high starting currents when an induction generator is connected, or harmonics in the current fed into the grid. Harmonics such as these can be generated to a small extent by the generator itself, but to a much larger extent they are associated with the use of static converters. The higher-frequency waves can interfere with the ripple control systems in the interconnected grids. However, they can be filtered out more easily than low-frequency oscillations. The harmonics load on the grid was an assessment criterion at least for some of the variable-speed generator systems with older inverter types. Modern inverters generate an alternating current which is almost completely free of harmonics.

In Germany, testing newly developed wind turbines for *grid compatibility* in accordance with uniform criteria has been common practice for some years (see Chapt. 18.5).

Synchronisation

Synchronising the generator with the grid presents entirely different problems for the two generator designs. Synchronising a synchronous generator with the grid poses considerable difficulties for a wind turbine. In practice, it can only be done by using an additional inverter or some speed elasticity and damping in the drive train. Nevertheless, induction generators, too, are connected to the grid by means of a "soft connection" arrangement using thyristors. This is intended to reduce the so-called "switch-on transient" with its momentarily high power import from the grid (see Chapt. 10.3.2). It is, however, much easier to connect induction generators to the grid.

Load disconnection

A sudden load disconnection, for example due to a failure of the grid or an electrical fault, is always a critical moment for a wind turbine. The loss of the generator torque requires immediate action from the rotor brake systems in order to avoid the rotor from "running away". A generator behaviour which sustains the electric generator torque for a certain period of time even after failure of the grid is therefore desirable. It is relatively easy to implement this "electric braking" in a synchronous generator. After failure of the grid, the turbine merely needs to be switched to an ohmic braking resistance. In principle, this is also possible with induction generators, but then the magnetising current for the rotor must be maintained, for example by means of rotor feedback. This is much more complicated to achieve and is, therefore, not done in most cases.

Efficiency

The difference in the electrical efficiency of synchronous generators and induction generators is small (1–1.5 %), at least when the nominal slip of the induction generators is small. The discussion of the electrical efficiency therefore focuses on the question of how the efficiency of the variable-speed generator/inverter systems is related to the direct grid coupling of the generators.

Until recently, it was only possible to build inverter systems with relatively poor efficiency. Modern power electronics, however, have changed this situation over the past ten years. Today, the overall electrical efficiency is only a few percent below that of fixed-speed generators, even including inverters. If the higher aerodynamic rotor efficiency, made possible by the variable-speed operation, is also included in the calculation, the resultant overall efficiency of the wind rotor and generator system is even higher. In the long term, even the higher investment costs can be compensated for. Given this background, the differences in efficiency of the electric generator systems are no longer significant enough to be a deciding factor.

Costs

One of the main criteria for the assessment of generator systems is the investment costs involved. However, the differences in cost of the different generator types are almost completely hidden within the overall cost of the electrical equipment in completed turbines which largely explains the often contradictory statements about the costs of the electrical systems of the wind turbines. This makes it difficult to obtain a precise cost comparison for the various generator systems. In addition, it must be taken into consideration that higher investment costs, for example for a variable-speed generator system with inverter, do not in any way lead to poor economics, i.e. higher power generation costs.

Maintenance and reliability

Different types of systems have differing maintenance requirements. The controllable variable-speed generators have slip-ring rotors and, therefore, require somewhat more maintenance than smaller induction generators with squirrel-cage rotors. Furthermore, the switching elements of the static converters are components requiring special servicing. On the whole, however, the maintenance work for the electrical system will be less significant than that for the mechanical components of the turbine and will therefore not represent a primary decision criterion.

However, this assessment should not lead one to conclude that the electrical and electronic equipment of a wind turbine is entirely without its problems from the point of view of maintenance and reliability. Past experience shows a different picture, at least for the time being. Electronic faults, mainly due to software 'bugs', account for a disproportionately high number of failures (see Chapt. 18.9).

10.3 Fixed-Speed Generator Systems

The majority of the smaller, older wind turbines is still equipped with generators which are coupled directly to the grid. In some cases, even today, cost considerations led to a preference for this concept in spite of considerable disadvantages for the aerodynamic operation of the rotor and the dynamic loads on the mechanical drive train components. It is only in recent years that with the progress in static converter technology, the indirect grid coupling with its advantage of variable speed operation of the generator has allowed this solution to become a serious and economically viable alternative.

10.3.1 Synchronous Generator Directly Coupled to the Grid

From the point of view of dynamic behaviour on the grid, coupling a synchronous generator directly to a fixed-frequency grid represents the "hardest" case and is thus an extreme case among the technical possibilities (Fig. 10.17). The advantages of this solution are its simplicity and compatibility with today's standard generator technology for feeding the three-phase grid. Moreover, the reactive power can be controlled very easily via the direct current excitation of the rotor. Isolated operation of a synchronous generator is possible without any additional equipment for reactive-power compensation. These advantages, however, are balanced by a series of grave disadvantages. Only very small load angles are possible for compensating for the dynamic loads imposed upon the generator by the wind rotor. Large load surges, for example due to strong gusts, can cause a loss of synchronisation. The synchronous generator, in response to even small load peaks (for example tower shadow in the case of a downwind rotor, or even frequency fluctuations on the grid), tends to produce oscillations which are only poorly damped. It is mandatory to take into consideration the "generator-grid's" characteristic frequencies in the dynamic behaviour of the grid-coupled turbine (see Chapt. 7.2.2).

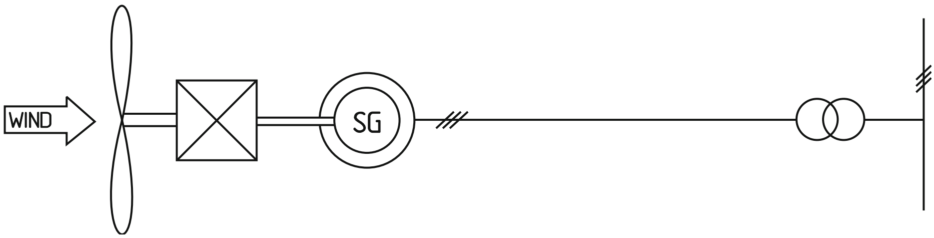

Fig. 10.17. Synchronous generator with direct grid coupling

In addition, difficulties arise with synchronisation to the grid, necessitating complex automatic synchronisation equipment. The stiffness of the direct grid coupling results in a highly uneven power output of the wind turbine. Every wind fluctuation captured by the rotor is passed on to the grid without any smoothing.

Apart from difficult operating characteristics, the direct coupling of a synchronous generator to the grid results in high dynamic loads being imposed on the mechanical drive train. The American wind turbines of the first and second generation (MOD-0, MOD-l and MOD-2), for example, had synchronous generators which were coupled directly to the grid. The MOD-0 turbines were equipped - in some cases retrofitted - with fluid couplings in the mechanical drive train, in order to achieve better damping and smoother power output (Chapt. 9.9). The torsionally compliant but undamped rotor shaft of the MOD-2 also proved to be inadequate to attain complete mastery over the dynamic problems.

Successful use of a synchronous generator can, therefore, be achieved only with complex compliance and damping arrangements in the mechanical drive train. This requires a torsionally compliant and damped transmission, or, even better, a hydraulic slip coupling between gearbox and generator (see Fig. 9.47). Apart from those measures in the mechanical drive train an active electrical damping system in the generator itself has been proposed [4]. This requires an extra field winding which would be controlled actively. But in view of the advances made in variable-speed generator systems, coupling a synchronous generator directly to the grid is no longer a serious alternative in wind turbine technology. Regardless the problems mentioned before, some very recent developments use a direct grid-coupled synchronous generator in combination with a variable-speed mechanical transmission (s. Chapt. 9.10).

10.3.2 Induction Generator Directly Coupled to the Grid

Induction generators coupled directly to the grid have been successfully used in wind turbines for decades (Fig. 10.18). Particularly in combination with the stall-controlled three-bladed wind rotors of Danish turbines, they initially represented by far the most commonly used electrical concept. The squirrel-cage rotors used in smaller systems are unsurpassed with respect to cost and low maintenance and do not require a complicated blade pitch control arrangement.

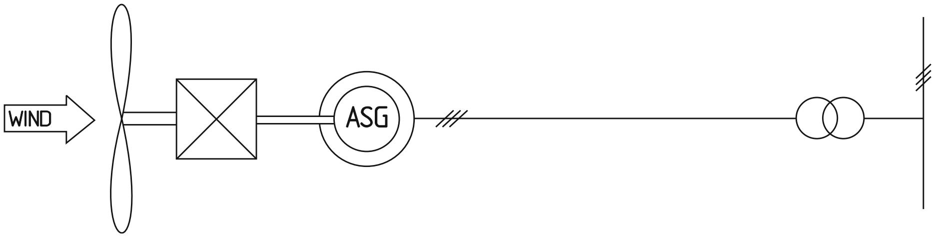

Fig. 10.18. Induction generator with direct grid coupling

Small induction generators have comparatively high nominal slip values which provide sufficient compliance to the grid. They can, therefore, be synchronised to the grid without field excitation and without elaborate synchronisation measures in the range of its synchronous speed.

In larger induction generators without special devices, however, the "inrush current" is in most cases unwanted. More recent turbines, therefore, have "soft grid coupling". After the generator has reached synchronous speed, it is initially connected to the grid via a thyristor controller with *phase-angle control.* This limits the inrush current to about 1.5-times the nominal current. After 1 to 2 seconds, the thyristor controller is bypassed by the line contactor. However, the phase-angle control produces a brief but relatively strong 5th-order harmonic.

The reactive power requirement of an induction generator depends on its power output. The reactive current increases with output, starting from a magnetising current needed for idling. Thus, various stages are required for more or less complete reactive-power compensation depending on the requirements. One set of permanently connected capacitors can only provide static compensation for one operating point. Discrepancies must be made up from the grid or the compensation has to be provided incrementally by means of a set of switchable capacitors.

If the reactive-power consumption is to be kept as low as possible, further improvements can be achieved by special idling compensation. In some cases (isolated operation) a rotating phase shifter, a synchronous machine with voltage or reactive-power control, may be installed.

In large wind turbines in the megawatt power range, however, the use of directly grid connected induction generators is not undisputed. Large induction generators are designed with a small nominal slip in favour of high efficiency. With respect to its grid-coupled operation, the behaviour of such a generator does not differ much from that of a synchronous model. Wind fluctuations are passed on to the grid almost as unsmoothed as with a synchronous generator. Although its oscillatory characteristics are less problematic, the dynamic loads imposed on the wind turbine are also high.

An improvement can only be achieved via a higher nominal slip value. This, however, is in conflict with efficiency, generator weight and cost. Nevertheless, the nominal slip of an induction generator can be manipulated to a certain extent. There are various methods to increase slip. The most obvious possibility is designing the rotor for a higher slip values. The example of an induction generator with a rated power of 1200 kW shows to what extent this affects efficiency (Fig. 10.19). Overall generator mass also increases with increasing nominal slip (Fig. 10.20). Up to a nominal slip of a few percent, the increase in cost is not so serious, if it is kept in mind that the generator itself constitutes only a small part of the cost of the total electrical system.

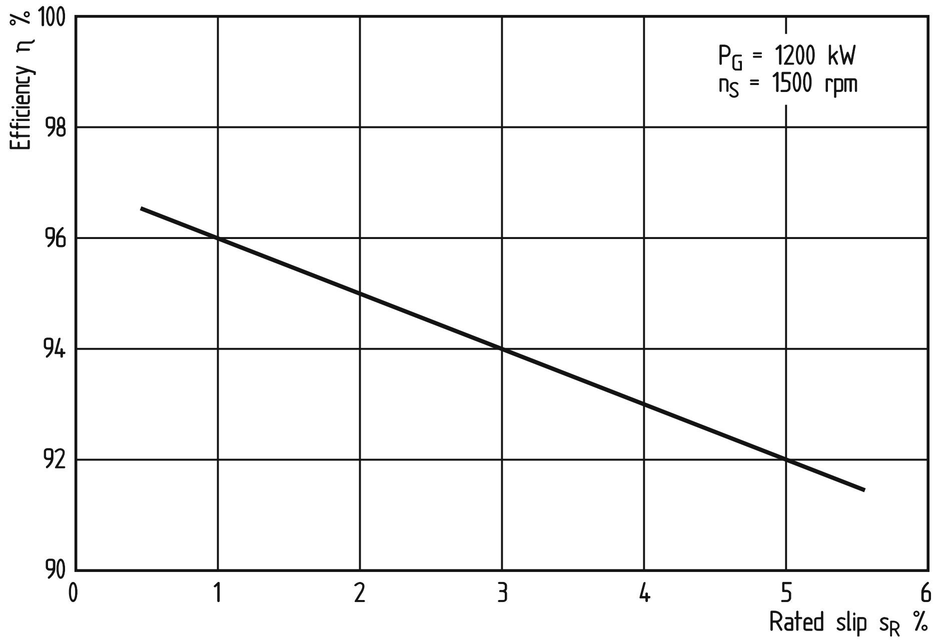

Fig. 10.19. Efficiency of an induction generator as a function of rated slip [9]

One disadvantage of induction generators with increased slip which must not be ignored is the problem of heat dissipation. Generator cooling and with it the entire cooling air ducting system in the nacelle must be designed for a higher throughput.

Seen overall, a generator design with a nominal slip of 2 to 3 % should represent a feasible compromise for providing a minimum amount of speed compliance with justifiable additional expenditure and loss of efficiency. On the other hand the variable speed systems including a frequency converter is the more advanced concept. The costs of the inverters have been reduced in the recent years whereas the efficiency could be increased considerably. Induction generators with a larger slip only are an option for small wind turbines, where a frequency inverter is considered as to sophisticated and to expensive.

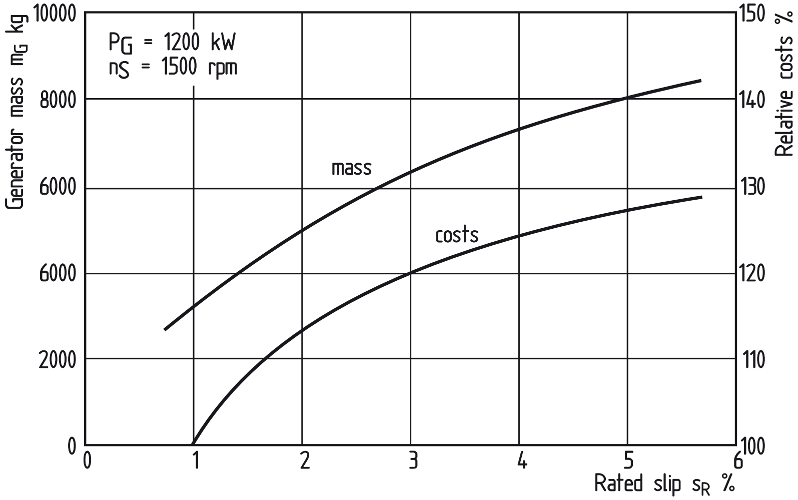

Fig. 10.20. Mass and relative cost of an induction generator as a function of rated slip [9]

10.3.3 Variable-Slip Induction Generator

The slip of the induction generator provides the opportunity for implementing greater speed compliance. To do this, external resistors can be connected into the rotor circuit which normally requires a slip ring rotor. The external resistors will only be connected in order to produce the desired slip when the load on the wind turbine becomes high. Using external resistors instead of a rotor with higher slip also creates somewhat simpler conditions for cooling the generator (Fig. 10.21).

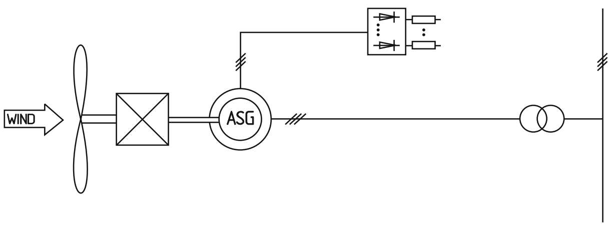

Fig. 10.21. Grid-coupled induction generator with external resistors for slip control

Some types of Vestas turbines, for example, have such a dynamic slip control system which is offered under the name "Optislip". The resistors are softly connected into the rotor circuit of the induction generator, thus providing for a speed compliance of approximately 10 % under turbulent wind conditions. As a special feature, co-rotating rotor resistors and control unit are mounted on the shaft of the generator which does away with the need for a slip ring rotor (Weier design). Quite generally, however, these solutions give rise to the question whether it wouldn't be more economic to use a variable-speed generator with inverter. Moreover, the loss of power is to be considered.

Although the average loss of electrical efficiency in operation is clearly less than at the maximum point, it is still within a range of 2 to 3 % on average.

10.3.4 Multi-Speed Generator Systems

To obtain an improved adaptation of the rotor speed to the wind speed, multi-speed operation can be considered. Generally, two constant speeds will be chosen, the lower one of which will be used for partial load conditions, i.e. when wind speeds are lower. It is true that this method of speed stepping is no replacement for speed variability, as it does not improve the dynamic characteristics. But with two fixed speeds, the rotor's energy yield can be increased somewhat, and the noise emission of the turbine under partial load operation can be reduced. There are various possibilities of implementing a stepped-speed rotor by electrical means, today mainly used in smaller turbines. But for the same reasons as mentioned in the previous chapter the multi-speed generator systems have been displaced by the variable speed generator systems at large turbines.

Dual generator

Older Danish wind turbines are frequently equipped with two generators, of which the smaller one, with lower speed, is used during low-wind conditions. Apart from the more advantageous rotor speed, an improvement in the electrical efficiency under partial load, and a more favourable power factor, owing to the lower reactive-power requirement of the smaller generator, is achieved (Figs. 10.22 and 10.23). In most cases, the turbines have a three-bladed rotor without pitch control. The second, larger generator is sized to the rated power to meet the requirements of the stall-controlled rotor to provide enough generator torque to keep the generator on the grid (s. Chapt. 5.3.2).

Naturally, the greater expenditure, not only for the two generators and the more complex gearing but also with regard to control and operation, is a disadvantage. In the case of large, aerodynamically controlled turbines, the use of two generators can be justified only if difficult situations involving isolated grid operation have to be coped with. In turbines in the megawatt power range, neither the drop in efficiency under partial load nor the reactive-power requirement are sufficient reason to justify the expense of a dual generator system.

Pole-changing generator

A basically simple solution is the use of a pole-changing induction generator. These generators have two electrically isolated windings in the stator with different numbers of poles. Normally, 4 and 6 poles or 6 and 8 poles are paired. The speed ratio is correspondingly 66.66 % to 100 % or 75 % to 100 %. The generators are much more expensive compared to standard generators, and their efficiency is slightly lower when operating at the lower speed (Fig. 10.24). The advantages of stepped-speed operation are, therefore, questionable, even with pole-changing generators, but it might be useful in areas of poor wind conditions.

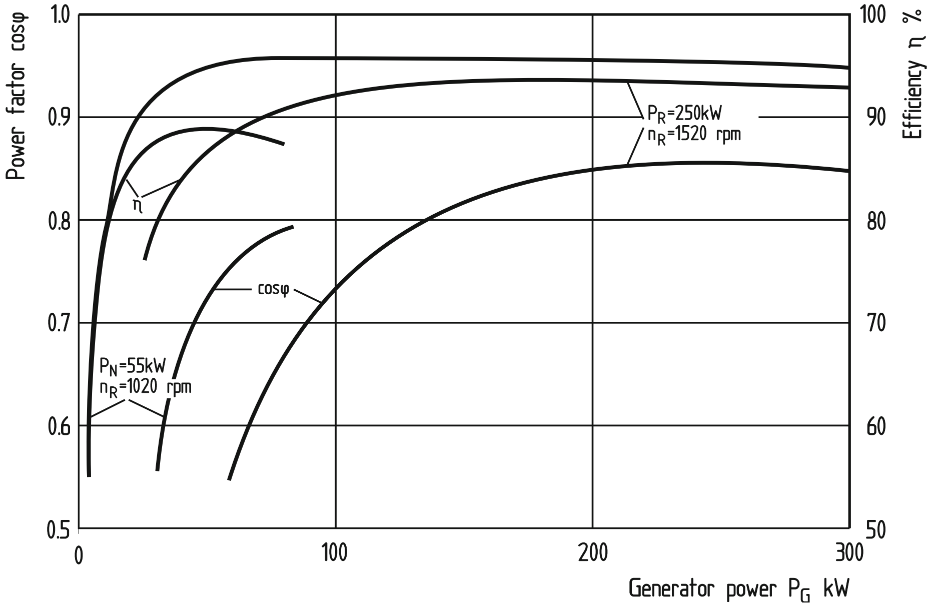

Fig. 10.22. Rotor power coefficient of the Volund turbine [10]

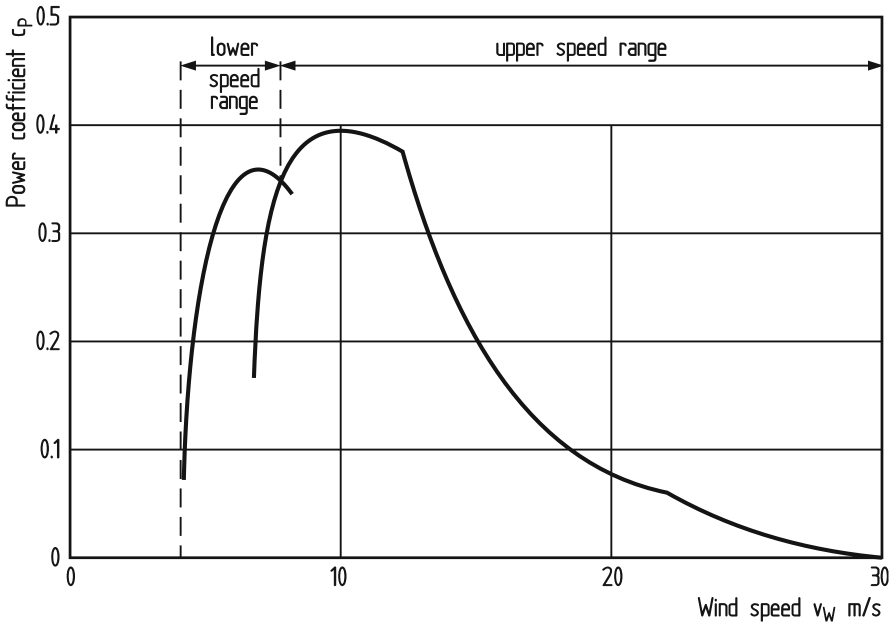

Fig. 10.23. Electrical efficiency and power factor of the prototype of an earlier Volund experimental wind turbine with two induction generators [10]

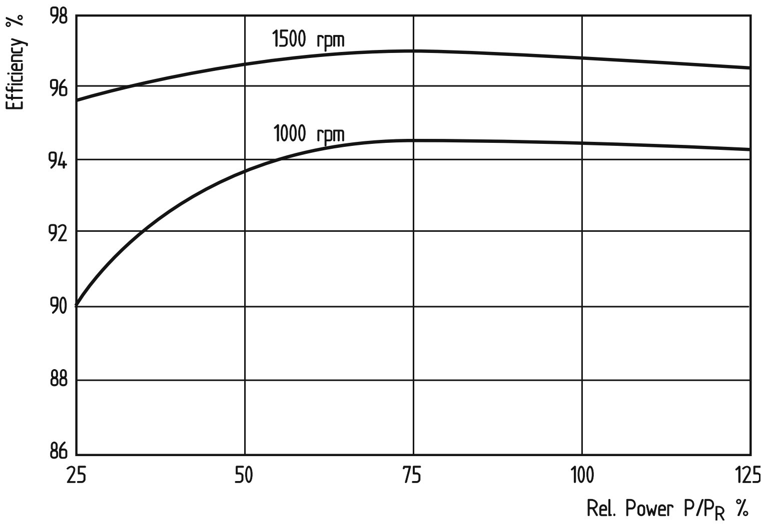

Fig. 10.24. Electrical efficiency of a pole-changing induction generator (rated power 750 kW) [11]

10.4 Variable Speed Generator Systems with Inverter

Controlled variable-speed operation of a wind rotor is only possible with an electric generator which is operated with a downstream inverter. An alternator operated with variable speed inevitably generates alternating current with varying frequency. The latter can only be adjusted to the required constant grid frequency by the inverter. Inverter technology is expensive and causes losses of efficiency. But apart from reducing the dynamic loads considerably, it permits an operation of the wind rotor which meets the requirements of its specific aerodynamic properties better than operation at constant speed. Generator-inverter systems are, therefore, used more and more.

Conventional generator technology supplies few models for this. Prime movers such as steam turbines or diesel engines do not require variable-speed generators. Variable-speed generator systems are only used in some special cases of application. In large ocean-going ships variable-speed generators with inverters and driven by a propelling shaft have been in use for about a decade [12]. The use of these "shaft generators" on ships has mainly economic reasons. If the generator is driven by the ship's propelling shaft and thus by the ship's main diesel engine, the electric energy is generated by cheap heavy fuel oil. The speed of the propeller shaft varies, however, especially in ships without variable-pitch propeller, so that the variable-frequency three-phase current generated must be converted to a constant frequency by an inverter for feeding the on-board power system.

In electric drive technology, variable-speed motors, needed for many different purposes, could not be implemented without inverters. In some cases these concepts represent the starting point for the development of variable-speed generator systems for wind turbines.

A variable-speed generator system can be implemented both on the basis of a synchronous generator or by using an induction generator. While in the synchronous generator, all the current generated must be converted, the induction generator offers slip as a starting point. The power loss (slip power) can be fed back into or added to the power output flow from the stator by means of suitable inverters. In this way, only a part of the electric power generated needs to be sent through the inverter. However, this implementation requires a slip ring rotor, which is associated with higher costs and more maintenance.

Today, variable-speed generator systems are the preferred design for large wind turbines, making the frequency inverter into an essential, component for a wind turbine with variable rotor speed. For this reason it is necessary to deal with some of the fundamental terms of static converter technology and the characteristics of the various designs of frequency inverters.

10.4.1 Frequency Inverters

As has already been pointed out in Chapter 9.1, it cannot be the task of this book to provide a fundamental introduction into generator engineering or into static converter engineering. This must be obtained from the relevant technical literature [13]. Nevertheless, some terms from static converter engineering will be presented here and the most important features of the frequency inverters currently used will be explained to the extent to which they play a role in the technology of wind turbines.

Technology

Modern inverter technology is based on the use of semiconductor components. These are used as so-called *converter valves* which only pass electrical current in one direction. They are periodically alternately put into an electrically conductive and non-conductive state and therefore also act as switches. The switching actions are very fast, within the microsecond range since they do not require any mechanical processes. In the simpliest case the function of a converter valve is fulfilled by a diode. They are continuously conductive in one direction and block the current in the opposite direction. However, they cannot be controlled from the outside. Inverters based on simple diodes cannot be considered for greater powers and do not, therefore, play any role in the power electronics for wind turbines.

In the case of controllable converter valves, so-called *thyristors*, it is possible to determine the time of conductivity. This process is called "ignition". Thyristors are manufactured in various types which have different control facilities, e.g. as so-called *gate turn-off* (GTO) or *integrated gate-commutated transistors* (IGCT). The introduction of thyristor technology resulted in a breakthrough of inverter technology into power electronics in many fields of application. Frequency inversion became possible without great losses even in the megawatt range.

The inverters of the older wind turbines were based on thyristors. These inverters need reactive current from the grid so that corresponding compensation devices became necessary. The harmonics generated, too, had to be suppressed as far as possible by means of relatively elaborate filters so that feeding into the grid was possible without too many problems. The problem of harmonics existed mainly in the case of the older inverters which were still operating in a 6-pulse mode. The number of pulses is determined by the current transitions (commutations) from one converter valve to another within one period. It is an essential characteristic of static converter circuits. Modern inverters operate with a 12-pulse circuit in three-phase systems which provides a much better approximation of the sinusoidal shape of the alternating current and largely dispenses with harmonics.

The most recent stage in the evolution of static converter technology is characterized by the use of transistors. Transistors require virtually no reactive power and have even better switching capabilities. They represent today's "state of the art" as so-called *insulated gate bipolar transistors*, (IGBT inverters). These inverters have virtually displaced the GTO inverters and are therefore also found increasingly in wind turbines.

Types of design

Independently of the semiconductor elements used, inverters are implemented in various types of design (Fig. 10.25).

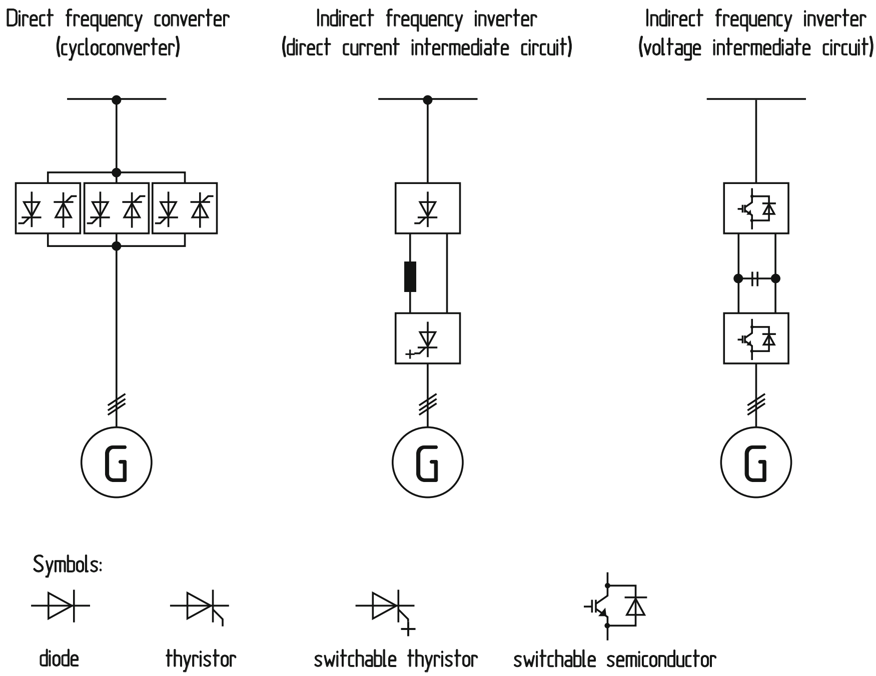

Fig. 10.25. Types of inverter system designs [14]

Using converter valves, so-called *cycloconverters* select certain voltage segments from the three phases and reassemble them so that a new frequency is produced. This type of design can be applied only up to a limited frequency ratio and requires great complexity in semiconductor elements and control technology. These inverters are no longer of significance in wind power technology.

Inverters with a *DC link circuit* consist of a rectifier which converts the frequency supplied into direct current, and an inverter which generates the desired frequency. The inverter frequency is controlled by the given grid frequency on the grid side *(line-commutated inverters).* In isolated operation, *self-commutated frequency inverters* are required, but these are much more complex and expensive. The link circuit inverters can be controlled in various ways and completely decouple the frequency generated by the generator from the grid frequency which is why inverter systems with DC or voltage link circuit are now being used almost exclusively for wind turbine installations. The transistor-based frequency inverters are implemented with a voltage link circuit. They also operate with a pulse modulation method, the *pulse width modulation* (PWM) which results in an almost perfect approximation of the ideal sinusoidal wave shape of the transformed frequency.

IGBT inverters with pulse width modulation in 12-pulse mode thus represent the last stage in inverter technology for the time being. In most cases they are located in the tower base of the wind turbine (Fig. 10.26).

Fig. 10.26. IGBT inverter, 2 MW rated power, in the tower of an ENERCON turbine (Enercon)

10.4.2 Synchronous Generator with Inverter

Variable-speed operation of a synchronous generator is usually effected via an inverter with DC link. The variable-frequency AC from the generator is rectified to DC and then fed into the grid via an AC inverter (Fig. 10.27).

This concept provides for a wide speed range as the DC link circuit results in complete decoupling of the generator speed, and thus of the rotor speed, from the grid frequency. This wide speed range permits an effective wind-oriented rotor operation so that a noticeable increase in its aerodynamics-related energy yield can be achieved. It almost goes without saying that this concept completely eliminates the disagreeable dynamic characteristics of synchronous generators coupled directly to the grid.

The generator torque can be controlled by controlling the DC link circuit. However, this can lead to undesirable low-frequency beat oscillations in the DC link, making it more difficult to control the system. The shaft generators on ships, therefore, frequently have synchronous generators without damper windings, enabling the system to be controlled more rapidly.

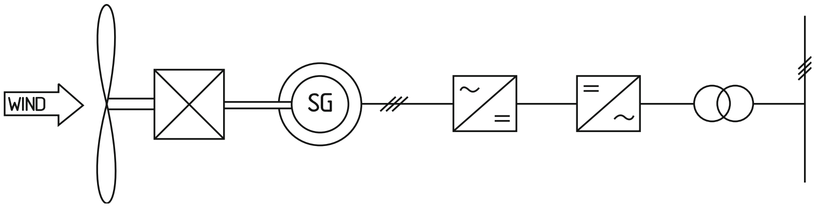

Fig. 10.27. Synchronous generator with DC link (rectifier and inverter)

The synchronous generator with inverter also offers further operational advantages. Without much additional expenditure, the rotational speed of the wind turbine can be accelerated with the generator used as a motor and decelerated with the generator used as an electrical brake. In contrast to induction generators, electric braking in case of a grid failure can be implemented very easily by means of an ohmic resistor. In addition, there are no problems with grid synchronisation or with inrush current on start-up.

In the earlier designs the reactive-power requirement of the system was considerable. The power of the earlier inverters necessary for control and commutation was high. Moreover, older and simpler inverters produced unwanted perturbations on the grid due to their harmonic frequencies. If the reactive-power requirement was to be completely compensated for and the harmonic frequencies are to be filtered out, the technical complexity increased markedly. Another important argument against the synchronous generator with a DC link was, apart from high costs, was poor overall electrical efficiency. As the total electric power output flows via the inverters, efficiency is basically lower than in variable-speed generator designs which use the inverter only in the rotor circuit of an induction generator.

For these reasons, the synchronous generator/DC link system was not the system of first choice for variable speed generator systems. Technical solutions based on an induction generator are more cost effective and have a somewhat better efficiency.

In the last years the situation has been changing. The technology of the inverter systems has improved so much, that the conversion of the total power via an inverter is not longer disadvantageous. The troublesome harmonics of the older inverters are virtually completely eliminated using pulse-width-modulated inverters. Therefore the favourable characteristics of the synchronous generator can also be used in wind turbines. The only disadvantage are the costs for the full power inverter.

In the case of the gearless drive train concepts the low-speed generators are built as synchronous generators in nearly all cases.

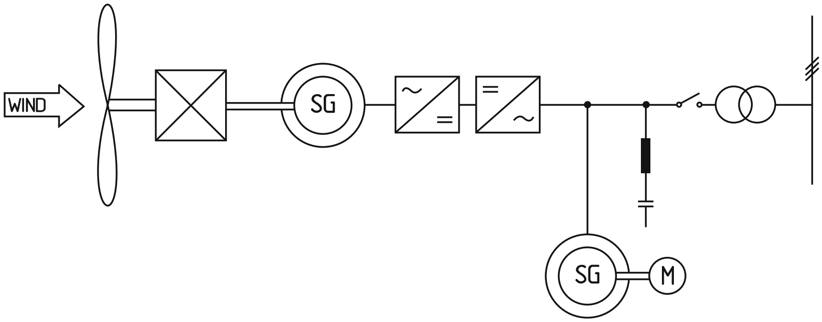

Fig. 10.28. Electric generator system of the WKA-60 wind turbine with synchronous generator and static inverter including rotating phase shifter and harmonic frequency filter for use in a weak island grid (AEG system)

A particularly complex development in this field was the electrical system of the WKA-60 wind turbine which was capable of isolated operation (Fig. 10.28). Here, too, a synchronous generator with a static converter, which had been derived directly from the shaft generator of a ship, was used. The turbine was installed on the German island of Heligoland. For the first time, a large wind turbine with a rated power of 1200 kW was operated in the comparatively small island grid with a maximum load of about 3000 kW. The main power source in this grid are two diesel generators each with 1800 kW of power output [9].

The generator system of the wind turbine had been designed for a relatively wide speed range to achieve extensive smoothing of the power output. Smoothing of the power output was necessary to facilitate the control interaction with the diesel generators. In addition, the wind turbine had been equipped with a rotating phase shifter, which provided for complete reactive-power compensation over the whole power output range. The harmonics produced by the inverter were largely filtered out. Thus, the technical complexity and the costs for such a variable-speed generator system with full isolated-operation capability were considerable.

10.4.3 Induction Generator with Oversynchronous Cascade

Another possibility for implementing a variable-speed generator is to influence the slip in the induction generator, as already mentioned. If it is possible to make use of the slip power, normally lost, the turbine can be operated over a larger speed range without great losses in efficiency. Feed-back requires a simple link circuit consisting of an uncontrolled rectifier and a line-commutated AC inverter (Fig. 10.29). This concept, however, only permits power delivery from the rotor via the static converter to the grid, a verse flow of power is not possible because of the uncontrolled rectifiers. The generator can, therefore, only be operated in the oversynchronous mode. The electric torque can be influenced by changing the current in the DC link. This configuration is known as subsynchronous converter cascade in electrical drive technology and is used in controlled-speed drive units. In the generator configuration, this is an oversynchronous cascade.

A considerable disadvantage of previous oversynchronous cascades was the high reactive-power requirement. The reactive-power requirement of the converter can be limited by restricting the speed range. The economic speed range is thus restricted to approximately 100 to 130 % of the nominal speed. Another disadvantage of the older systems hitherto built is the relatively high proportion of unwanted harmonics passed on to the grid. Up to now, very few large wind turbines have been equipped with an oversynchronous converter cascade, for example the Spanish AWEC-60 experimental turbine, which was derived from the German WKA-60 [15].

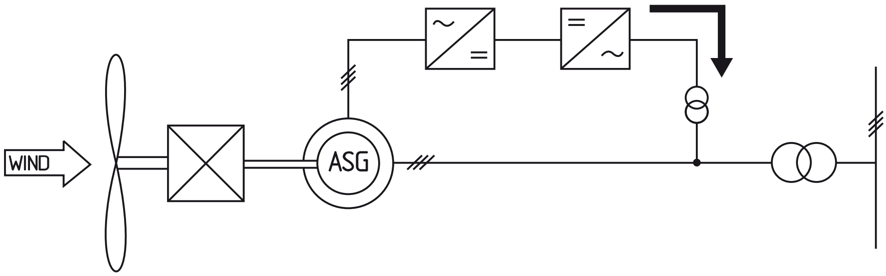

Fig. 10.29. Oversynchronous converter cascade for variable-speed operation of an induction generator

10.4.4 Double-Fed Induction Generator

The *double-fed induction generator* (DFIG) as a variable-speed system was implemented for the first time in the large experimental Growian wind turbine (Fig. 10.30). In contrast to the oversynchronous converter cascade, the slip power of the induction generator is not only fed into the grid, but, conversely, the rotor is also supplied with power from the grid. In this way, both oversynchronous and subsynchronous operation of the generator is possible.

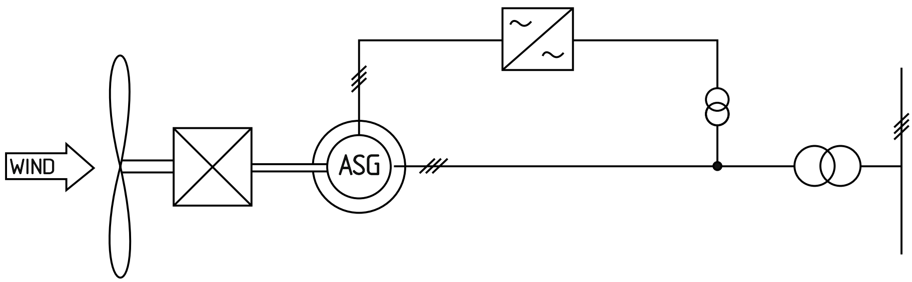

Fig. 10.30. Double-fed induction generator with cycloconverter of the experimental Growian wind turbine

The frequency generated by the inverter is superimposed on the frequency of the rotating field of the rotor, so that the resulting superimposed frequency remains constant, regardless of the rotor speed. A cycloconverter was selected as inverter for the experimental Growian turbine. The speed range is determined by the frequency being fed into the rotor. If a cycloconverter is used as inverter, the frequency deviation is restricted to approximately ± 40 % of the nominal speed. Since inverter power increases with the speed range, a considerably smaller range was selected for Growian. The chosen speed range of ± 15 % was primarily intended as "speed elasticity" to reduce the dynamic structural loads on the wind turbine and to smooth out the power.

The double-fed induction generator can be operated in the over- or sub-synchronous speed range, as a motor or as a generator (Fig. 10.31). In the normal operating range, it behaves like a synchronous machine. By controlling the magnitude and phase of the AC in the rotor circuit, any desired reactive or active current can be set, i.e. the generator can be operated with any power factor required.

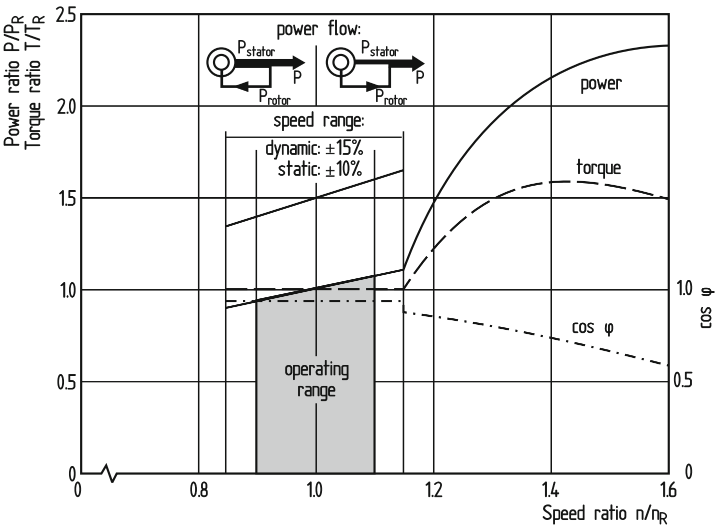

Fig. 10.31. Operating modes of the double-fed induction generator of Growian [16]

These different operational modes require a complex control system which is particularly in evidence in the switching and control arrangements for the inverter. On the other hand, the controlled double-fed induction generator combines the operating advantages of both the synchronous and the asynchronous machine. Apart from variable-speed operation, it offers the special advantage of separate active- and reactive-power control. A further advantage of the double-fed generator is associated with the fact that only about a third of the nominal generator power flows via the rotor circuit, i.e. via the inverter. As a result, the inverter becomes much smaller than e.g. in the case of the variable-speed synchronous generator where all the power is converted. This reduces the costs and the loss in efficiency due to the inverter.

The first models of this design (Siemens), for the Growian turbine and somewhat later for the American MOD-5 turbine on the island of Hawaii, were still complicated and correspondingly expensive but the operating experience was good right from the start. For years, however, this electrical concept was not pursued further because of the high costs involved and was only taken up again by a number of generator manufacturers towards the middle nineties.

In recent years, the double-fed induction generator has been developed further and simplified. Today, it is being offered as off-the-shelf generator system and is used in many large wind turbines (Fig. 10.32). Instead of the cycloconverter, a so-called

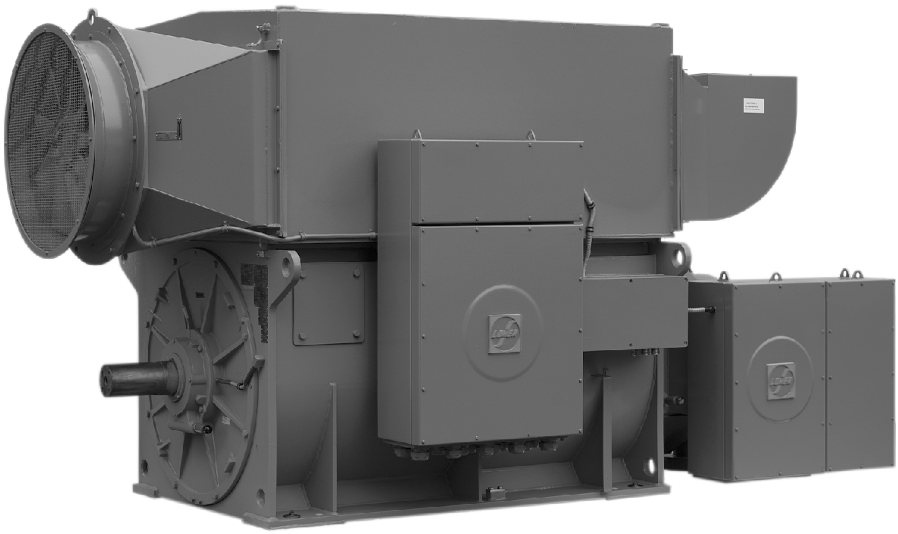

Fig. 10.32. Double-fed induction generator with 1.5 MW rated power (LOHER)

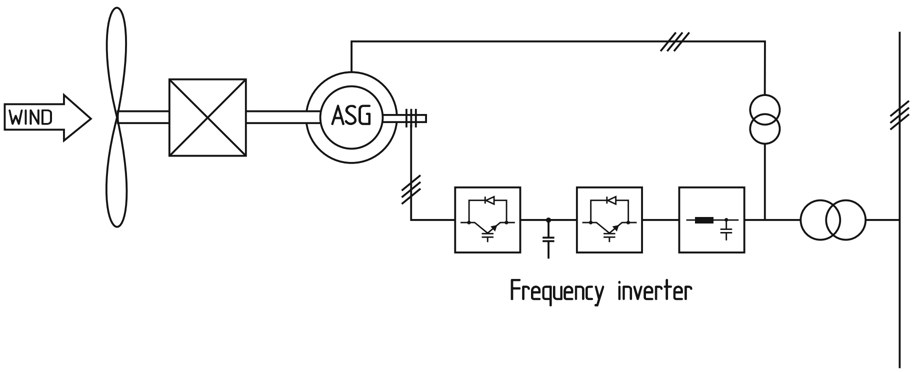

Fig. 10.33. Double-fed induction generator with cascade converter (LOHER) [17]

"cascade converter" with DC link, which is superior to a cycloconverter with respect to its control characteristics and speed range, is used today (Fig. 10.33). About 30 % of the total generated power flows via the inverter to the grid. Therefore the total efficiency of the system is only 1 to 2 % lower compared to a fixed-speed induction generator.

10.5 Directly Rotor-Driven Variable-Speed Generators

The idea of driving the electric generator directly from the rotor without intermediate gearbox is as old as modern wind energy technology. However, due to the slow rotor speed in large wind turbines, the generator requires such a large number of poles to reach the grid frequency that the generator diameter and weight assume unacceptable dimensions (see Chapt. 8.1). In the meantime, efficient and cost-effective inverters are available so that the generator itself no longer needs to generate the required grid frequency (Fig. 10.34).

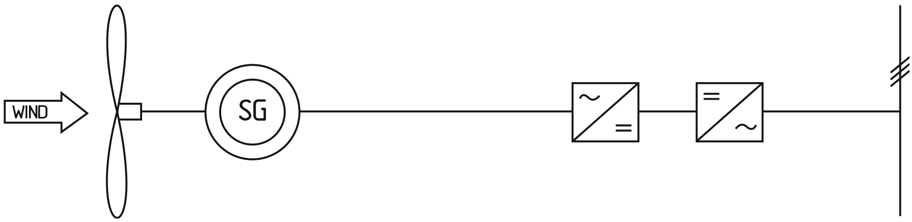

Fig. 10.34. Directly rotor-driven variable-speed synchronous generator with inverter

10.5.1 Synchronous Generator with Electric Excitation

The credit for having been the first to successfully implement the design of a direct-drive generator with inverter is due to the German manufacturer Enercon. The generator developed in the mid-nineties for the E-40 type is an electrically excited synchronous machine with 84 poles. Its diameter is approximately 4.8 m (Fig. 10.35). The nominal power of 500 kW is reached at a speed of 38 r.p.m.. The usable speed range is between 20-40 r.p.m.. The generator generates a frequency of 16 ⅔ Hz at the nominal operating point, which is then converted to the grid frequency of 50 Hz by the inverter. Electrical efficiency of the generator with inverter is specified as approx. 0.94 at maximum economical rating and is almost constant over the operating range.

The input to the grid is effected via a DC link circuit with an inverter which has virtually no harmonics. The output voltage is already at a medium-voltage level (20 kV) so that no separate transformer is necessary if a medium-voltage system is being fed. The control system offers several adaptive options, which facilitate operation on weak grids. Power limitation depending on grid voltage fluctuations prevents inadmissible voltage peaks in the grid. As in all synchronous generators, reactive-power output, i.e. cos φ, is regulated. In addition, it is possible to set the minimum and maximum frequency for operation on the grid. This grid-voltage- and frequency-controlled operation stabilises the grid frequency, which can be very important with weak feeders.

In the meantime, direct-drive generators of this design are used in all Enercon turbines of up to 6 MW and proved worthwhile. But only few manufacturers have adapted the concept of direct driven generators with electric excitation (Lagerwey, Torres).

Fig. 10.35. Direct-drive multi-pole synchronous generator of the Enercon E-30

The concept of a generator driven directly by the rotor has become a serious alternative to the standard design of a high-speed generator with gearbox. Nevertheless, its disadvantages must not be overlooked. As the size of the wind turbine increases, its assembly raises considerable problems. Maintaining an accurate air gap between rotor and stator becomes a problem as the large-diameter stator can only be assembled from several ring segments. Moreover, it is not simple to cool the generator. Closed cooling systems as required for offshore installations are difficult to implement.

The heavy weight as well as the torque loading caused by the slowly rotating generator are of greater importance than the production and assembly problems. Both parameters have unavoidable negative consequences for the entire wind turbine. In comparison with the standard design, it is found that the gearless drive train with an electrically excited generator still has distinct weight disadvantages, particularly in the multi-megawatt models developed by Enercon (s. Fig. 19.8).

The series production of the extremely large ring-type generators with electrical excitation, i.e. wound poles, can be mechanised only with difficulty and requires much manual work (Fig. 10.36). Therefore manufacturing costs of this kind of electrical generators are high. Also with respect to a large amount of copper which is needed. The price for copper as well as for all kind of new materials are expected to rise in the future significantly.

Fig. 10.36. Production of synchronous multi-pole generators by Enercon (Enercon)

10.5.2 Direct-Drive Generators with Permanent-Magnet Excitation

The goal of reaching a more compact construction has moved especially the developers of direct-driven multipole generators for wind turbines to employ the permanent-magnet technology. An increasing number of manufactures are developing new turbines incorporating this technology. Some manufactures already are producing gearless wind turbines with permanent magnet generators in series production for example Vensys, Leitner of ScanWind in Norway. The Chinese company Goldwind produces large numbers of the Vensys 1.5 MW design since 2009 (Fig. 10.37).

But the first generation of direct-driven generators, particularly those with electric excitation had the disadvantage that the tower-head weight and the manufacturing costs were higher compared to the standard design including a gearbox. Certainly one could argue that the gearless design will have lower maintenance costs and probably also its service life is more advantageous. Some representatives of the latest generation of gearless turbines based on permanent magnet generators obviously can beat the standard design with respect to the specific tower head mass (Vensys 2.5 MW, Siemens 3.0 MW). Therefore this is a good reason for the hope, that the manufacturing costs will be competitive in the future as well (s. Chapt. 19). This statement would be undisputable if the prices of the raw material for the permanent magnet will not rise again. As long as China has a kind of monopoly for the material there will be a great uncertainty about the development of the future prices. Some people also refer to the environmental problems at the mining of these materials in China.

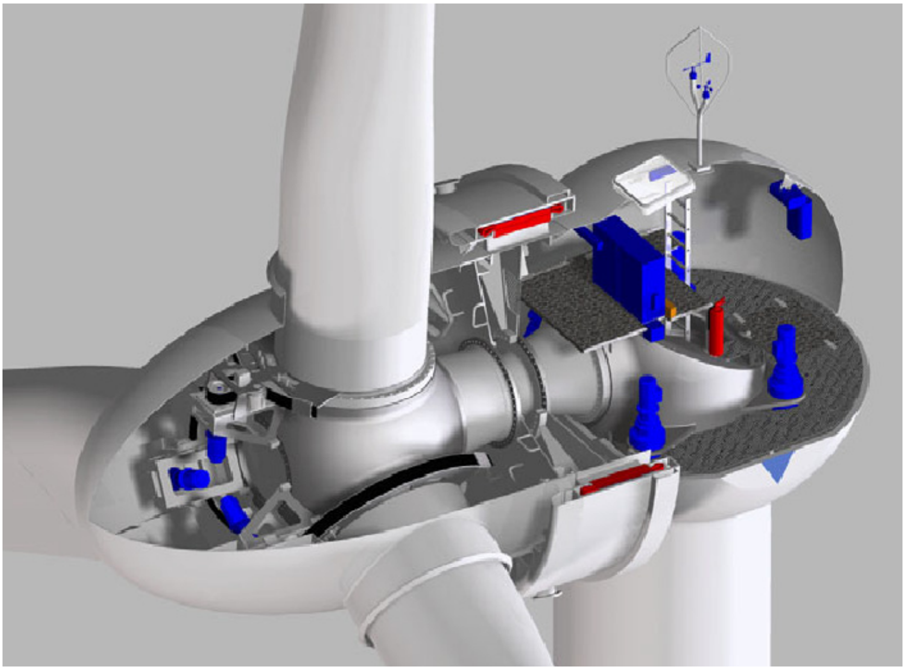

Fig. 10.37. Vensys 1.5 MW with direct-drive generator and permanent magnet excitation. The generator is built as outer rotor design.

Apart from the electrical characteristics, there is one further aspect to be observed in conjunction with the generator being driven directly by the rotor regardingless the kind of excitation. The bulky generator can only be integrated into the nacelle if the generator and the nacelle designs are completely matched spatially and statically. The generator mounting is at the same time also the rotor mounting. The bearing structure of the generator rotor thus becomes a part of the supporting nacelle structure which is why the generator can now only be designed mechanically in conjunction with the entire nacelle design (s. Chapt. 9). It is for this reason that the weight and the manufacturing costs of direct driven generator systems depends not only on the electrical part. The optimisation of the integrated electric and mechanical design concept is the road to success and remains a challenge for the designer.

10.6 Complete Electrical System of a Wind Turbine

From the electrical engineering point of view, wind turbines are electricity generating power plants, like hydroelectric plants or diesel-powered plants. Their electrical systems are similar and must meet the common standards for systems connected to the utility grid. This requirement mainly concerns the technical systems for safety, supervision and power quality. Moreover, the control system must be designed for fully automatic operation.

Although the electric generator is the heart of the electrical system, the complete system includes a multiplicity of electrotechnical and electronic equipment components. Apart from the general VDE safety requirements, the type and extent of the electrotechnical equipment also depends on the size of the wind turbine up to a certain degree.

In addition, the technical requirements set for the wind turbines by the power system operators are of significance. With the increasing number of wind turbines feeding into the interconnected grid, the supply conditions for parallel grid operation are becoming ever more strictly. Since 2003, it is especially the grid supply rules issued by E-on which have to be observed in Germany [1] (s. Chapt. 16.7.2). It is especially this set of regulations, which is also being adopted by other electricity supply companies, which determines the electrical equipment of today's wind turbines in numerous points.

10.6.1 Large Turbines

The complexity and extent of the complete electrical equipment depends to a certain degree on the generator system and the conditions of use. A turbine with a simple constant-speed induction generator operated in parallel with the grid requires less sophisticated electrical equipment than a turbine with variable-speed generator and inverter which must meet the requirements of isolated operation. Regardless of these differences, there is a certain basic electrotechnical complement as can be shown in the example of a turbine designed for variable-speed operation (Fig. 10.38).

Generator

In the example chosen, a series-production synchronous alternator with an output voltage of 690 Volt was selected. The 4-pole alternator has a nominal speed of 1500 r.p.m..

Inverter

The inverter with AC-DC-AC link also consists of off-the-shelf components but is customised for this special application. The rectifier is in the nacelle and the inverter is in the base of the tower. Today in the most cases the entire inverter system is located in the tower base. The inverter needs a cooling system, which also has to be accommodated in the tower.

Control and supervisory system

The control functions for power and speed control and the supervisory monitoring systems for the operational sequence are accommodated in a switch cabinet in the nacelle and a central control unit in the tower. In addition, the generator/inverter system has an internal control system which is integrated in the inverter.

Power supply for the control system

The instrumentation and control functions require a DC control voltage supply (24 V). There may also be a 220 V AC-voltage distribution system for the generator control system.

Medium-voltage distribution for the auxiliary services

The electrical supply for the numerous auxiliary drive units such as pumps, actuators etc requires its own supply system at low-voltage level, 220/400 V.

Power transmission

In current turbines, freely suspended torsionally flexible cables are used in the upper tower area. Twisting angles of up to 500 or 600 degrees are permissible with the appropriate lengths and fixings. For safety reasons, however, an automatic "untwisting" switch is necessary for when the permissible limit angle is reached.

Transformer

Most of the commercial wind turbines have their own transformer which changes the generator output voltage of 690 Volt or 6 kV to a medium-voltage level of 20 kV. The transformer of very large turbines can be installed in the tower base, but very often in a separate housing nearby the tower.

A feature of importance for its installation in the wind turbine is the cooling of the transformer. The older transformers are mostly cooled with special oil. These oil-cooled transformers are considered to be sensitive with regard to fire safety and can, therefore, not be installed in the nacelle, at least not in accordance with German regulations. They are in most cases housed in a separate container next to the tower.

In the meantime, however, dry-cooled transformers are being increasingly used, the windings of which are cast in resin. The design is more compact and less susceptible to fire hazards. Today, the cast-resin transformers are installed either in the rear part of the nacelle (e.g. Vestas) or in the tower base (e.g. Enercon).

At high ambient temperatures, however, cooling the cast-resin transformers is not without problems so that they cannot be used for some installation sites or a powerful and costly cooling system in the tower becomes necessary. On the other hand in most cases a cooling system in the tower is necessary due to the increasing number of electronic systems.

Reactive-power compensation

In wind turbines with induction generators, reactive power must be compensated for in accordance with the requirements of the relevant utility. This requires the provision of corresponding capacitors in the electrical system. In addition, the inverter emits harmonics which must be filtered out.

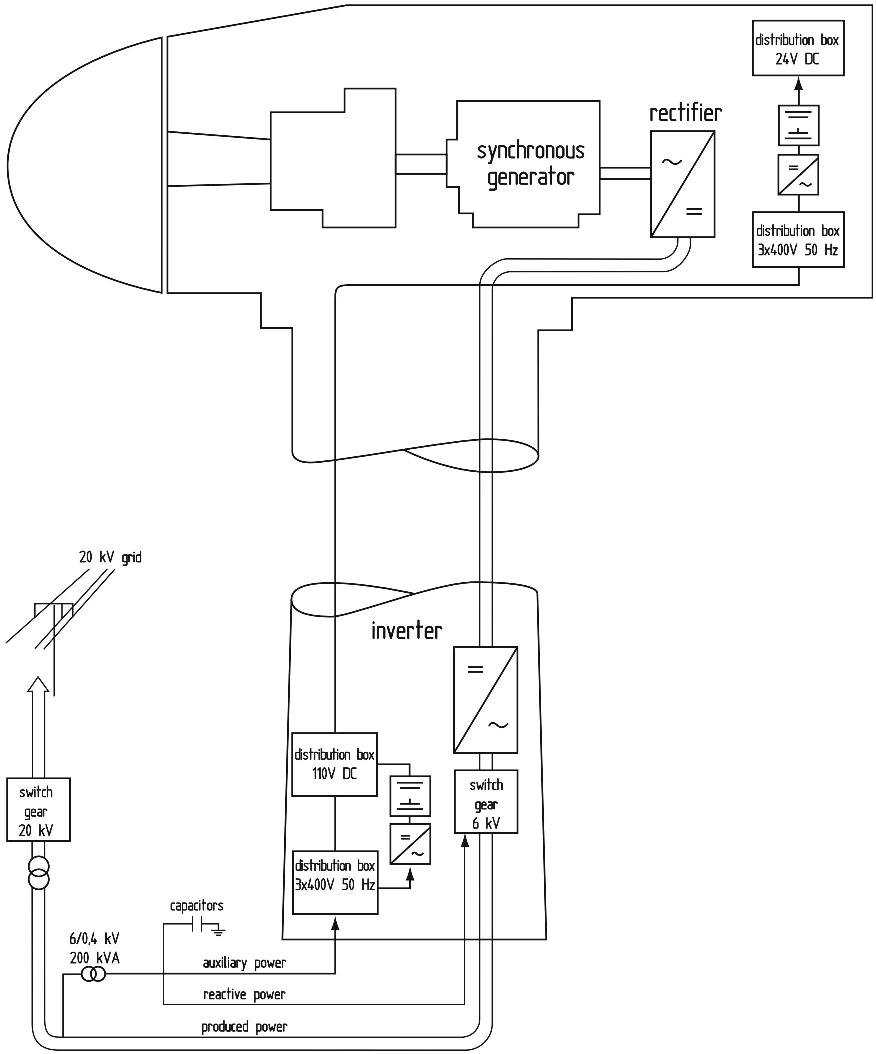

Fig. 10.38. Electrical system and equipment of a large wind turbine with synchronous generator and inverter

Electrical safety devices and lightning protection

The electrical safety devices include primarily the lightning protection system, the aircraft warning lights and a fire detection system. As the size of the wind turbines increased, a comprehensive lighting protection system was found to be indispensable and this is associated with a significant electrical installation. The aircraft warning lights are associated with a certain expenditure. Depending on the siting of the turbine, an ice warning device or even electrical resistance heating for de-icing the rotor blades may also be necessary (see Chapt. 18.8).

10.6.2 Small Wind Turbines

The electrotechnical equipment of small wind turbines must basically meet the same requirements as large turbines if they are used for feeding into the grid. However, turbines yielding some tens or hundreds of kilowatts commonly have electrotechnical solutions which overall result in much simpler systems. Above all, combining the electrotechnical and control-related equipment in one "switchbox", as is possible in small turbines, creates more favourable conditions for service and maintenance (Fig. 10.39).

Fig. 10.39. Switchbox of a small Aeroman wind turbine

Combining the general electrical equipment and electronic control system in compact form reduces the price both of component production as well as of the assembly of the electrical system, a considerable cost factor in large turbines. The switchbox is mounted at the foot of the tower, or also free-standing next to the turbine. The electrical system of a small turbine of the Aeroman type is shown in Fig. 10.40.

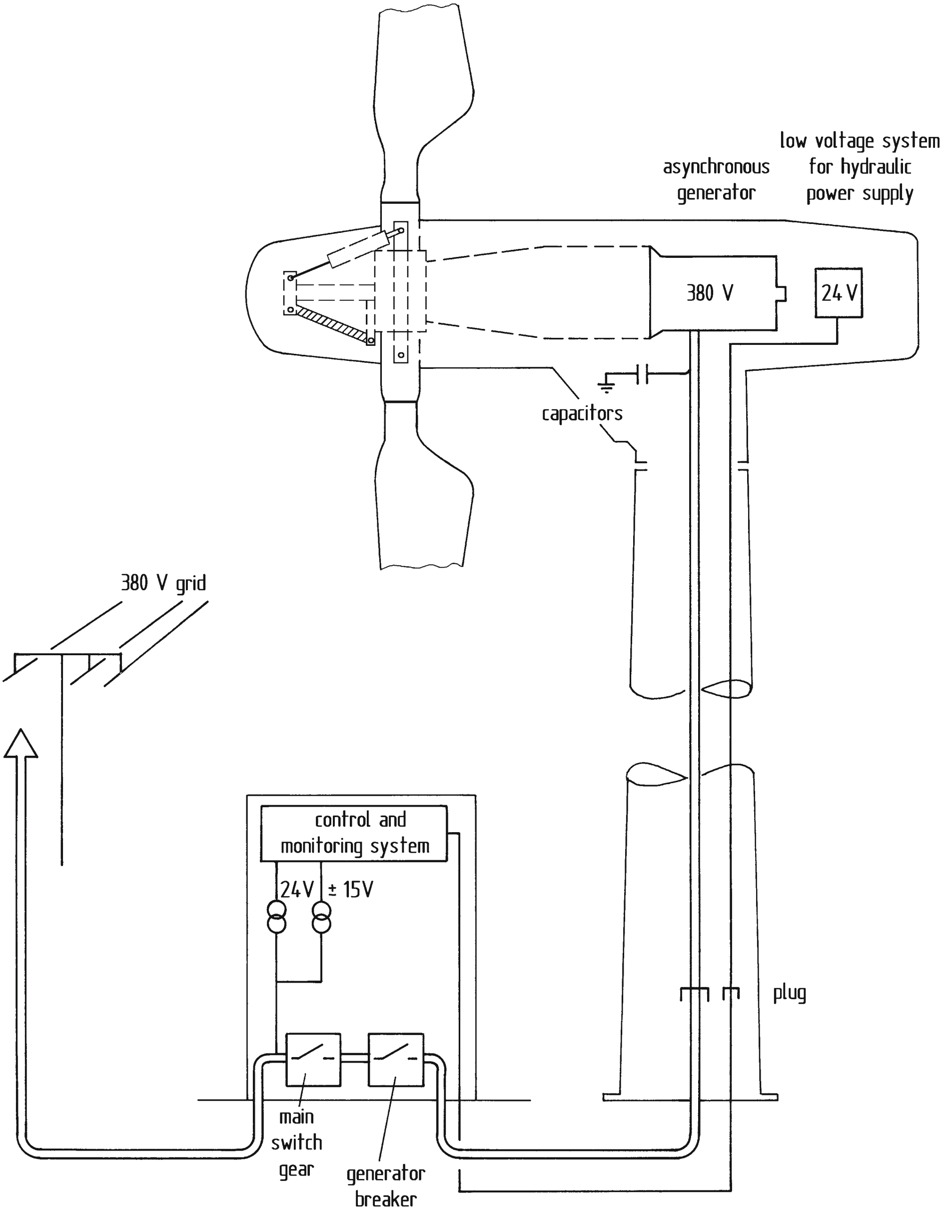

Fig. 10.40. Electrotechnical system of a small turbine of the Aeroman type

10.7 Comparison of Electrical Concepts

The fact that there are different electrotechnical concepts for wind turbines calls for a comparison. For several reasons, however, a quantitative comparison is not simple. For one, the advantages and disadvantages of the electrical concepts can only be assessed within the framework of the overall "wind turbine and its applications". Moreover, a complex electrical concept may indeed lead to a cheaper overall solution, if it is associated with advantages on the mechanical or operational side. Regardless of these difficulties and at the risk of being justifiably contradicted, some basic data are compiled in Table 10.41 in the sense of a comparative overview. However, the problems involved in such a comparison require some explanatory remarks:

Table 10.41. Electrical efficiencies and approximate cost ratio of electric generator systems of wind turbines in the 0.5 to 3 MW power range

System	Typical speed range	Maximum efficiency	Approx. cost ratio
Induction generator (squirrel-cage rotor)	100 ± 0.5 %	0.965	100 %
Pole-changing two-speed induction generator	100 ± 0.5 % 66 ⅔ ± 0.5 %	0.965 0.945	110 %
Induction generator with oversynchronous cascade	100 + 30 %	0.95	150 %
Double-fed induction generator with inverter (AC-DC-AC)	100 ± 50 %	0.955	160 %
Synchronous generator (electric excitation)	100 ± 0	0.97	110 %
Synchronous generator (permanent magnet excitation)	100 ± 0	0.985	120 %
Synchronous generator with inverter (AC-DC-AC), electric excitation, perm. magnet excitation	100 ± 50 %	0.945 0.96	250 % 280 %
Direct-drive synchronous generator with inverter (AC-DC-AC), electric excitation, permanent magnet excitation	100 ± 50 %	0.93 0.94	400 - 450 % 300 - 350 %

The comparison is based on a rated power of approximately 1500 kW. The numerical values should remain valid within a range of from approximately 500 kW to several megawatts. However, they cannot be applied to low outputs of less than 100 kW.

The above cost comparison relates to the complete electrotechnical equipment of a wind turbine on the basis of the selected generator system. As a result, the cost differences of the generator systems are greatly equalized which is exactly what this comparison is intended to show.

The assessment of the electrical efficiency requires a differentiated approach. It is of little use to compare the efficiencies of the different electric generators only by taking data merely from the catalogue. The actual differences will only become apparent in the context of the electrical system, on the basis of the selected type of generator, but also taking into consideration an inverter, if necessary for the connection to the grid.

The efficiency of the transformer, approx. 98 to 99 %, has been excluded. The figures for reactive power compensation and harmonic frequency filtering have to be considered. If they are required, these two devices will degrade the total efficiency. The following losses of efficiency can be assumed as guide values:

- static reactive power compensation 0.8 - 1.0 %,
- harmonics filter approx. 0.5 %.

The speed range of the generator system has a considerable influence on the electrical efficiency and on the cost. In comparison, an "economic" speed range, adapted to the individual concept, has been assumed. Regardless of the efficiency and cost, a wider speed range can be selected.

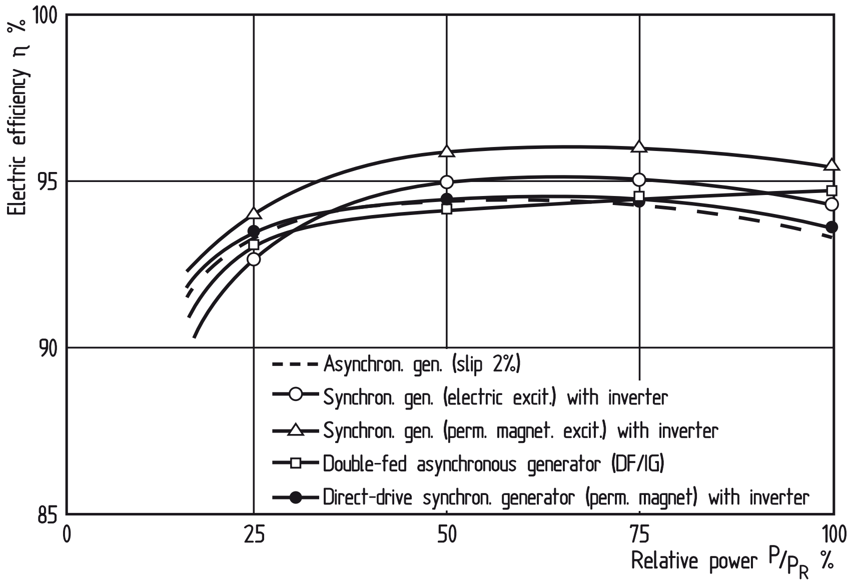

Fig. 10.42. Total efficiency of generator-inverter systems

The efficiencies listed in Table 10.41 are to be understood as at rated power. In the range of partial load the efficiency decreases by different amounts depending on the system. The differences are not very great at rated power (Fig. 10.42). But at partial load the various systems show larger differences. The direct-drive concepts and generators with permanent magnet excitation are remarkably superior to the others. This is quite important for the energy yield on low wind speed sites, for example on the inland sites in Europe.

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